

## 3.4. Israel and USA

A. GALPERIN, BEN-GURION UNIVERSITY OF THE NEGEV, BEER-SHEVA, ISRAEL  
M. TODOSOW, BROOKHAVEN NATIONAL LABORATORY, NEW YORK, USA

### 3.4.1. Introduction

The design objective of the present design is to use thorium based fuel for an efficient incineration of the excess plutonium. Two plutonium compositions were considered: the weapon grade weapons-grade plutonium and the reactor-grade plutonium. A heterogeneous, seed-blanket (SBU) fuel assembly design was adopted [1,2]. The main design approach is to use plutonium as a seed fuel providing neutrons to a subcritical blanket loaded mainly with thorium.

The seed fuel consists of Pu/Zr metal alloy and the blanket fuel consists of Th-Pu-U mixed oxide. The blanket plutonium provides a fissile component, while natural uranium part is added to denature (dilute) the U-233 built-up in thorium.

The efficiency of incinerating the excess weapons-grade- and reactor-grade plutonium and reactor-grade plutonium stockpiles by utilization of the mixed oxide fuel (MOX) is significantly reduced by the production of the “new” or the second-generation plutonium. For the MOX fuel based on the reactor-grade plutonium and natural uranium the residual plutonium amounts to 60-70% of the initial plutonium load. Thus, using the MOX fuel is equivalent to a transformation of the pure weapons-grade plutonium or the reactor-grade plutonium into reactor-grade plutonium contained within the discharged fuel. Replacing uranium by thorium as a (fertile) matrix material for plutonium incinerating cycle is investigated in this work as an alternative to the MOX fuel cycle.

A well-known design problem associated with the heavy plutonium loading required in the plutonium incinerating cycles is the reactivity control problem. The higher thermal absorption cross-section of plutonium, as compared with uranium, causes reduction of the reactivity worth of all LWR control mechanisms: control rods (CR), burnable poisons (BP's) and soluble poison. This leads to a reduction of the reactivity worth of the standard PWR control system by approximately a factor of two. Several solutions were proposed and investigated, such as using enriched boron, Gd, or even additional CR's to compensate this effect.

An alternative approach is provided by a heterogeneous, SBU fuel assembly geometry. The SBU geometry allows separate lattice optimization for the seed and blanket parts. Thus, the seed region is well moderated ( $V_m/V_f = 3.5$ ) while the blanket region lattice is similar to that of a standard PWR ( $V_m/V_f = 1.7$ ). In the present design the CR's and BP's are concentrated mainly in the seed region with a high moderator content leading to an increased reactivity worth of all control mechanisms based on thermal absorption materials.

The fuel management scheme, reflecting the heterogeneous fuel assembly design, is based on two separate material flows for the seed and blanket fuel parts. The seed part of the core (consisting of all seed sub-assemblies) is managed in three batches, each residing in core 300 full power days (FPD's). Thus, the seed in-core residence time is 900 FPD's. The blanket is managed as a single batch residing for 6 seed cycles, i.e., 1800 days. This fuel management scheme is designed to assure an efficient utilization of thorium, in terms of natural uranium savings. In addition, a 3-batch seed reload scheme was chosen to provide an “optimal” balance between two different performance parameters: the plutonium incineration rate and

the residual plutonium content in the discharged fuel. The first one should be maximized and the second one should be minimized.

The thorium-based fuel cycle proposed and investigated in this work was designated for a standard PWR core, similar to Westinghouse and/or EPR design. Two plutonium composition cases were considered: a weapons-grade plutonium composition case and a reactor-grade plutonium composition case. The main core and lattice parameters for both cases were kept identical, the fuel composition being the main difference between the two cases.

### 3.4.1.1. Weapons-grade plutonium case

The main design parameters for the weapons-grade plutonium case are summarized in Table 3.4.1.

TABLE 3.4.1. CORE DESIGN PARAMETERS

Power output (MWth)	= 3 400
Number of fuel assemblies (SBU's)	= 193
Average power density (w/cc)	= 104
Total coolant flow (kg/s)	= 19 480
<b>Seed design parameters:</b>	
Assembly Volume fraction (%)	= 40.1
Composition	7.0 weight % weapons-grade Pu + 93.0% weight % zircalloy
Number of fuel rods	= 96
Number of guide tubes	= 24 (+ one central)
Moderator to fuel volume ration	= 3.535
Lattice (cell positions)	= 11x11
Cell Geometry: fuel pellet radius (cm)	= 0.310
Clad outside radius (cm)	= 0.350 (no gap)
Lattice pitch (cm)	= 1.205
Average fuel temperature (°C)	= 470.0
Average cladding temperature (°C)	= 340.0
Average moderator temperature (°C)	= 306.0
Average specific power (Mw/t)	= 186.0
<b>Blanket design parameters:</b>	
Assembly volume fraction (%)	= 59.9
Composition:	= 0.8% weapons-grade Pu oxide + 8.2% Natural U oxide + 91.0% Th oxide
Cell geometry: Fuel pellet radius (cm)	= 0.4095
Clad outside radius (cm)	= 0.475
Lattice pitch (cm)	= 1.258
Average fuel temperature (°C)	= 750.0
Average cladding temperature (°C)	= 340.0
Average moderator temperature (°C)	= 306.0
Number of fuel rods	= 168
Number of guide tubes	= 0
Moderator to fuel volume ratio	= 1.659
Average specific power (Mw/t)	= 30.0

