2. EXECUTIVE SUMMARY AND CONCLUSIONS

2.1. COMPARISON OF METHODS AND BASIC NUCLEAR DATA

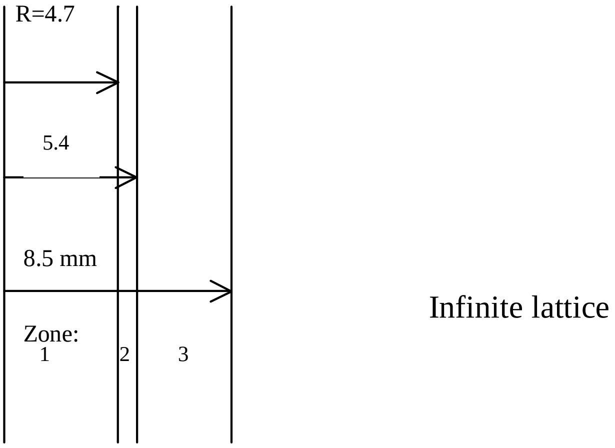
2.1.1. Cell-burnup calculations

In order to establish a comparison of the effect of different methods and databases applied in the countries participating in the CRP, benchmark calculations had to be performed before the start of the actual fuel cycles studies. For the first plutonium incineration benchmark calculations, the PWR-type reactor has been chosen because it is the reactor type that has the largest share in the current production of nuclear energy. The following topic was selected for the Agency benchmark 1:

“Calculation of the isotopic composition, cross-sections and fluxes for a typical PWR-cell loaded with (Pu-Th)O_2 - fuel, as a function of the fuel burnup.”

2.1.1.1. Definition of the fuel cell and tasks

The geometry of the reference fuel cell is displayed in Fig. 2.1. Table 2.1 gives the description of the material composition in terms of nuclide concentrations for the different cell zones.



Average power: P = 211 W/cm

Average temperature of the fuel: T_{fuel} = 1023 K

Average temperature of the water: T_{mod} = 583 K

FIG. 2.1. Layout of the reference fuel cell.

TABLE 2.1. INITIAL NUCLIDE DENSITIES IN THE CELL (atoms/cm^3)

	average in cell	zone 1	zone 2	zone 3
Th-232	6.45E+21	2.11E+22		
Pu-238	2.97E+18	9.72E+18		
Pu-239	1.83E+20	5.99E+20		
Pu-240	7.10E+19	2.32E+20		
Pu-241	2.35E+19	7.69E+19		
Pu-242	1.46E+19	4.78E+19		
Cr	1.99E+20		8.14E+19	3.20E+20
Mn	1.26E+19			2.11E+19
Fe	5.20E+20		1.60E+20	8.46E+20
Ni	2.24E+20			3.76E+20
Zr	4.27E+21		4.37E+22	
C	1.60E+18			2.68E+18
H	2.86E+22			4.80E+22
O	2.78E+22	4.41E+22		2.40E+22

The task to be performed for this benchmark exercise was defined as follows:

Calculate the fuel burnup at constant power (211 W/cm) as a function of time, not using any neutron poison for reactivity control. For a burnup of 0, 30, 40, and 60 MWd per kg of heavy metal report the following items:

1) Neutron multiplication (k_{eff});
2) Total neutron flux;
3) Average energy per fission;
4) Residual amount of plutonium;
5) Fraction of fissile plutonium;
6) Amount of generated minor actinides;
7) Average, (1-group, for the comparison) microscopic cross sections for absorption, and fission for the heavy metal isotopes from ^{232}Th through ^{244}Cm.

2.1.1.2. Benchmark results

The comparison of the results achieved by the participants is displayed in Figs 2.2 - 2.8 and in Tables 2.2 and 2.3. The results show some deviations, e.g., in the calculated cell reactivity (ranging from $\Delta\rho \approx 2\%$ initially to $\Delta\rho \approx 5\%$ at the end of burnup) and in the average effective energy per fission of the respective mixture of fissionable isotopes (discrepancy up to 4%). The results for the incineration rate of the plutonium isotopes, and for the build-up of minor actinides out of plutonium, as well as the ^{233}U build-up from ^{232}Th are in a good agreement.

Based on these results, the participants of the CRP came to the conclusion that:

- generally, the different methods and databases are comparable to the degree, needed to permit sharing of the research for different reactor types among different groups of countries;
- however, a second benchmark should be performed for the special heterogeneity of a PWR-lattice.

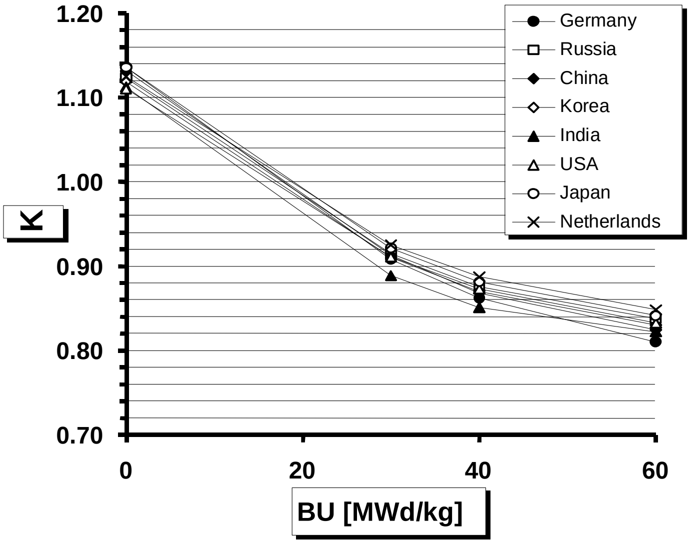


FIG. 2.2. Neutron multiplication vs. heavy-metal burnup.

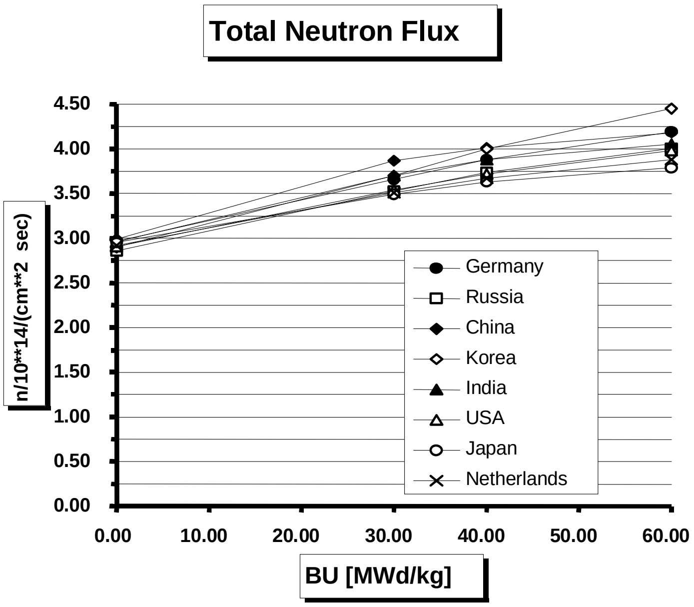


FIG. 2.3. Total neutron flux vs. heavy-metal burnup.

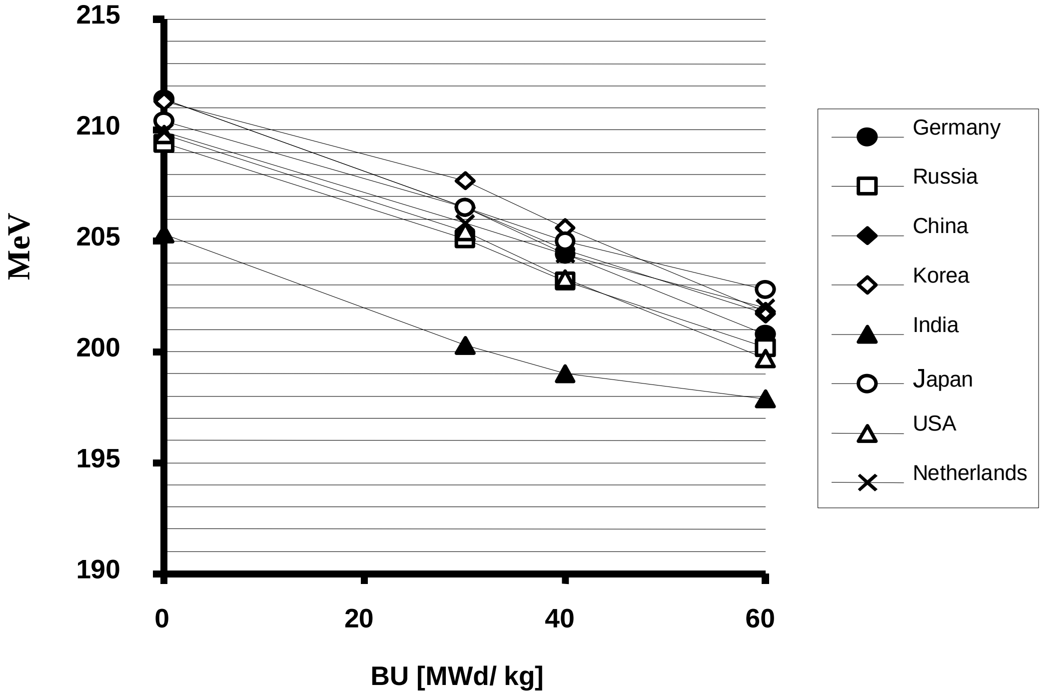


FIG. 2.4. Average energy per fission vs. heavy-metal burnup.