#### 3.4.1.1.1. Results of calculations (equilibrium cycle)

A full simulation of the proposed cycle involves calculations of a complete blanket life-time, which is equivalent to 6 seed reload cycles. In this work this full simulation is approximated by a calculation of the “equilibrium” cycle assuming that its performance parameters are representative of a complete simulation, i.e., 6 seed cycles.

The equilibrium cycle for a 3-batch fuel management scheme is represented by a core which includes three seed fuel types - fresh, once-burned, and twice-burned, and a single blanket fuel type with an averaged burnup value of 900 FPD's.

A low-leakage reload pattern, typical for PWR's of the current generation, was adopted with once and twice burned seed subassemblies positioned at the core periphery.

The following table presents a summary of the main performance parameters of the weapons-grade plutonium cycle analysis. The reactivity run-down curve demonstrates that the amount of fuel loaded is sufficient to sustain 300 Full Power Days (FPD's) of power operation with an excess reactivity of about 6%. This excess reactivity will be compensated by insertion of CR's, while the soluble poison system will be used for the reload operation, cold to hot reactivity shift and possibly Xe effect.

The second and the third columns show the power share of the seed and blanket parts of the fuel respectively. The values are given in total MWatts for a quarter of the core. It is shown that about 60% of the total power, averaged over the cycle, are produced in the seed and the remaining 40% are generated in blanket.

It should be noted, that for the plutonium incinerator design the seed-blanket power sharing impacts mainly the maximum local power density of the seed. This power density, in turn, defines the maximum local fuel temperature (fuel rod centerline), which is constrained by safety considerations. This temperature is presented in the last column, showing values consistent with thermal limits of a typical PWR plant.

TABLE 3.4.2. REACTIVITY, POWER SHARING, AND FUEL TEMPERATURE SUMMARY

Days	$k_{eff}$	Power (MWatts) seed	Power (MWatts) blanket	Max. fuel temperature (°C)
0	1.06931	507.0	343.0	681.6
20	1.06460	503.4	346.6	648.7
100	1.04801	490.6	359.4	583.9
160	1.03633	481.2	368.8	572.3
200	1.02845	474.7	375.3	570.4
260	1.01613	464.6	385.4	570.6
300	1.00745	457.5	392.5	570.2
310	1.00522	455.6	394.3	571.1

The power density map showing the averaged values in units of w/cc in fuel is presented in Fig. 3.4.1. Drastically different values may be noted for the seed (upper value) and for the blanket (lower value) that is consistent with the chosen design approach, where the seed fuel is metallic alloy and the blanket fuel is oxide. Relatively low maximum fuel temperatures of the seed fuel (see last column in Table 3.4.2) illustrate this approach.

1240.3					
247.6					
933.5	885.0				
233.1	223.8				
896.5	941.1	869.1			
222.3	204.4	218.2			
973.7	876.8	953.5	895.7		
207.8	219.9	206.9	226.3		
921.8	974.8	916.3	939.0	956.8	
227.9	211.6	231.0	238.4	242.1	
1030.0	937.6	1054.8	1152.5	1060.8	1146.6
219.9	235.8	228.8	249.9	229.7	234.3
979.5	1047.0	1146.6	1018.0	1053.7	895.5
242.5	227.2	248.5	219.4	208.2	170.0
899.7	1059.9	1032.7	875.6		
211.1	208.1	202.9	166.1		

FIG. 3.4.1. Power distribution map – 1/8 core (subassembly averaged, w/cc in fuel).

The fuel cycle mass flow summary is summarized Table 3.4.3.

#### 3.4.1.1.2. Discussion: weapons-grade plutonium case

Results of the thermal-hydraulic analysis of the hot-channel, i.e., SBU with the highest power density indicated that all major thermal constraints typical for a PWR were satisfied, e.g., fuel temperatures, and that relevant heat flux values were well below the critical heat flux (DNBR limit).

The results of the equilibrium cycle simulation presented above demonstrate the basic feasibility of the proposed design. The criticality rundown curve shows that amount of fissile material weapons-grade plutonium is sufficient to sustain the 300 full power days and that the excess criticality is about 7%.

Additional data is provided for the thermal-hydraulic parameters. The power distribution between seed and blanket shows 0.6 power share for the seed and 0.4 for the blanket. This power distribution reflects the design objective of the proposed design: efficient plutonium incineration. Clearly, higher seed power share results in higher plutonium destruction rates. Increase of the seed power share will lead to increased power density and higher fuel temperatures correspondingly.