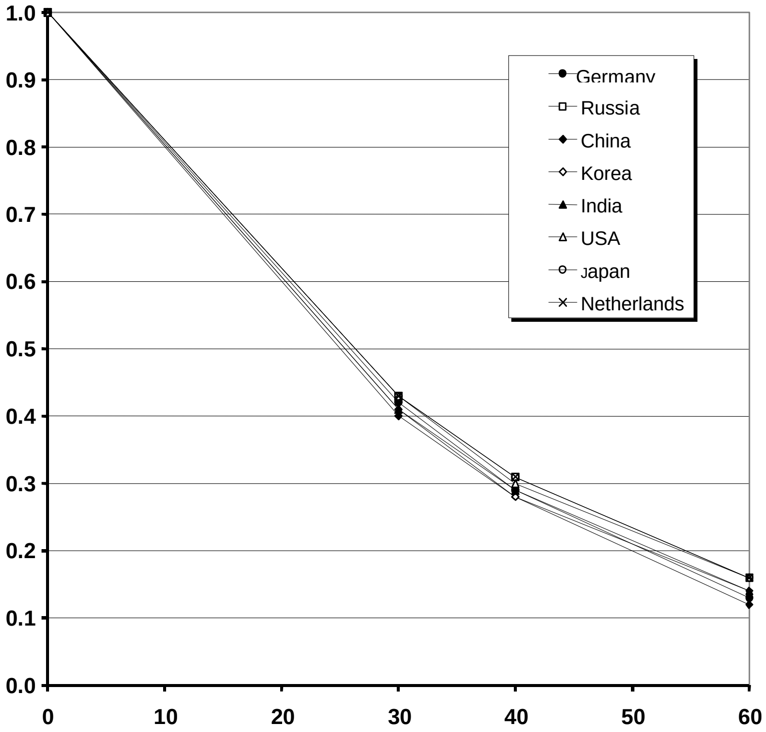


FIG. 2.5. ($Pu/Pu_{initial}$) vs. heavy-metal burnup (MWd/t).

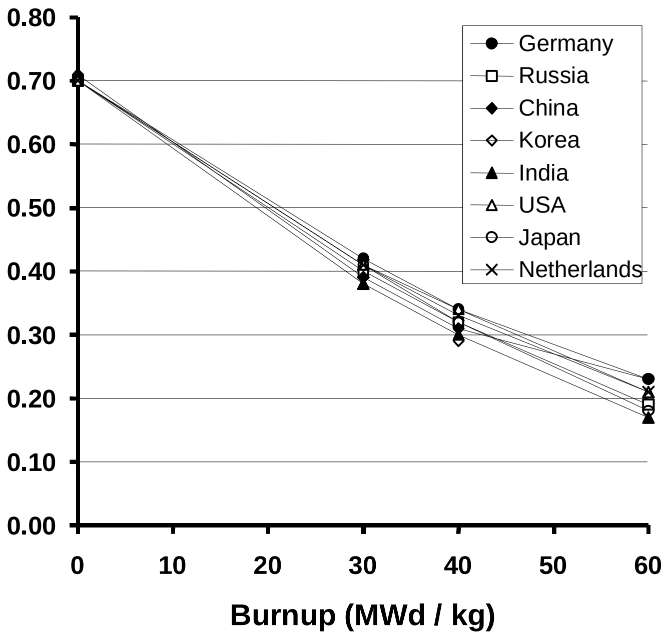
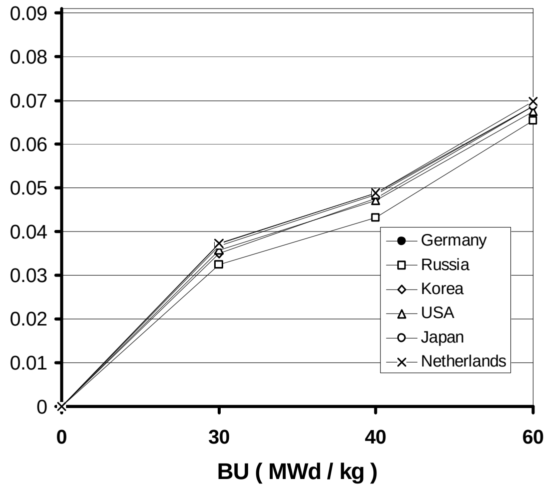


FIG. 2.6. (Pu-fiss/Pu-total) vs. heavy-metal burnup.



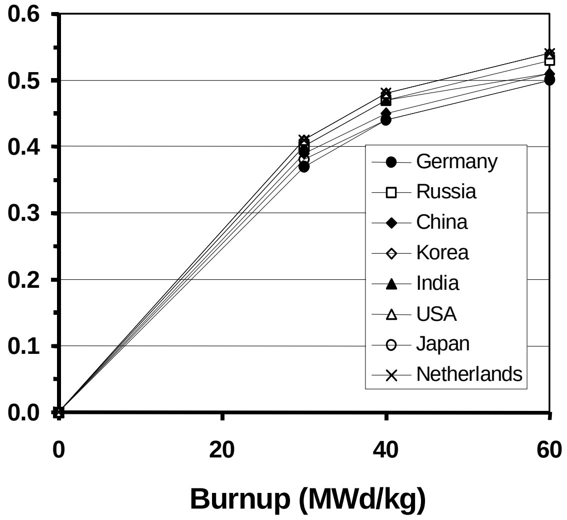


FIG. 2.7. Minor actinides/initial plutonium.

FIG. 2.8. ^{233}U bred from Th/initial fissile plutonium.

TABLE 2.2. CROSS SECTIONS AT BURNUP = 0 MWd/kg

		Germany	Russia	China	Korea	India	USA	Japan	NL
Th-232									
	fission	0.0249	0.0260	0.0247	0.0281	0.0259	0.0276	0.029	0.0264
	absorption	0.7889	0.8579	0.7986	0.8557	0.8664	0.858	0.817	0.849
Pa-233									
	fission	0.1631	0.3879		0.175	0.3836		0.128	0.1743
	absorption	24.95	28.11		24.55	27.7		24.97	25.11
U-233									
	fission	35.45	36.77		34.29	35.7		34.93	35.16
	absorption	40.6	42.05		39.37	41.3		40.03	40.29
U-234									
	fission	0.531	0.4961		0.5607			0.549	0.565
	absorption	22.46	21.97		22.66			20.9	22.22
U-235									
	fission	22.43	22.5		21.51	22.6		21.65	22.12
	absorption	29.07	28.81		27.55	29.3		27.73	28.32
U-236									
	fission	0.3466	0.2119		0.3528			0.352	0.357
	absorption	10.85	9.669		10.11			10.12	10.6
U-238									
	fission	0.11	0.1062					0.114	0.114
	absorption	8.219	8.200					7.785	7.923
Np-237									
	fission	0.528	0.5607		0.5656			0.571	0.564
	absorption	27.92	25.56		27.14			27.21	27.7
Np-239									
	fission	0.621	0.6383		0.6578			0.659	0.664
	absorption	15.28	15.03		15.9			14.55	14.74
Pu-238									
	fission	1.981	2.171		1.963	2.04	2.037	2.038	2.05
	absorption	17.94	17.60		17.3	17.5	17.05	16.83	17.3
Pu-239									
	fission	44.63	44.98	44.31	43.23	44.1	44.05	43.89	44.09
	absorption	69.74	69.90	69.00	66.98	68.5	69.06	68.11	68.4
Pu-240									
	fission	0.630	0.5847	0.6224	0.6209	0.5459	0.5659	0.618	0.6593
	absorption	49.72	50.90	42.70	49.62	48.3	48.38	50.24	49.57
Pu-241									
	fission	55.03	55.32	56.27	52.89	53.6	54.18	52.29	54.27
	absorption	72.97	73.04	74.56	69.74	74.16	71.84	69.68	71.69
Pu-242									
	fission	0.4502	0.4448	0.4455	0.4754		0.4988	0.475	0.4979
	absorption	33.91	19.84	35.49	19.14	27.2	29.68	22.81	23.63
Am-241									
	fission	0.8569	0.8580		0.9062	0.923		0.881	0.9617
	absorption	62.47	63.68		60.6	65.09		60.24	64.72
Am-242m									
	fission	289.3	312.0		277.31			264.0	287.1
	absorption	346.0	382.9		331.8			314.9	352.1
Am-243									
	fission	0.4479	0.4638		0.5038			0.485	
	absorption	49.67	49.51		48.77			50.04	
Cm-242									
	fission	0.4503	1.295		0.4705			1.312	1.0818
	absorption	5.699	5.326		4.222			5.056	4.952
Cm-243									
	fission	72.51	74.18		70.51			58.34	61.33
	absorption	80.97	82.82		78.77			66.72	71.8
Cm-244									
	fission	0.9772	0.8405		1.082			0.872	1.041
	absorption	18.29	19.6		23.55			19.90	18.01

TABLE 2.3. CROSS SECTIONS AT BURNUP = 60 MWd/kg

		Germany	Russia	China	Korea	India	USA	Japan	NL
Th-232									
	fission	0.0228	0.0240	0.0226	0.0246	0.0237	0.0254	0.025	0.0234
	absorption	1.0893	1.141	1.085	1.295	1.170	1.1425	1.163	1.132
Pa-233									
	fission	0.1492	0.3568	0.1482	0.1512	0.3500	0.3669	0.113	0.155
	absorption	21.78	23.85	21.78	22.96	24.3	23.6	22.21	21.34
U-233									
	fission	57.42	57.56	57.16	67.68	58.9	56.35	60.79	55.4
	absorption	64.40	64.23	64.17	75.68	66.2	63.41	68.06	62.12
U-234									
	fission	0.5056	0.4561	0.5025	0.5093		0.468	0.483	0.528
	absorption	23.56	16.74	24.29	24.44		16.73	19.66	19.1
U-235									
	fission	47.45	46.79	47.27	57.63	48.6	47.14	50.66	45.8
	absorption	58.36	57.03	58.23	69.62	59.7	57.5	61.56	55.91
U-236									
	fission	0,3086	0.1951	0.3116	0.2818		0.203	0.309	0.309
	absorption	9.252	8.289	9.627	6.829		8.342	8.82	8.64
U-238									
	fission	0.1006	0.0792				0.1071	0.10	0.101
	absorption	7.595	7.227				7.207	7.241	7.234
Np-237									
	fission	0.4830	0.5160	0.4796	0.483		0.5083	0.505	0.509
	absorption	34.69	31.66	34.07	39.19		34.59	35.48	34.19
Np-239									
	fission	0.5667	0.5864		0.5581		0.5981	0.583	0.6001
	absorption	15.69	15.08		19.68		15.03	15.25	15.01
Pu-238									
	fission	2.468	2.635		2.655	2.58	2.538	2.615	2.525
	absorption	38.75	36.92		47.22	38.9	36.96	39.61	36.36
Pu-239									
	fission	116.7	116.9	113.3	146.3	120.9	116.5	129.3	114.01
	absorption	182.8	183.0	177.0	228.3	189.0	184.1	202.3	178.1
Pu-240									
	fission	0.5927	0.5572	0.5836	0.5611	0.5117	0.5322	0.566	0.6163
	absorption	126.3	135.5	97.98	172.6	123.6	121.0	143.27	126.9
Pu-241									
	fission	126.3	124.9	125.3	153.7	124.6	124.7	133.6	121.8
	absorption	168.5	166.9	167.1	205.6	175.3	166.4	180.0	162.8
Pu-242									
	fission	0.4115	0.4089	0.4087	0.4060		1.437	0.419	0.446
	absorption	29.49	16.75	31.91	14.00	21.70	79.95	17.24	17.84
Am-241									
	fission	1.090	1.118		1.269	1.283	1.285	1.204	1.256
	absorption	111.8	116.3		136.5	123.9	119.6	126.4	116.01
Am-242m									
	fission	718.7	784.7		888.5			745.8	706.01
	absorption	864.0	967.6		1069			892.2	870.5
Am-243									
	fission	0.4094	0.4262		0.4363		0.4268	0.431	0.423
	absorption	42.02	41.98		46.39		43.09	44.22	41.73
Cm-242									
	fission	0.5550	14.18		0.6125			1.457	1.184
	absorption	6.2300	5.893		5.26			5.837	5.597
Cm-243									
	fission	98.66	97.21		112.3			88.11	73.7
	absorption	109.0	107.4		123.8			102.28	87.47
Cm-244									
	fission	0.9174	0.8148		0.9747			0.829	0.964
	absorption	16.98	17.06		21.67			18.56	15.39

2.1.2. Lattice calculations for LWR

While for a Pebble-bed HTR, having a nearly homogeneous core structure, a neutronics calculation for the entire core is regarded to be the adequate step following the cell calculation, an additional inter-comparison of the heterogeneous lattice calculation methodology appeared to be useful in case of the PWR. Thus, for the PWR part of the CRP, a second benchmark was established. Five countries participated in this benchmark: India, Israel, Japan, Republic of Korea, and Russian Federation. The benchmark was designed to compare assembly-level calculation methods, by defining a 2-D lattice simulating a typical PWR fuel assembly.

2.1.2.1. Benchmark definition and tasks

General:

17x17 array of the fuel rods, including 25 water hole positions.
No guide tubes material. No assembly casing.
No buckling. Quarter assembly symmetry.
Burnup calculations with constant specific power of 37.7 MW/t (initial heavy metal).

Geometry:

Outer dimensions, cm:	22.662×22.662
Cell pitch, cm:	1.33306
Fuel pellet radius, cm:	0.4127
Cladding thickness, cm:	0.0617
Equiv. cell radius, cm:	0.7521

Material compositions (atoms/barn x cm):

Fuel:

5% PuO_2 + 95% ThO_2. Temperature: 900 K.

Th-232	2.0592E-2
Pu-238	2.2900E-5
Pu-239	7.4780E-4
Pu-240	2.9030E-4
Pu-241	1.5340E-4
Pu-242	5.0100E-5
O-16	4.3710E-2

Cladding:

Natural Zr. Temperature: 600 K.

Zr-nat.	4.3241E-2

Moderator:

Light water, with 500 ppm natural boron. Temperature: 573 K.

H-1	4.7708E-2
O-16	2.3854E-2
B-10	3.9518E-6
B-11	1.5906E-5

Results for comparison:

1. Criticality as a function of burnup. Burnup range from 0 to 60 GWd/t;
2. Fuel composition as a function of burnup (major actinides and fission products);
3. Local pin-by-pin power distribution;
4. Moderator temperature coefficient for 0 and 60 GWd/t;
5. Doppler coefficient for 0 and 60 GWd/t;
6. Soluble boron worth for 0 and 60 GWd/t.

2.1.2.2. Benchmark results

Infinite multiplication factor:

The results are summarized in Table 2.4 and Fig. 2.9.

TABLE 2.4. k_{inf} AS A FUNCTION OF BURNUP

Burnup, GWd/T	Russian Federation	Japan	Republic of Korea	India	Israel
0	1.189	1.1987	1.1864	1.2076	1.1956
0.5	1.1569	1.1670	1.1551	1.1736	1.1643
20	1.0298	1.0521	1.0303	1.0372	1.0290
40	0.9147	0.9527	0.9167	0.9104	0.9119
60	0.8315	0.8657	0.8310	0.8294	0.8314

Significant discrepancies are found between k_{inf} values: ~ 2.3% ΔK at BOL and ~ 3.5% ΔK at EOL. It is also noted that there is no clear burnup dependency of the discrepancies.

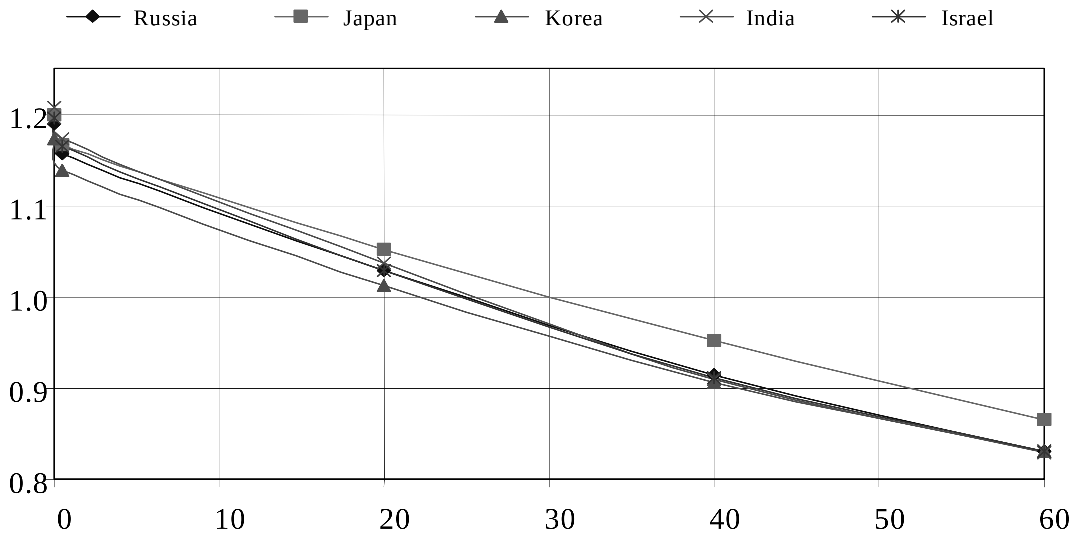


Fig. 2.9. k_{inf} as a function of burnup.

Fuel composition:

The results obtained for the composition of the actinide fuel are listed in Table 2.5 as a function of the heavy metal burnup. Note that there is:

- a good agreement for the ^{238}Pu concentration;
- a reasonable agreement for the even plutonium isotopes concentrations;
- significant discrepancies are found for the odd plutonium isotopes;
- a reasonable agreement in the case of the ^{232}Th and ^{233}U concentrations.