The results also indicate that the thermal limits of a standard PWR core are observed. The maximum fuel temperature (centerline) is somewhat above the design limit of 500°C. It seems reasonable to suppose that a further optimization of the reload design and possible improvement in burnable poison loading patterns may lead to a further flattening of the power distribution, a reduction of an overall power peaking factor and subsequently a reduction of the maximum fuel temperature.

The summary of the cycle mass flow may be used to evaluate an overall fuel cycle performance. All main actinide isotopes are accounted for in Table 3.4.3, showing the annual (cycle) charge, the core inventories, and the cycle discharge. This table also shows an estimate

of the annual plutonium destruction rates and residual plutonium content in the discharged fuel stockpile.

The plutonium incineration rate for a complete cycle is estimated as 677 kg of weapons-grade plutonium per year. This value accounts for 95 kg incinerated annually in the blanket and represents a value, which is equivalent to 383 kg of weapons-grade plutonium incinerated in blanket during its six years of the in-core residence time.

The residual fraction of plutonium in the discharged fuel is 0.35 in seed and may be reduced significantly by shifting from a 3-batch to a 4-batch fuel management scheme. Clearly, this will lead to a corresponding reduction in the plutonium incineration rate by approximately 10%.

### 3.4.1.2. Reactor-grade plutonium case

The second variant of the plutonium incineration cycle considered is based on reactor-grade plutonium. The main core and assembly parameters are identical to those of the weapons-grade plutonium design. In addition, the fuel management scheme, the load configurations, and the resulting power distributions are also almost identical to the weapons-grade plutonium case. The main difference between the two design options is restricted to the fuel composition and subsequently the cycle mass flow balance.

TABLE 3.4.3. MASS FLOW SUMMARY (kg)

Core charge		Core inventory				Core discharge	
Material	Weight, kg	Material	Weight, kg	Material	Weight, kg	Material	Weight, kg
Seed (fresh)		Seed (fresh)		Seed (once)			
		Pu-238		Pu-238	0.05		
Pu-239	873.07	Pu-239	873.07	Pu-239	546.37		
Pu-240	55.73	Pu-240	55.73	Pu-240	125.09		
		Pu-241		Pu-241	32.50		
		Pu-242		Pu-242	2.15		
		Seed (once)		Seed (twice)			
		Pu-238	0.04	Pu-238	0.25		
		Pu-239	565.82	Pu-239	276.51		
		Pu-240	128.33	Pu-240	165.34		
		Pu-241	29.10	Pu-241	53.91		
		Pu-242	1.80	Pu-242	9.26		
		Seed twice		Seed out		Seed out	
		Pu-238	0.21	Pu-238	0.83	Pu-238	0.83
		Pu-239	278.72	Pu-239	91.54	Pu-239	91.54
		Pu-240	163.40	Pu-240	154.35	Pu-240	154.35
		Pu-241	52.95	Pu-241	57.67	Pu-241	57.67
		Pu-242	8.60	Pu-242	21.97	Pu-242	21.97
Initial load		Blanket					
Th-232	47484.0	Th-232	46098.16	Th-232	45629.82		
Pa-231		Pa-231	3.95	Pa-231	4.38		
U-232		U-232	2.62	U-232	3.73		
U-233		U-233	633.70	U-233	708.64		
U-234		U-234	81.19	U-234	115.20		
U-235	33.4	U-235	20.32	U-235	26.09		
U-238	4664.8	U-238	4376.22	U-238	4279.75		
Pu-238		Pu-238	1.33	Pu-238	2.10		
Pu-239	475.0	Pu-239	63.09	Pu-239	59.82		
Pu-240	30.3	Pu-240	42.91	Pu-240	29.95		
Pu-241		Pu-241	43.78	Pu-241	33.94		
Pu-242		Pu-242	35.12	Pu-242	40.78		
Summary		Total Pu, ncinerated (kg/y)		<sup>239</sup> Pu, incinerated (kg/y)		Residual fraction	
Seed		602		778		0.35	
Blanket		75		70		0.11	
Total		677		848			

TABLE 3.4.4. FUEL COMPOSITION FOR THE REACTOR-GRADE PLUTONIUM CASE

Seed composition: 9.0 weight % of RG Pu + 91.0 weight % of zircalloy.

Blanket composition: 1.0 weight % of RG PuO<sub>2</sub> + 8.5 weight % of Nat. UO<sub>2</sub> + 91.0 weight % of ThO<sub>2</sub>.

The fuel composition was chosen to sustain a 300 FPD's inter-refueling interval for an equilibrium cycle, i.e., represented by the average blanket burnup and three seed fuel types: fresh, once-burned and twice-burned. The main performance parameters of the reactor-grade plutonium case are summarized in Table 3.4.5. The excess reactivity, seed and blanket power sharing, and maximum centerline temperatures indicate, similarly to the weapons-grade plutonium case, a basic compatibility of the proposed design with a PWR plant.

TABLE 3.4.5. REACTIVITY, POWER SHARING, AND FUEL TEMPERATURE SUMMARY

Days	k <sub>eff</sub>	Power (MWatts) seed	Power (MWatts) blanket	Max. fuel temp. (°C)
0	1.04162	505.0	345.0	665.9
20	1.03885	502.3	347.3	644.4
100	1.02691	491.7	358.3	590.0
160	1.01747	483.9	366.1	574.8
200	1.01091	478.7	371.3	571.3
260	1.00069	470.5	379.5	567.8
300	0.99362	464.8	385.2	570.2
310	0.99184	463.4	386.6	566.0

The seed (upper value) and blanket (lower value) power densities show reasonable values, which are consistent with the basic thermal limits of a PWR plant.

1135.8					
242.9					
909.4	920.5				
235.0	228.6				
949.2	968.9	928.6			
231.0	214.4	229.3			
1008.0	935.6	986.0	952.7		
219.4	231.0	218.2	236.5		
977.7	997.3	961.9	978.3	980.1	
237.4	220.8	238.2	243.9	243.4	
1036.6	967.0	1037.8	1111.6	1024.0	1098.7
225.6	238.9	229.5	246.9	226.1	227.2
994.3	1019.4	1089.3	969.0	1005.4	853.4
241.7	225.3	241.6	212.9	201.3	164.4
1061.3	1019.6	983.2	831.3		
207.3	203.0	195.8	160.1		

FIG. 3.4.2. Power distribution map – 1/8 core (subassembly averaged) (w/cc in fuel).

### 3.4.1.2.1. Discussion: reactor-grade plutonium case

The results of the equilibrium cycle simulation presented above demonstrate the basic feasibility of the proposed design. The criticality rundown curve shows that the amount of the fissile material (reactor-grade plutonium) is sufficient to sustain the 300 full power days inter-refueling interval and that the excess criticality is about 4%. Results of the thermal-hydraulic analysis of the hot-channel, i.e., SBU with the highest power density indicated that all major

thermal constraints typical for a PWR were satisfied, e.g. fuel temperatures, and that relevant heat flux values were well below the critical heat flux (DNBR limit).

TABLE 3.4.6. MASS FLOW SUMMARY (kg)

Core charge		Core inventory				Core discharge	
Material	Weight, kg	Material	Weight, kg	Material	Weight, kg	Material	Weight, kg
Seed fresh		Seed fresh		Seed once			
Pu-238	17.90	Pu-238	17.90	Pu-238	15.94		
Pu-239	665.15	Pu-239	665.15	Pu-239	439.97		
Pu-240	251.97	Pu-240	251.97	Pu-240	261.13		
Pu-241	193.45	Pu-241	193.45	Pu-241	171.03		
Pu-242	65.68	Pu-242	65.68	Pu-242	77.67		
		Seed once		Seed twice			
		Pu-238	16.32	Pu-238	14.89		
		Pu-239	448.48	Pu-239	244.26		
		Pu-240	269.98	Pu-240	260.62		
		Pu-241	168.92	Pu-241	141.00		
		Pu-242	79.56	Pu-242	95.37		
		Seed twice		Seed out		Seed out	
		Pu-238	14.90	Pu-238	13.97	Pu-238	13.97
		Pu-239	244.37	Pu-239	98.33	Pu-239	98.33
		Pu-240	258.42	Pu-240	221.66	Pu-240	221.66
		Pu-241	138.87	Pu-241	106.86	Pu-241	106.86
		Pu-242	93.27	Pu-242	111.26	Pu-242	111.26
Initial load		Blanket					
Th-232	47226.1	Th-232	46172.69	Th-232	45413.86		
Pa-233		Pa-233	58.41	Pa-233	58.36		
U-232		U-232	2.58	U-232	3.75		
U-233		U-233	635.76	U-233	712.91		
U-234		U-234	78.13	U-234	111.28		
U-235	37.5	U-235	20.76	U-235	26.14		
U-238	4832.6	U-238	4537.40	U-238	4438.36		
Pu-238	12.5	Pu-238	6.38	Pu-238	6.32		
Pu-239	350.1	Pu-239	69.02	Pu-239	65.69		
Pu-240	131.3	Pu-240	51.47	Pu-240	35.20		
Pu-241	100.0	Pu-241	54.64	Pu-241	40.77		
Pu-242	37.5	Pu-242	78.57	Pu-242	79.18		
Summary		Total Pu incinerated (kg/y)		<sup>239</sup> Pu, incinerated (kg/y)		Residual fraction	
Seed		642		567		0.46	
Blanket		101		71		0.16	
TOTAL		743		638			

### 3.4.1.3. Reactivity control issues

A well-known problem of the reactivity control of a plutonium-loaded core is investigated and discussed in this section. The presence of plutonium leads to a reduction in the reactivity worth of various control mechanisms based on parasitic absorption of thermal neutrons. A series of assembly level calculations were carried out to evaluate the reactivity worth of the different control mechanisms and the moderator temperature coefficients. It should be noted that the values were generated on the assembly level representing “core averaged” values and, therefore, are applicable only for the comparison of different cycle options.