TABLE 2.5. FUEL COMPOSITION (ACTINIDES) AS A FUNCTION OF BURNUP

	Number Density (atoms/barn×cm)				
Burnup, GWd/T	Russia	Japan	Rep. of Korea	India	Israel
Th-232					
0.0	2.059×10^{-2}	2.059×10^{-2}	2.059×10^{-2}	2.059×10^{-2}	2.059×10^{-2}
0.5	2.059×10^{-2}	2.059×10^{-2}	2.059×10^{-2}	-	-
20.0	2.037×10^{-2}	2.036×10^{-2}	2.037×10^{-2}	2.036×10^{-2}	2.037×10^{-2}
40.0	2.011×10^{-2}	2.008×10^{-2}	2.011×10^{-2}	-	2.010×10^{-2}
60.0	1.977×10^{-2}	1.975×10^{-2}	1.978×10^{-2}	1.970×10^{-2}	1.977×10^{-2}
Pu-238					
0.0	2.290×10^{-5}	2.290×10^{-5}	2.290×10^{-5}	2.290×10^{-5}	2.290×10^{-5}
0.5	2.279×10^{-5}	2.279×10^{-5}	2.279×10^{-5}	-	-
20.0	1.940×10^{-5}	1.952×10^{-5}	1.928×10^{-5}	1.829×10^{-5}	1.937×10^{-5}
40.0	1.834×10^{-5}	1.879×10^{-5}	1.798×10^{-5}	-	1.793×10^{-5}
60.0	1.687×10^{-5}	1.816×10^{-5}	1.636×10^{-5}	7.488×10^{-6}	1.611×10^{-5}
Pu-239					
0.0	7.478×10^{-4}	7.478×10^{-4}	7.478×10^{-4}	7.478×10^{-4}	7.478×10^{-4}
0.5	7.348×10^{-4}	7.351×10^{-4}	7.349×10^{-4}	-	-
20.0	3.174×10^{-4}	3.270×10^{-4}	3.175×10^{-4}	2.993×10^{-4}	3.147×10^{-4}
40.0	0.810×10^{-4}	0.961×10^{-4}	0.820×10^{-4}	-	0.773×10^{-4}
60.0	0.118×10^{-4}	0.170×10^{-4}	0.121×10^{-4}	0.479×10^{-4}	0.105×10^{-4}
Pu-240					
0.0	2.903×10^{-4}	2.903×10^{-4}	2.903×10^{-4}	2.903×10^{-4}	2.903×10^{-4}
0.5	2.911×10^{-4}	2.909×10^{-4}	2.911×10^{-4}	-	-
20.0	2.826×10^{-4}	2.678×10^{-4}	2.820×10^{-4}	2.846×10^{-4}	2.853×10^{-4}
40.0	1.981×10^{-4}	1.845×10^{-4}	1.991×10^{-4}	-	2.014×10^{-4}
60.0	0.809×10^{-4}	0.839×10^{-4}	0.874×10^{-4}	0.670×10^{-4}	0.846×10^{-4}
Pu-241					
0.0	1.534×10^{-4}	1.534×10^{-4}	1.534×10^{-4}	1.534×10^{-4}	1.534×10^{-4}
0.5	1.540×10^{-4}	1.543×10^{-4}	1.541×10^{-4}	-	-
20.0	1.591×10^{-4}	1.703×10^{-4}	1.605×10^{-4}	1.545×10^{-4}	1.578×10^{-4}
40.0	1.233×10^{-4}	1.360×10^{-4}	1.231×10^{-4}	-	1.214×10^{-4}
60.0	0.650×10^{-4}	0.741×10^{-4}	0.641×10^{-4}	0.539×10^{-4}	0.639×10^{-4}
Pu-242					
0.0	0.5010×10^{-4}	0.5010×10^{-4}	0.5010×10^{-4}	0.5010×10^{-4}	0.5010×10^{-4}
0.5	0.5050×10^{-4}	0.5043×10^{-4}	0.5051×10^{-4}	-	-
20.0	0.7088×10^{-4}	0.6813×10^{-4}	0.7248×10^{-4}	0.7203×10^{-4}	0.7020×10^{-4}
40.0	0.9877×10^{-4}	0.9245×10^{-4}	1.0380×10^{-4}	-	0.9832×10^{-4}
60.0	1.1890×10^{-4}	1.1030×10^{-4}	1.2880×10^{-4}	1.1624×10^{-4}	1.1940×10^{-4}
U-233					
0.0	-	-	-	-	-
0.5	0.7319×10^{-6}	0.7918×10^{-6}	0.7378×10^{-6}	-	-
20.0	1.5150×10^{-4}	1.5996×10^{-4}	1.5350×10^{-4}	1.5960×10^{-4}	1.5330×10^{-4}
40.0	2.6120×10^{-4}	2.7492×10^{-4}	2.6400×10^{-4}	-	2.6750×10^{-4}
60.0	3.1350×10^{-4}	3.3109×10^{-4}	3.1600×10^{-4}	3.1910×10^{-4}	3.2350×10^{-4}
U-234					
0.0	-	-	-	-	-
0.5	0.2361×10^{-7}	0.2522×10^{-7}	0.1556×10^{-7}	-	-
20.0	0.8565×10^{-4}	0.9714×10^{-5}	0.8025×10^{-5}	0.9627×10^{-5}	0.7913×10^{-5}
40.0	2.6680×10^{-4}	2.8855×10^{-5}	2.5200×10^{-5}	-	2.5290×10^{-5}
60.0	5.3200×10^{-4}	5.4315×10^{-5}	4.9070×10^{-5}	6.1950×10^{-5}	5.0450×10^{-5}

Pin-by-pin power distribution:

The local power distributions are shown in Figs 2.10a and 2.10b for the BOL and 60 GWd/t burnup points, respectively. A very good agreement for the BOL is indicated, with less than 2% relative power differences. The “hot rod” is identified with almost identical power of 1.124. A divergence of the local power values with burnup resulted in 5-10% differences, which may be partially attributed to different fissile (odd numbers) plutonium isotope concentrations.

xxxx	Russia
xxxx	Japan
xxxx	Korea
xxxx	Israel

0 GWd / t

W								
1.071 1.068 1.071 1.075	1.025 1.019 1.015 1.015							
1.059 1.068 1.071 1.076	1.014 1.020 1.015 1.016	1.015 1.021 1.017 1.018						
W	1.068 1.068 1.070 1.075	1.072 1.071 1.073 1.078	W					
1.063 1.066 1.070 1.074	1.016 1.018 1.015 1.015	1.009 1.023 1.019 1.020	1.084 1.084 1.087 1.091	1.080 1.068 1.077 1.074				
1.072 1.061 1.066 1.069	1.013 1.014 1.011 1.011	1.005 1.019 1.016 1.017	1.08 1.085 1.088 1.092	1.122 1.107 1.126 1.124	W			
W	1.053 1.051 1.056 1.060	1.058 1.054 1.061 1.064	W	1.099 1.081 1.100 1.100	1.049 1.045 1.053 1.055	0.963 0.965 0.964 0.964		
1.051 1.021 1.031 1.034	0.979 0.977 0.978 0.980	0.98 0.978 0.980 0.981	1.033 1.024 1.034 1.036	0.973 0.976 0.976 0.976	0.922 0.941 0.928 0.931	0.910 0.915 0.902 0.904	0.886 0.899 0.884 0.884	
0.925 0.929 0.926 0.926	0.924 0.925 0.923 0.922	0.921 0.925 0.922 0.921	0.930 0.929 0.924 0.923	0.922 0.921 0.914 0.914	0.907 0.910 0.898 0.897	0.889 0.901 0.886 0.885	0.889 0.896 0.878 0.876	0.876 0.898 0.876 0.872

FIG. 2.10a. Relative power distribution.

60 GWd / t

xxxx Russia
xxxx Japan
xxxx Korea
xxxx Israel

W								
0.951 1.037 1.025 1.054	0.926 1.027 1.015 1.027							
0.944 1.037 1.025 1.055	0.931 1.027 1.015 1.027	0.939 1.027 1.015 1.028						
W	0.955 1.037 1.024 1.054	0.96 1.038 1.025 1.056	W					
0.959 1.034 1.023 1.051	0.952 1.024 1.013 1.025	0.950 1.027 1.014 1.028	0.986 1.042 1.027 1.064	0.975 1.039 1.022 1.057				
0.979 1.028 1.019 1.046	0.957 1.018 1.010 1.019	0.967 1.021 1.011 1.023	1.001 1.038 1.024 1.060	0.922 1.041 1.026 1.074	W			
W	0.984 1.017 1.013 1.034	0.991 1.019 1.013 1.037	W	1.024 1.024 1.015 1.052	1.003 1.007 1.004 1.022	1.014 0.978 0.983 0.969		
1.026 0.997 1.003 1.013	1.009 0.989 0.994 0.988	1.022 0.989 0.994 0.989	1.032 0.997 1.001 1.012	1.030 0.985 0.989 0.981	1.051 0.971 0.978 0.952	1.029 0.957 0.968 0.930	1.027 0.946 0.960 0.912	
1.054 0.966 0.985 0.955	1.045 0.965 0.983 0.952	1.049 0.965 0.983 0.952	1.055 0.965 0.982 0.952	1.044 0.961 0.977 0.942	1.036 0.954 0.970 0.927	1.024 0.948 0.962 0.914	1.017 0.944 0.956 0.903	1.013 0.945 0.953 0.897

FIG. 2.10b. Relative power distribution.

Temperature coefficients and boron worth values are presented in Table 2.6.

TABLE 2.6. TEMPERATURE COEFFICIENTS AND BORON WORTH (×10^{-4})

	0 GWd/T			60 GWd/t		
	MTC[a]	DC[b]	BW[c]	MTC	DC	BW
Russian Federation	-3.500	-0.280	-0.380	-1.5	-0.360	-1.100
Japan	-2.696	-0.283	-0.341	-0.969	-0.378	-0.864
Republic of Korea	-3.200	-0.311	-0.408	-1.289	-0.397	-1.125
Israel	-3.333	-0.292	-0.400	-1.142	-0.477	-1.119

$$MTC = \frac{\Delta K}{K_1 * K_2 * \Delta T_m}$$ - Moderator temperature coefficient, T_m – moderator temperature.

$$\mathrm{DC} = \frac{\Delta \mathrm{K}}{\mathrm{K}_1 * \mathrm{K}_2 * \Delta \mathrm{T}_\mathrm{f}}$$ - Doppler coefficient, T_f – fuel temperature.

$$\mathrm{BW} = \frac{\Delta \mathrm{K}}{\mathrm{K}_1 * \mathrm{K}_2 * \Delta \mathrm{C}}$$ - Soluble boron worth, C – boron concentration in ppm.

Note 1: All temperature coefficients are negative, the burnup dependence, i.e., plutonium depletion effect is correct.

Note 2: All BOL values show reasonable agreement, the divergence of the EOL values may be attributed to different plutonium concentrations.

2.2. EVALUATION OF THE POTENTIAL OF LWRs, HTRs, HWRs, AND MSRs for PLUTONIUM INCINERATION

2.2.1. Incentives

The aim of the research during the second stage of the CRP was to find fuelling strategies, which – on the basis of proven reactor technology are suitable to incinerate plutonium most effectively on the one hand, and to minimize the amount of plutonium to be disposed, on the other hand. Only plutonium of the first generation, namely typical LWR-plutonium, and weapons-plutonium were regarded within scope of this CRP.

Four types of reactors were investigated in view of their potential to burn plutonium, each by one group of countries. Israel, Republic of Korea, Russian Federation, and the USA have done research on LWRs; China, the Netherlands and Germany have studied plutonium burning in Modular HTRs; India studied the respective potential of the PHWR, and Japan that of the MSR.

Two characteristic values – aiming at two different optimization goals - may describe the effectiveness of plutonium incineration in the different reactors:

(1) The amount of plutonium, which is burned per unit of produced electric energy. Maximization of this characteristic optimizes the reduction rate of existing plutonium stockpiles.

(2) The relation between the amount of plutonium, which is burned during the lifetime of the fuel elements, and the amount of plutonium, which is residual in the unloaded fuel. Maximization of this characteristic minimizes the plutonium quantity, which either has to be finally disposed or has to be re-fabricated a second time.

Some initial remarks have to be made concerning the admissibility of a comparison and the assessment of the data presented by the countries participating in this CRP.

Each country did the research on its favorite reactor concept, using its own methods and computer codes as well as its specific database. Although, as already mentioned, benchmark calculations for a PWR-cell and for a PWR-lattice were performed during the first stage of this CRP, the numerical simulation of a complete reactor and of his fuel cycle is a much more complex matter, and the results may well be influenced by the degree of detail of the numerical modeling. Also, the restrictions of the reactor fuelling in view of safety aspects (power peaking, temperature coefficients, transient behavior) may have been observed by the various groups up to different degrees. Nevertheless, the information resulting from the comparison presented in this report seems to be well appropriate and sufficiently reliable to show the potential of the different reactor concepts incinerating plutonium in an effective manner, and to help the suggesting a demonstration of plutonium burning in a reactor in one of the member countries.

By the time the data presented here was compiled the Netherlands had not yet performed calculations for an entire reactor, but for an HTR-fuel cell only. Thus, general effects and operational constraints resulting from, e.g., neutron leakage, local power peaking, and requirements of reactor control may not be observed. Furthermore, a fuel cell containing only plutonium and no thorium was investigated. Therefore, the data is excluded from the summary tables in order to avoid confusion. Results of this research have been published elsewhere [1].

2.2.2. Results

Tables 2.7 and 2.8 show the results of the research work, which has been done based on LWR plutonium and on weapons-grade plutonium, respectively. Blank spaces indicate that results have not yet been evaluated so far. The thermal efficiency 0.33 for water-cooled reactors and a value 0.4 for HTR and for MSR has been assumed when compiling these tables. Two countries (Russian Federation and Germany) investigated 2 different alternative fuelling strategies each, to be used for their favored reactor concept:

Russian Federation studied the VVER-reactor applying:

a) partial (1/3 of the core) loading with PuO_2 – ThO_2 fuel (“Partial Pu-Inv.”);
b) loading PuO_2-ThO_2 in the entire core (“Full Pu-Inv.”).

Germany in its study made use of the capability of the coated particle fuel of the HTR for a very high heavy metal burnup in order to minimize the amount of residual plutonium in the discharged fuel elements (core “minimal residual plutonium”). The possibility to increase the incineration rate by a reduction of the burnup is demonstrated by the case “increased inciner.” (for “LWR-Pu” only, Table 2.7).

The amount of LWR plutonium (Table 2.7), which is burned per unit of produced energy in the different reactor concepts generally decreases with increasing heavy metal burnup of the fuel. In view of the minimization of the residual plutonium in the discharged fuel elements, however, a distinct advantage of the high burnup is obvious. This is indicated by the ratio between the amount of plutonium, which is burned until the fuel element is discharged, and the residual amount, which either has to be disposed or has to be re-fabricated a second time (ratio Pu-burned/Pu-discharged).

Incinerating weapons-grade plutonium (Table 2.8) is generally more effective, especially if a high burnup is applied as for PHWR (India) and HTR (China and Germany). The practically complete absence of plutonium isotopes higher than ^{240}Pu in the fresh fuel shifts the occurrence of increased parasitic neutron absorption by ^{242}Pu and by minor actinides to a high burnup of this fuel. Thus, the plutonium can be burned to a high degree, achieving a high yearly destruction rate at the same time. The ratio between burnt and residual plutonium can go up to a value of 5.9 compared to 4.2 in the case of LWR plutonium.

Figure 2.11a and b expressively elucidates these relations. The incineration rate of plutonium (ordinate) is given in units of 200 kg/GW$_{el}$a, which is approximately the amount of plutonium produced by current LWRs. In other words, this number indicates, how many LWRs units could have their spent fuel plutonium incinerated by one unit of the considered plutonium burner.

2.2.3. Conclusions

— Incinerating LWR plutonium:
Water-cooled reactors (LWR and HWR), having a relatively low heavy-metal burnup (40-50 GWd/to) reach a large plutonium-incineration rate in the range of about 700-850 kg/GW$_{el}$a. On the other hand, this amount of incinerated plutonium is small compared to that remaining for disposal or reuse at the end of burnup (Pu burned/Pu discharged equals 0.8-1.7, which corresponds to a residual plutonium fraction in the range of 56 to 37%). Achieving a large heavy metal burnup (e.g., by HTR-fuel) results in a smaller amount of incinerated plutonium per unit of produced energy (500-650 kg/GW$_{el}$a), but distinctly reduces the fraction of residual plutonium down to 19%.

— Burning weapons-grade plutonium:
The higher neutronic value of weapons-grade plutonium and the strongly reduced build-up of minor actinides out of ^{242}Pu generally make weapons-grade plutonium incineration more effective than for LWR plutonium. While the amount of incinerated weapons plutonium per unit of produced electric energy is comparable to the incineration rate of LWR plutonium, the quantity of residual plutonium can be strongly reduced in case of weapons-grade plutonium. The ratio “Pu-burned/Pu-discharged” equals 1.5 to 2 (40 to 33% residual plutonium fraction) for LWRs, about 4 (20% residual plutonium fraction) for the HWR and up to 6 (14% residual plutonium fraction) in case of the HTR. Here, the advantage of reactors having high burnups, becomes obvious once more.

TABLE 2.7. BURNING LWR PLUTONIUM: MASS BALANCE: kg/GW$_{el}$a (FULL POWER)

	China	Germany (HTR)	India (PHWR)	Israel +USA (LWR)	Japan (MSR)	Republic of Korea (LWR)	Russian Federation (LWR)		
		minimal resid – plutonium	increased inciner.					Partial Pu-Inv.	Full Pu-Inv.
U-235/ U-233 charged	-	624/0	578/0				6/0	612 / 0	
Pu-charged	2521	615	929	1098	1419	1435	1708	519	1803
Pu-discharged	1576	119	288	405	614	435	875	401	953
Pu-burned	945	496	641	693	805	1000	833	117	850
Ratio Pu-burned/ Pu-discharged	0.6	4.2	2.2	1.7	1.3	2.3	0.95	0.29	0.89
U-233 produced		116	161	286		141	366	100	291
Average HM burnup (MWd/kg)		192	128	46		100	40	41	40

TABLE 2.8. BURNING WEAPONS-GRADE PLUTONIUM: MASS BALANCE: kg/GW$_{el}$a (FULL POWER)

	China (HTR) (Case “11g”)	Germany (HTR)	India (PHWR)	Israel + USA (LWR)	Japan (MSR)	Republic of Korea (LWR)	Russian Federation (LWR)	
							Partial Pu-Inv.	Full Pu-Inv.
U-235/ U-233 charged	-	188	-	-		7	612	-
Pu-charged	1097	820	725	1095	1425	1264	354	1220
Pu-discharged	212	118	141	361	521	507	266	462
Pu-burned	885	702	584	734	904	757	87	758
Ratio Pu-burned/ Pu-discharged	4.2	5.9	4.1	2.0	1.7	1.5	0.33	1.64
U-233 produced	207	151	204		233	397	100	294
Average HM burnup (MWd/kg)	103	128	70		100	40	41	41

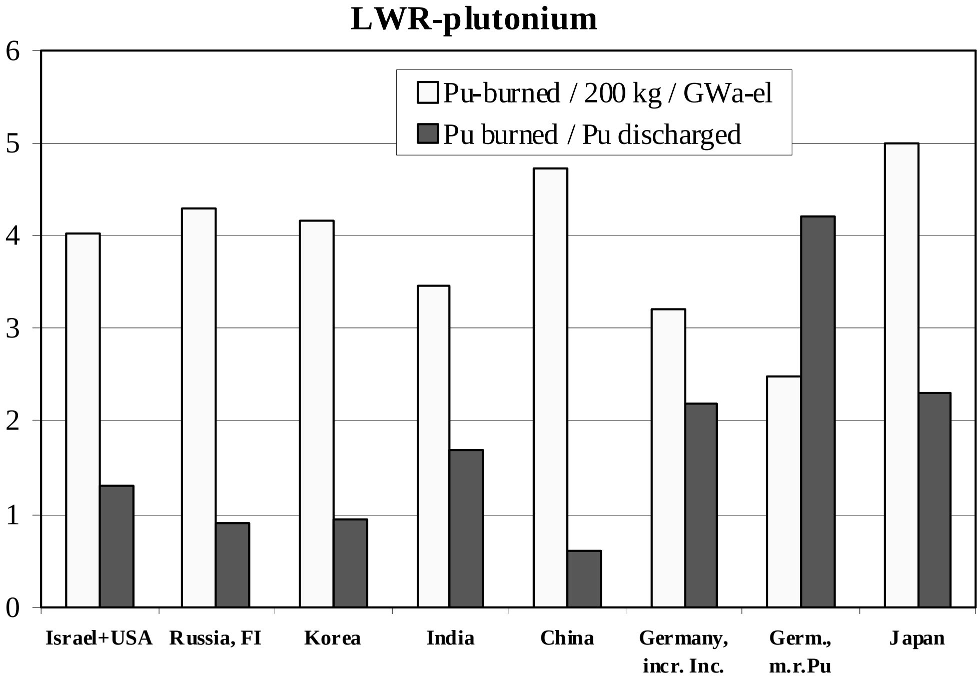


FIG. 2.11a. Burning LWR-grade plutonium.

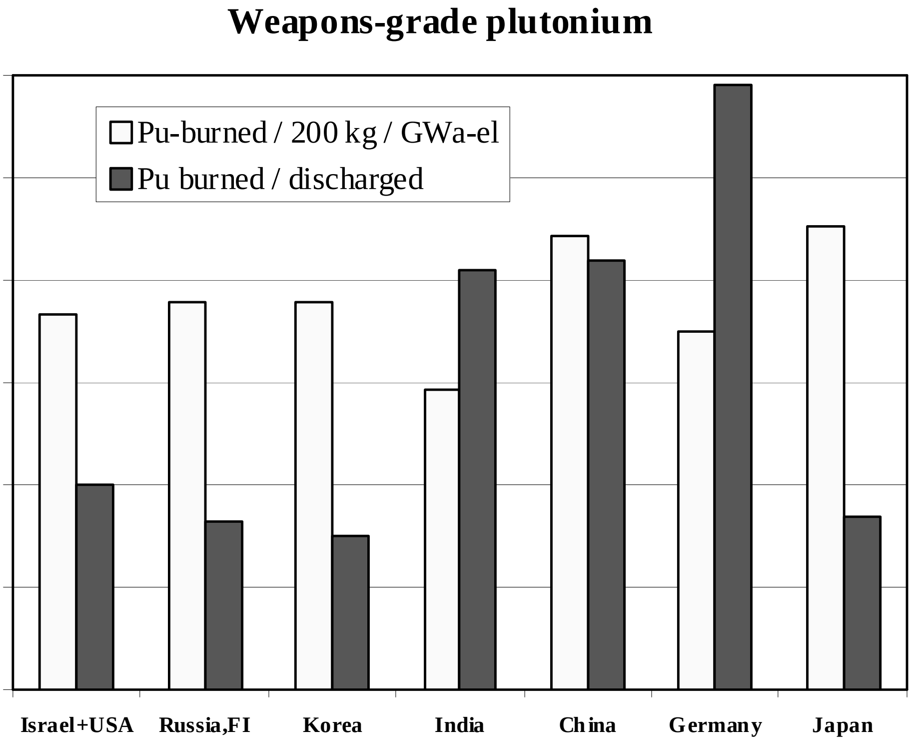


FIG. 2.11b. Burning weapons-grade plutonium.