Several plutonium-based cycle options were considered and designated as follows:

PWR	A standard slightly enriched uranium fuel;
MOX – RG	A mixed oxide fuel (uranium-plutonium oxide, reactor-grade plutonium);
MOX- WG	A mixed oxide fuel (uranium-plutonium oxide, weapons-grade plutonium);
TMOX – RG	A thorium based homogeneous mixed oxide fuel (Th-Pu oxide reactor-grade plutonium);
TMOX – WG	A thorium based homogeneous mixed oxide fuel (Th-Pu oxide weapons-grade plutonium);
RTF – RG	Radkowsky thorium fuel SBU (reactor-grade plutonium);
RTF – WG	Radkowsky thorium fuel SBU (weapons-grade plutonium);

TABLE 3.4.7. SUMMARY OF REACTIVITY WORTH AND MTC VALUES

Fuel cycle option	MTC $\Delta\rho/^\circ\text{C}$	Soluble boron $\Delta\rho/\text{ppm bron}$	CR worth - $\Delta\rho$ (all rods inserted)
PWR	-3.19E-04	-6.50E-05	-0.3332
MOX-RG	-5.16E-04	-2.97E-05	-0.2157
MOX-WG	-3.47E-04	-3.21E-05	-0.2217
TMOX-RG	-5.07E-04	-3.05E-05	-0.2318
TMOX-WG	-2.81E-04	-2.97E-05	-0.223
RTF-RG	-2.79E-04	-5.60E-04	-0.2688
RTF-WG	2.52E-04	-5.82E-05	-0.2936

The results presented in Table 3.4.7 demonstrate the advantages of the RTF design with regard to the reactivity control issue. The moderator temperature coefficient (MTC) of a plutonium fuel homogeneously mixed with the matrix fuel, either uranium or thorium, shows much higher values in comparison with the reference PWR case. The immediate effect of such increase is the corresponding increase in cold-to-hot reactivity effect, and consequently an increase in the reactivity control requirements. In addition, a reduction of the reactivity worth of soluble boron and control rods for the RTF cases is 10-20%, while homogeneous cases show a reduction of more than 50%. Clearly, the reactivity control problem is alleviated by the heterogeneous (SBU) assembly geometry.

### 3.4.2. Toxicity calculations

#### 3.4.2.1. RTF plutonium indicator

The results described below are for an RTF fuel cycle as an incinerator cycle for the burnout of weapon grade plutonium. The basic RTF core design is maintained, namely a seed-blanket core, keeping the same overall core dimensions as well as the SBU dimensions. The stock pile

hazards of this cycle are compared, for a power generation of 1000 MWe, with those emanating from MOX cores, designed for the same purpose. The seed fuel is Pu/Zr metallic alloy, where the plutonium is weapon grade. One t of seed H.M. contains 940 kg <sup>239</sup>Pu and 60 kg Pu-240. The seed residence time in the core is 3 years, namely each year a third of all seeds, the thrice burned, are discharged into the stock pile. The blanket fuel is oxide; one t of blanket H.M. contains 900 kg Th-232, 90 kg U-238, 9 kg Pu-239, and about ½ kg of both U-235 and Pu-240. The core residence time of the blankets is 7 years, after which they are added to the stock pile. The reference MOX core operates on oxide fuel; one t H.M. in the MOX core contains 956 kg U-238, 35 kg Pu-239, 7 kg U-235, and 2 kg Pu-240.

#### *3.4.2.2. Methodology*

Three major codes are involved. Point burnup, followed by decay, is performed with ORIGEN. This simplistic calculation is improved, using results obtained from calculations with the ELCOS system codes BOXER and SILWER, for actual 3 dimensional setups of the cores under consideration. The improvement is in replacing, prior to the ORIGEN decay calculation, the ORIGEN derived density values of 33 discharged actinides, and 56 major fission products, with the more accurate ELCOS values. The toxicity estimates are based on the ICRP-68 library.

All calculations are performed first on the basis of 1 t of H.M. The results are then normalized to annual outputs into the stock pile. The annual tonnage discharges are 30 t from the MOX core, and an average of 8.5 t from the RTF core, divided up to 1.4 t from the seeds and 7.1 t from the blankets. More details can be found in Table 3.4.8.

#### *3.4.2.3. Summary of toxic hazards*

The stock pile inhalation and ingestion hazards are summarized in Tables 3.4.9 and 3.4.10 for the MOX core, and in Tables 3.4.11 and 3.4.12 for the RTF core. Comparative results, RTF vs. MOX, are to be found in Table 3.4.13 and Fig. 3.4.3, for the inhalation, and in Table 3.4.14 and Fig. 3.4.4, for the ingestion. Hazard comparisons of actinides vs. fission products are to be found in Table 3.4.15 and Fig. 3.4.5, for the MOX, and in Table 3.4.16 and Fig. 3.4.6, for the RTF.