2.3. EFFECT OF PLUTONIUM INCINERATION ON THE TOXICITY OF DISPOSED NUCLEAR WASTE

2.3.1. Incentives and database

The research reported in Section 2.2 primarily aims at the minimization of the proliferation risk by minimizing the plutonium production and maximizing the plutonium incineration. The question still remains, whether and to which degree the incineration of plutonium furthermore is an appropriate tool to significantly reduce the hazard potential of the nuclear waste, which in the end remains for final disposal.

The most common procedure in order to assess the toxicity of nuclear materials is based on the recommendations of the *International Commission on Radiological Protection*, defining "Annual Limits on Intake" for the radio-toxic isotopes. Recent recommendations are given in Sv/Bq and are called "Dose Coefficients for Intake (DCI)". It was agreed to use the values according to *ICRP Publications 68 /*ICRP 1994*/ and 61 /*ICRP 1991*/* as the common database within the frame of this CRP. A comparison between the waste of uranium-fuelled LWRs (providing no reprocessing of the discharged fuel) on the one hand and the waste produced at a scenario applying plutonium burning reactors on the other hand helps to assess the related effect on the toxicity.

2.3.2. Toxicity benchmark

In order to assure that the computer codes used in the different countries have been correctly updated in the sense of the statements of Section 2.3.1, the first step of this evaluation was a benchmark with respect to the toxicity of the spent fuel resulting from one year operation of a $1GW_{el}$ reference-PWR. The composition of the unloaded heavy metal isotopes is defined in Table 2.9.

TABLE 2.9. DISCHARGE RATE OF HEAVY METAL ISOTOPES (kg/year) FOR A TYPICAL PWR*

U-234	4.51E 00
U-235	2.70E 02
U-236	1.07E 02
U-237	2.70E-01
U-238	2.69E 04
Np-237	1.11E 01
Np-239	2.27E 00
Pu-238	3.12E 00
Pu-239	1.43E 02
Pu-240	5.78E 01
Pu-241	3.11E 01
Pu-242	1.02E 01
Am-241	8.87E-01
Am-242m	1.66E-02
Am-242	2.12E-03
Am-243	1.77E 00
Am-244	6.41E-05
Cm-242	2.38E-01
Cm-243	5.17E-03
Cm-244	4.56E-01
Cm-245	1.66E-02
Σ	2.75E 04

* All data normalized to 1000 MW_{el} the electric power output and 300 full-power days.

The tasks to be commonly performed then were to evaluate:

— The ingestion hazard of the complete heavy metal waste;

— The inhalation hazard of the complete heavy metal waste;

— The ingestion hazard of the heavy metal waste remaining after separation of 99% of all plutonium isotopes;

— The inhalation hazard of the heavy metal waste remaining after separation of 99% of all plutonium isotopes.

Dose Coefficients of Intake (DCI) for the heavy metal isotopes and for the fission products, to be commonly used, are given in Table 2.10.

On this basis the benchmark definition was:

— Calculate the total toxicity of the given heavy metals and of their daughter products for a decay period ranging from 10^0 years through 10^6 years;

— Exclude the bulk of plutonium and its daughter products from the calculation by a reduction of all initial plutonium isotopes by the factor 0.01. Calculate the remaining toxicity.

TABLE 2.10. DOSE COEFFICIENTS OF INTAKE (DCI)

Unit: Sv/Bq
NUCL: Isotope identification number = Z×10000 + W×10 + IS, with
Z: the atomic number
W: the atomic weight
IS: equal 0 or 1 for ground or metastable state, respectively
DCI-W: DCI value for water
DCI-A: DCI value for air

References:
ICRP Publication 68 (1994)
ICRP Publication 61 (1991), DCI calculated for reference dosis 20 mSv/a

NUCL	DCI-W	DCI-A	NUCL	DCI-W	DCI-A	NUCL	DCI-W	DCI-A
20040	0.E+00	0.E+00	882250	1.E-07	6.E-06	942360	9.E-08	2.E-05
812070	5.E-10	5.E-09	882260	3.E-07	2.E-05	942380	2.E-07	4.E-05
812080	5.E-10	5.E-09	882280	7.E-07	3.E-06	942390	3.E-07	5.E-05
812090	5.E-10	5.E-09	892250	2.E-08	8.E-06	942400	3.E-07	5.E-05
822060	0.E+00	0.E+00	892270	1.E-06	6.E-04	942410	5.E-09	9.E-07
822070	0.E+00	0.E+00	892280	4.E-10	3.E-08	942420	2.E-07	4.E-05
822080	0.E+00	0.E+00	902270	9.E-09	1.E-05	942430	9.E-11	1.E-10
822090	6.E-11	3.E-11	902280	7.E-08	4.E-05	942440	2.E-07	4.E-05
822100	7.E-07	1.E-06	902290	5.E-07	1.E-04	942450	7.E-10	7.E-10
822110	2.E-10	6.E-09	902300	2.E-07	4.E-05	952410	2.E-07	4.E-05
822120	6.E-09	3.E-08	902310	3.E-10	4.E-10	952421	2.E-07	4.E-05
822140	1.E-10	5.E-09	902320	2.E-07	4.E-05	952420	3.E-10	2.E-08
832090	0.E+00	0.E+00	902330	5.E-10	5.E-09	952430	2.E-07	4.E-05
832100	1.E-09	8.E-08	902340	3.E-09	7.E-09	952440	5.E-10	2.E-09
832110	9.E-10	3.E-08	912310	7.E-07	1.E-04	952450	6.E-11	8.E-11
832120	3.E-10	4.E-08	912320	7.E-10	1.E-08	962420	1.E-08	5.E-06
832130	2.E-10	4.E-08	912330	9.E-10	4.E-09	962430	2.E-07	3.E-05
832140	1.E-10	2.E-08	912341	5.E-10	5.E-09	962440	1.E-07	3.E-05
842100	2.E-07	3.E-06	912340	5.E-10	6.E-10	962450	2.E-07	4.E-05
842110	9.E-10	3.E-08	922320	3.E-07	4.E-05	962460	2.E-07	4.E-05
842120	9.E-10	3.E-08	922330	5.E-08	9.E-06	962470	2.E-07	4.E-05
842130	9.E-10	3.E-08	922340	5.E-08	9.E-06	962480	8.E-07	1.E-04
842140	9.E-10	3.E-08	922350	5.E-08	8.E-06	962490	3.E-11	5.E-11
842150	9.E-10	3.E-08	922360	5.E-08	8.E-06	962500	4.E-06	8.E-04
842160	9.E-10	3.E-08	922370	8.E-10	2.E-09	972490	1.E-09	2.E-07
842180	9.E-10	3.E-08	922380	4.E-08	7.E-06	972500	1.E-10	1.E-09
852170	9.E-10	3.E-08	922390	3.E-11	4.E-11	982490	4.E-07	7.E-05
862190	3.E-11	7.E-11	922400	1.E-09	8.E-10	982500	2.E-07	3.E-05
862200	3.E-11	7.E-11	932360	2.E-08	3.E-06	982510	4.E-07	7.E-05
862220	3.E-11	7.E-12	932370	1.E-07	2.E-05	982520	9.E-08	2.E-05
872210	9.E-10	3.E-08	932380	9.E-10	2.E-09	982530	1.E-09	1.E-06
872230	2.E-09	1.E-09	932390	8.E-10	1.E-09	982540	4.E-07	4.E-05
882230	1.E-07	7.E-06	932401	5.E-10	5.E-09	992530	6.E-09	3.E-06
882240	7.E-08	3.E-06	932400	8.E-11	1.E-10			

The results of the benchmark are displayed in Figs 2.12 and 2.13. The ingestion hazard and the inhalation hazard, respectively, resulting from the given initial isotope mixture, is plotted as a function of the decay time. The agreement between the participants is quite satisfying except that Israel+USA generally evaluate somewhat higher toxicity values for a decay time of about 10^6 years and longer. However – as can be seen from the figures – this fact does not appear to be important for the assessment of plutonium separation, because the impact of plutonium and its daughter nuclides on the toxicity of the waste tends to vanish at such a decay time, anyway.

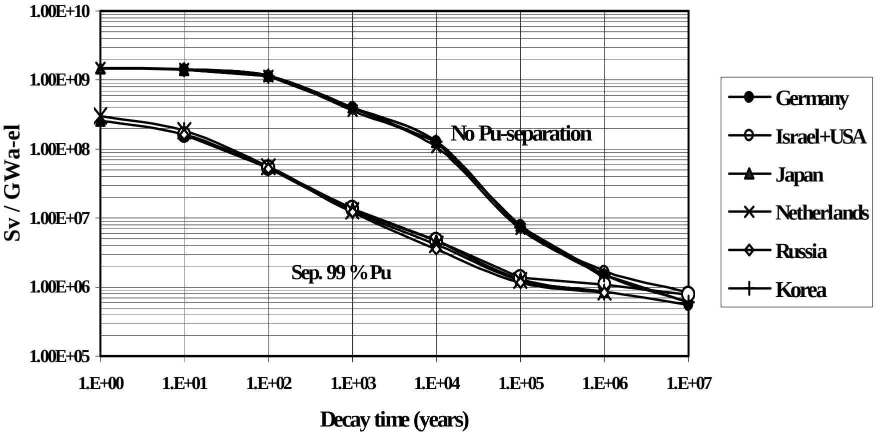


FIG. 2.12. Benchmark: ingestion hazard of the heavy metal isotopes.

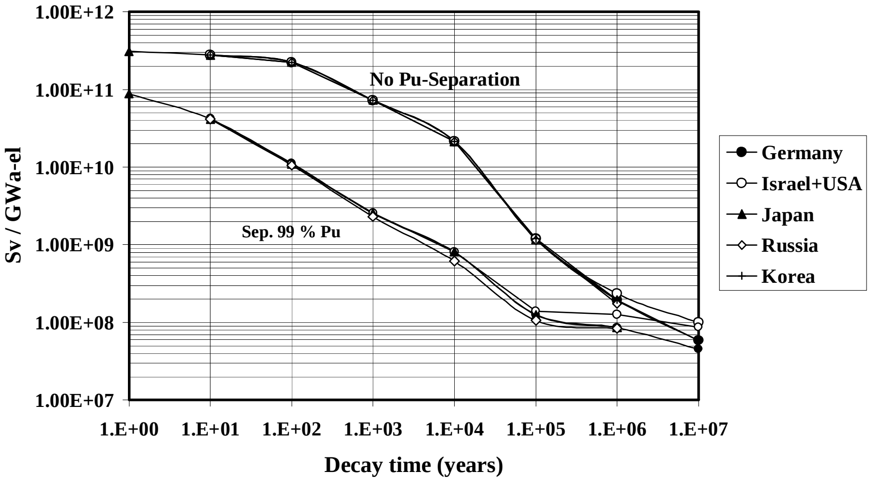


FIG. 2.13. Benchmark: inhalation hazard of the heavy metal isotopes.

2.3.3. Possible reduction of the waste radio-toxicity

In the realistic scenario of the worldwide population of nuclear reactors we are faced with an increasing number of reactors producing plutonium at an increasing yearly amount. Once a decision will be made, to build plutonium incinerators, the yearly rate of incinerated plutonium would have to increase with time, too. In order not only to compensate future production of plutonium but to also reduce current stockpiles, the number of incinerators would have to increase as rapidly as possible until an equilibrium between plutonium production in uranium-fuelled reactors, on the one hand, and plutonium burning in thorium/plutonium-fuelled reactors, on the other hand, could be reached. Switching over from uranium to thorium in as many existing reactors and as soon as possible could limit the necessary number of plutonium incinerators.

Future scenarios are hard to evaluate. Therefore, we restricted ourselves in the CRP to a relatively simple model, comparing two alternative reactor scenarios:

Scenario 1:

Assume a given reactor population which we name “conventional reactor”(e.g., typical PWRs). These are all operated by use of uranium fuel, and their waste is disposed without separation of any isotopes. These reactors produce a certain, yearly amount of radio-toxicity, which we measure in Sv/GW$_{el}$a.

Scenario 2:

Alternatively, we assume a nuclear scenario of the same size (in GW), where we have an equilibrium combination of "conventional", uranium fuelled reactors and of a certain fraction of "plutonium incinerators" using thorium based fuel. The principle mass flow of the fuel is illustrated in Fig. 2.14.

The bulk waste of "conventional" reactors is disposed and it produces a certain, yearly amount of radio-toxicity (Tox. (a)). 99% of the unloaded plutonium, however, are separated to be used as feed fissile material (or part of it, respectively) of the "plutonium incinerator". The spent fuel of these burners is finally disposed, representing another yearly amount of radio-toxicity, Tox. (b). We add the amounts of toxicity disposed from both the "producers" and the "burners", normalized to 1 GW$_{el}$a.

The sharing of the power production between the two reactor types depends on the amount of plutonium, which the respective incinerator (according to each country's proposal) is able to load each year:

PDR: the plutonium discharge rate of one "conventional reactor, commonly assumed to be equal 245 kg/GW$_{el}$a in this study;

PCR: the plutonium charge rate of the regarded plutonium burner;

X: at equilibrium, number, the power share of plutonium producers;

Y: at equilibrium, the power share of plutonium incinerators, Y=1-X.

Then it follows (Fig. 2.14):

$$X = \frac{PCR}{PCR + PDR}$$

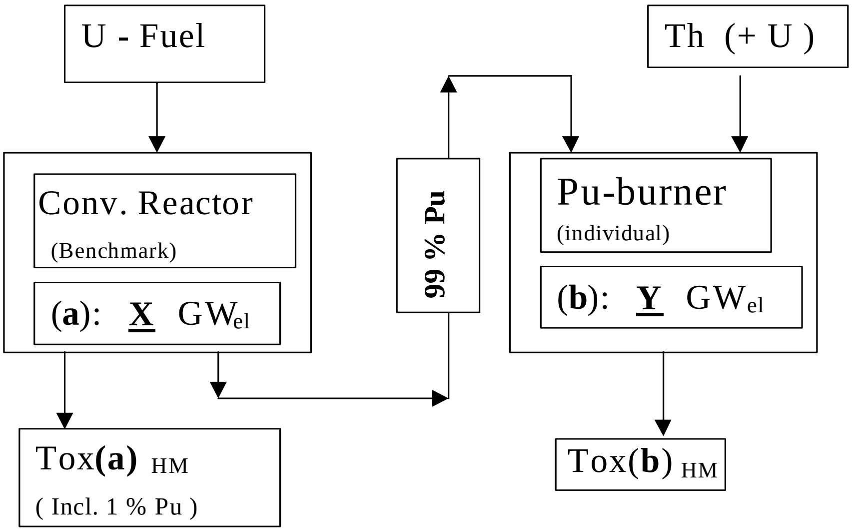


FIG. 2.14. Symbiosis of plutonium producers and plutonium burners.

The comparison of the radio-toxicity produced by this combined system of reactors (Tox.(a) + Tox.(b)) to the toxicity produced by scenario 1 is an indication of the potential of plutonium incineration with the help of thorium fuelled reactors, not only in view of the proliferation concern, but also in order to reduce the long-term waste radio-toxicity.

2.3.4. Results and conclusions

Figures 2.15 and 2.16 elucidate the principal impact of plutonium incineration on the amount and on the time dependence of the waste radio-toxicity. Here, the German results (HTR, increased incineration) have been taken as an example; all other contributions show similar characteristics.

A certain reduction of the radio-toxicity occurs at a decay time of the waste between some 10^2 and $5x10^4$ years as the consequence of the strongly reduced amount of plutonium and of its daughter nuclides in the disposed waste. However, during the first two decades, the radio-toxicity of the heavy metal fuel is even increased due to the highly toxic minor actinides, which are produced by neutron captures in ^{242}Pu (since plutonium is being recycled). This is true for the ingestion hazard (Fig. 2.15), as well as for the inhalation hazard (Fig. 2.16).

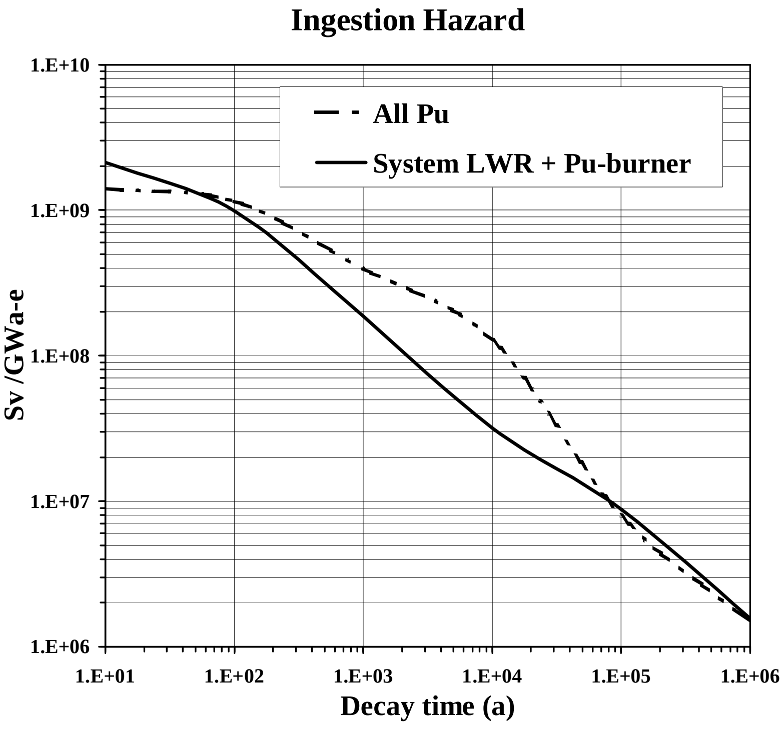


FIG. 2.15. Comparison: ingestion hazard of heavy metal waste with and without plutonium incineration (example, German burner variant).

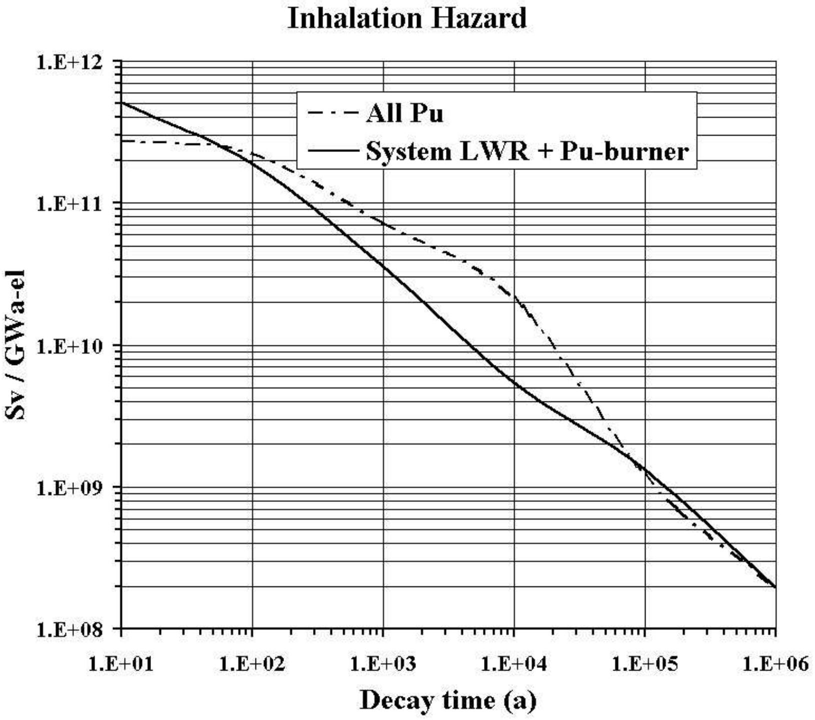


FIG. 2.16. Comparison: inhalation hazard of heavy metal waste with and without plutonium incineration (example, German burner variant).