#### *3.4.2.4. Discussion*

During the period of 10 years to 40 000 years in stock pile residence, the RTF and MOX hazards, as concerns both inhalation and ingestion, is practically the same. This is attributed to the domination of the plutonium and minor actinides in the accumulated hazard. Between 40 000 years and 1 000 000 years the RTF hazard is slightly (at most 60%) higher than the MOX hazard. This is due to the growth of Th-229, Pb-210, and Ra-226 in the thorium-based fuel of the blankets that is faster than in the uranium based fuel of the MOX. From 1 000 000 years and onward these isotopes lose importance in the RTF pile, attaining peak values in the MOX pile, with the result that the RTF becomes less hazardous. In the light of the intrinsic inaccuracies, the stock pile hazards of the RTF and MOX seem to be quite the same for the duration of 10 000 000 years. With regard to the hazards posted by actinides vs. the fission products hazards, Tables 3.4.15 and 3.4.16, or, graphically, Figs 3.4.5 and 3.4.6, show that, both in the RTF and in the MOX, they are comparable for the first few tens of years in stock pile life, upon which the FP hazards drop fast below those of the AC, to 4 orders of magnitude already at 1000 years in stock pile life.

TABLE 3.4.8. ANNUAL FUEL DISCHARGE WEIGHT, G/1 GWE

	Reference MOX	Seed	Blanket	RTF Total
Actinides	2.88E+07	5.46E+05	6.63E+06	7.18E+06
Fission products	1.14E+06	8.22E+05	4.66E+05	1.29E+06
Total	3.00E+07	1.37E+06	7.10E+06	8.47E+06

TABLE 3.4.9. REFERENCE MOX, RADIOACTIVE INHALATION TOXICITY, SV.

Time (years)	10	10 <sup>2</sup>	10 <sup>3</sup>	10 <sup>4</sup>	10 <sup>5</sup>	10 <sup>6</sup>	10 <sup>7</sup>
Actinides	7.31E+11	6.77E+11	2.51E+11	7.09E+10	3.26E+09	4.56E+08	1.21E+08
Fission products	8.12E+09	8.45E+08	2.18E+05	2.00E+05	1.29E+05	4.34E+04	3.53E+03
Total	7.39E+11	6.78E+11	2.51E+11	7.09E+10	3.26E+09	4.56E+08	1.21E+08

TABLE 3.4.10. REFERENCE MOX, RADIOACTIVE INGESTION TOXICITY, SV.

Time (years)	10	10 <sup>2</sup>	10 <sup>3</sup>	10 <sup>4</sup>	10 <sup>5</sup>	10 <sup>6</sup>	10 <sup>7</sup>
Actinides	3.83E+09	3.53E+09	1.39E+09	4.25E+08	1.97E+07	2.80E+06	9.44E+05
Fission products	2.17E+09	2.40E+08	1.25E+05	6.18E+04	2.17E+04	7.42E+03	3.24E+03
Total	5.99E+09	3.77E+09	1.39E+09	4.25E+08	1.97E+07	2.81E+06	9.47E+05

TABLE 3.4.11. RTF INCINERATOR, RADIOACTIVE INHALATION TOXICITY, SV.

Time (years)	10	10 <sup>2</sup>	10 <sup>3</sup>	10 <sup>4</sup>	10 <sup>5</sup>	10 <sup>6</sup>	10 <sup>7</sup>
Actinides	8.71E+11	6.33E+11	2.21 <sup>E</sup> +11	5.65E+10	5.47E+09	4.42E+08	3.35E+07
Fission Products	1.20E+10	1.30E+09	2.49 <sup>E</sup> +05	2.28E+05	1.49E+05	5.54E+04	4.21E+03
Total	8.83E+11	6.34E+11	2.21 <sup>E</sup> +11	5.65E+10	5.47E+09	4.42E+08	3.35E+07

TABLE 3.4.12. RTF INCINERATOR, RADIOACTIVE INGESTION TOXICITY, SV.

Time (years)	10	10 <sup>2</sup>	10 <sup>3</sup>	10 <sup>4</sup>	10 <sup>5</sup>	10 <sup>6</sup>	10 <sup>7</sup>
Actinides	4.23E+09	3.28E+09	1.22 <sup>E</sup> +09	3.34E+08	3.36E+07	2.95E+06	1.71E+05
Fission Products	2.99E+09	3.31E+08	1.43 <sup>E</sup> +05	6.99E+04	2.36E+04	8.66E+03	3.93E+03
Total	7.22E+09	3.61E+09	1.22 <sup>E</sup> +09	3.34E+08	3.36E+07	2.96E+06	1.75E+05

TABLE 3.4.13. RADIOACTIVE INHALATION TOXICITY COMPARISON MOX VS. RTF, SV.