Figures 2.17 and 2.18 give a comparison of the investigation results, which have been worked out by the participating countries, making use of their individual, favored reactor concept for plutonium incineration. A "Decontamination-Factor (DF)" is plotted versus the decay time. The factor DF is equal to the radio-toxicity of the heavy metal waste, which appears after the (partial) incineration of the LWR plutonium in the various burner concepts, divided by the radio-toxicity resulting from direct disposal of the heavy metal waste. A cubic fit of the calculated values has been used as a guide to the eyes.

With the exception of the common results of Israel and USA, the results of all participants show the same principal effects:

— For the first decades after disposal, the radio-toxicity of the waste is increased (up to a factor ≈ 2). It is obvious, that the initial increase of the radio-toxicity is the more distinct, the higher the heavy metal burnup of the plutonium incinerator (particularly HTR and MSR) is.

— The radio-toxicity is also increased at decay times larger than 10^5 years (up to a factor ≈ 2).

— It is decreased for the period between about 10^2 years and about 0.5-1.0x10^5years by at maximum the factor 2 to 4. Here, the high burnup achieved in the HTR causes by far the strongest reduction.

A reduction of the waste radio-toxicity by an order of magnitude or more seems not to be achievable by any of the considered concepts.

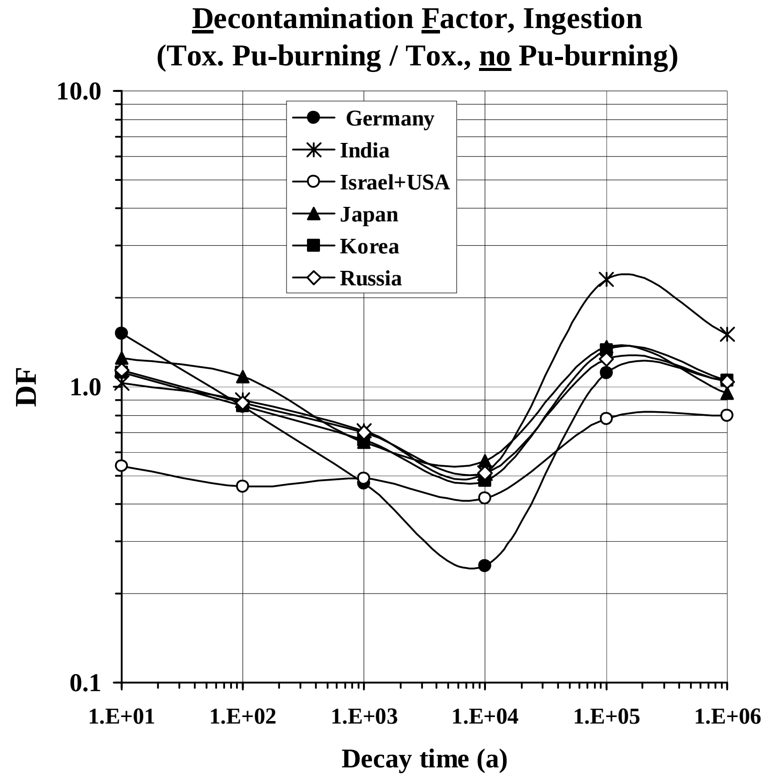


FIG. 2.17. Relative change of the ingestion hazard of heavy-metal waste achieved by plutonium incineration in the various burner concepts.

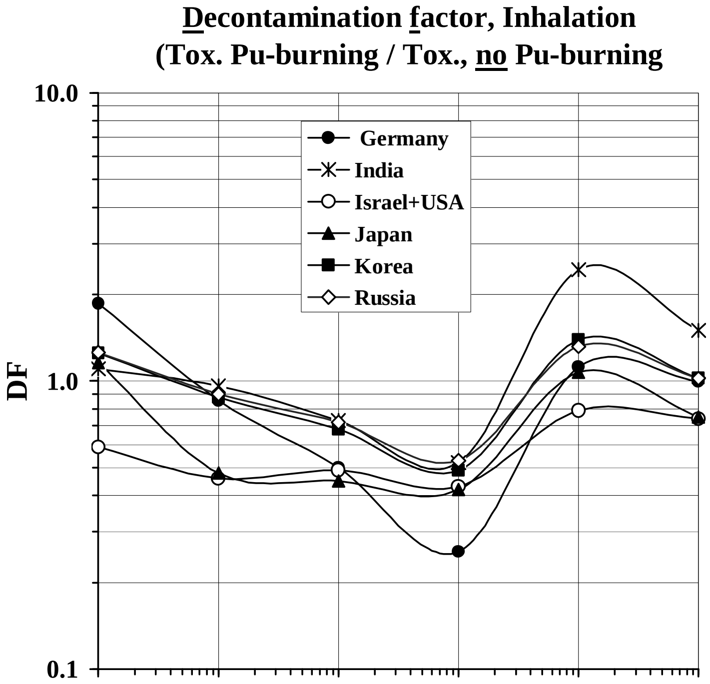


FIG. 2.18. Relative change of the inhalation hazard of heavy-metal waste achieve by plutonium incineration in the various burner concepts.

2.4. CONCLUSIONS

The CRP examined the different fuel cycle options in which plutonium can be recycled with thorium to incinerate plutonium. The potential of the thorium-matrix has been examined through computer simulations. Each participant has chosen his own cycle, and the different cycles are compared through certain predefined parameters (e.g., annual reduction of plutonium stockpiles). The radio-toxicity accumulation and the transmutation potential of thorium-based cycles for current, advanced and innovative nuclear power reactors were investigated.

The collaborative research activities were divided into three stages:

- Stage 1: Benchmark calculations;
- Stage 2: Optimisation of the incineration of plutonium in various reactor types;
- Stage 3: Assessment of the resulting impact on the waste radio-toxicity.

The Stage 1 benchmark exercises were performed in order to ensure a sufficient reliability of the conclusions from the comparison of the research work done by different groups and for various reactor concepts. The results obtained are very satisfactory and deemed to constitute a sufficiently reliable basis for overall conclusions on the potential of thorium-based fuel cycles to constrain plutonium and to reduce the long-term potential radiotoxic hazard of the waste.

In Stages 2 and 3, an assessment of thorium fuelled thermal reactors in view of their potential for the utilization of plutonium and for a possible, combined reduction of the waste radio-toxicity has been performed. The analyses looked at the utilization, on the one side, of first generation reactor grade plutonium, i.e., plutonium typically discharged from current reactors (LWRs), and, on the other side, of weapons-grade plutonium.

Plutonium utilization may be looked at from the point of view of two main optimisation goals: firstly, to achieve a large incineration rate in relation to the amount of electricity produced, and, secondly, to minimize the amount of plutonium, which is still residual in the discharged fuel elements after their use in a plutonium incinerating reactor.

For each of the two plutonium types, the overall conclusions to be drawn with regard to both optimisation goals mentioned above can be summarized as follows:

LWR plutonium:

Water-cooled reactors (LWR and HWR), characterized by a relatively low heavy metal burnup, attain a large plutonium incineration rate. On the other hand, the amount of plutonium incinerated is low compared to the remaining plutonium inventory in the spent fuel (to be disposed off or recycled). Achieving a large heavy metal burnup (e.g., in the HTR case) results in a smaller amount of plutonium incinerated per unit of produced energy, but distinctly reduces the fraction of residual plutonium. Typically, one plutonium incinerating reactor burns approximately 2.5 to 4 times the amount of plutonium which is produced by an LWR of the same power.

Weapons-grade plutonium:

The higher neutronic value of weapons-grade plutonium, and the strongly reduced build-up of minor actinides starting from ^{242}Pu, generally makes its incineration more effective than in the case of LWR plutonium. While the amount of weapons-grade plutonium, which is burned per unit of produced electricity, is comparable to that of LWR plutonium, the quantity of residual plutonium in the spent fuel assemblies can be strongly reduced in the case of weapons-grade plutonium. In view of the minimization of the amount of plutonium remaining for final disposal, there is a clear advantage for reactors having an especially high heavy metal burnup.

Summing up, there is a remarkable potential to effectively constrain the production of plutonium and to reduce existing plutonium stockpiles, by implementing the thorium fuel cycle in a large number of current reactors. This path offers a promising near future plutonium management solution in view of, e.g., the proliferation concerns linked to plutonium. However, plutonium incineration in thermal reactors turns out to be less effective from the point of view of the reduction of the long-term radio-toxicity of the nuclear waste. A reduction by an order of magnitude or more of the potential long-term radiotoxic hazard of the waste seems not to be achievable by any of the considered plutonium incinerating thermal reactors. Most of the calculations performed for LWR plutonium indicate that the waste radio-toxicity will be decreased by not more than a factor of 2 to 4, and only for the period between approximately 10^2 to 10^5 years after disposal. The waste radio-toxicity is even increased during the first decades and for extremely long times after disposal.

long-term radio-toxicity of the nuclear waste. A reduction by an order of magnitude or more of the potential long-term radiotoxic hazard of the waste seems <u>not</u> to be achievable by any of the considered plutonium incinerating thermal reactors. Most of the calculations performed for LWR plutonium indicate that the waste radio-toxicity will be decreased by not more than a factor of 2 to 4, and only for the period between approximately long times after disposal. The waste radio-toxicity is even increased during the first decades and for extremely long times after disposal.

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