Total actinides + fission products	Time (years)	10	10 <sup>2</sup>	10 <sup>3</sup>	10 <sup>4</sup>	10 <sup>5</sup>	10 <sup>6</sup>	10 <sup>7</sup>
	Reference MOX		7.39E+11	6.78E+11	2.51 <sup>E</sup> +11	7.09E+10	3.26E+09	4.56E+08
RTF		8.83E+11	6.34E+11	2.21 <sup>E</sup> +11	5.65E+10	5.47E+09	4.42E+08	3.35E+07

TABLE 3.4.14. RADIOACTIVE INGESTION TOXICITY COMPARISON MOX VS. RTF, SV.

Total actinides + fission products	Time (years)	10	10 <sup>2</sup>	10 <sup>3</sup>	10 <sup>4</sup>	10 <sup>5</sup>	10 <sup>6</sup>	10 <sup>7</sup>
	Reference MOX		5.99E+09	3.77E+09	1.39 <sup>E</sup> +09	4.25E+08	1.97 <sup>E</sup> +07	2.81E+06
RTF		7.22E+09	3.61E+09	1.22 <sup>E</sup> +09	3.34E+08	3.36 <sup>E</sup> +07	2.96E+06	1.75E+05

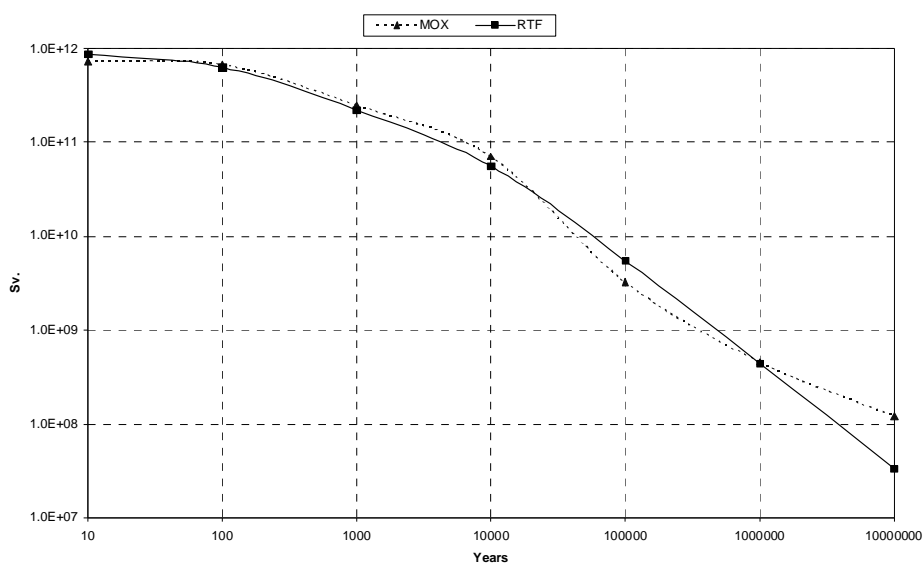


FIG. 3.4.3. Radioactive inhalation toxicity comparison MOX vs. RTF (Sv).

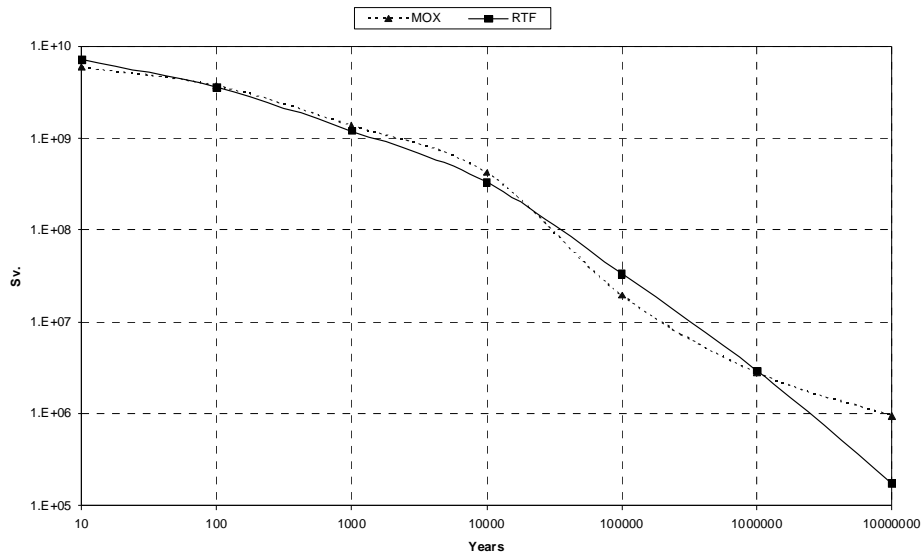


FIG. 3.4.4. Radioactive ingestion toxicity comparison MOX vs. RTF (Sv).

TABLE 3.4.15. REFERENCE MOX RADIOACTIVE INGESTION TOXICITY COMPARISON (ACTINIDES VS. FISSION PRODUCTS), SV.

Time (years)	10	10 <sup>2</sup>	10 <sup>3</sup>	10 <sup>4</sup>	10 <sup>5</sup>	10 <sup>6</sup>	10 <sup>7</sup>
Actinides	3.83E+09	3.53E+09	1.39E+09	4.25E+08	1.97E+07	2.80E+06	9.44E+05
Fission Products	2.17E+09	2.40E+08	1.25E+05	6.18E+04	2.17E+04	7.42E+03	3.24E+03

TABLE 3.4.16. RTF RADIOACTIVE INGESTION TOXICITY COMPARISON (ACTINIDES VS. FISSION PRODUCTS), SV.

Time (years)	10	10 <sup>2</sup>	10 <sup>3</sup>	10 <sup>4</sup>	10 <sup>5</sup>	10 <sup>6</sup>	10 <sup>7</sup>
Actinides	4.23E+09	3.28E+09	1.22E+09	3.34E+08	3.36E+07	2.95E+06	1.71E+05
Fission Products	2.99E+09	3.31E+08	1.43E+05	6.99E+04	2.36E+04	8.66E+03	3.93E+03

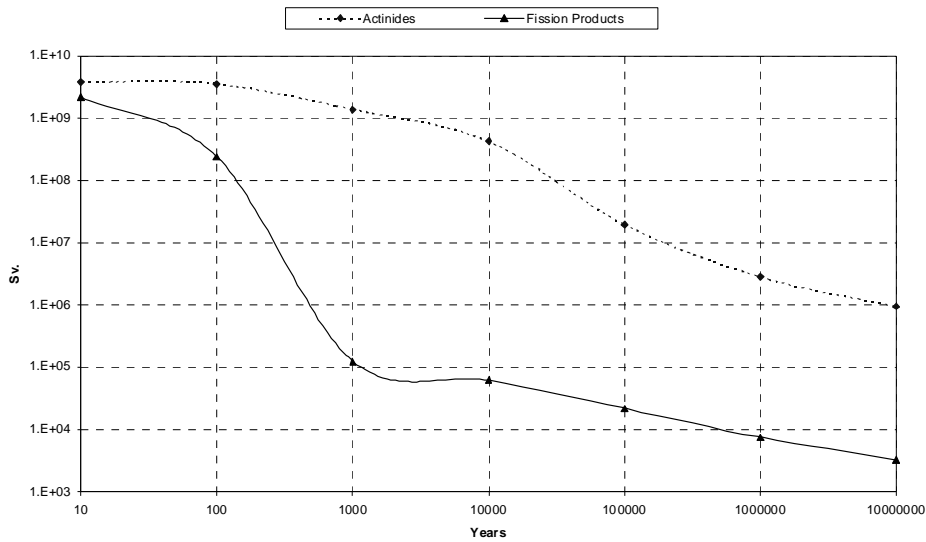


FIG. 3.4.5. Reference MOX radioactive ingestion toxicity comparison (Sv).

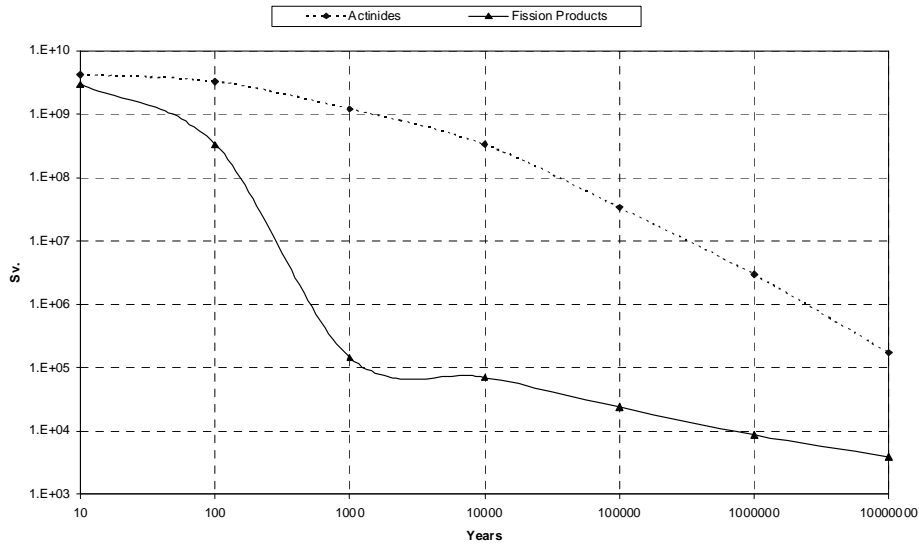


FIG. 3.4.6. RTF radioactive ingestion toxicity comparison (Sv).

#### REFERENCES TO SECTION 3.4.

- [1] RTPC Report, The Non-proliferative Light Water Thorium Reactor, VVERT Preliminary Reference Design 1996 (unpublished).
- [2] GALPERIN, A., REICHERT, P., RADKOWSKY, A., Thorium Fuel for Light Water Reactors – Reducing Proliferation Potential of Nuclear power Fuel Cycle, Science & Global Security 6 (1997).
- [3] A collection of Progress Reports by Kurchatov Institute prepared for Brookhaven National Laboratory, 1996-1998 (unpublished).