Annex E

SPENT FUEL COMPOSITION AS A FUNCTION OF BURN-UP AND COOLING TIMES

Table E.1 **General description of PWR assemblies**

Type of assembly		**AFA 900 MW**	**AFA 1300 MW or N4**
Geometry		square 17x17	square 17x17
Rod lattice pitch	(mm)	12.6	12.6
Characteristic width	(mm)	214.2	
Assembly lattice pitch (mm)	(mm)	215	
Height: overall (mm)	(mm)	4 058	4 793
fissile (mm)	(mm)	3 658	4 267
Total mass	(kg)	670	780
Mass of heavy metal (U and Pu)	(kg)	461.7	538.5
Number of “fuel” rods		264	264
Number of thimble guides		25	25
Clad outside diameter	(mm)	9.50	9.50
Clad thickness	(mm)	0.57	0.57
Clad material		zircaloy 4	zircaloy 4
Rod support system		8 grids top nozzle bottom nozzle	10 grids top nozzle bottom nozzle
Maximum linear power density	(W/cm)	419	426

Table E.2 **Changes in radioactive properties of UOX fuels as a function of burn-up (Expressed per ton of initial heavy metal)**

ATB = 33 GWd/tHM E = 3.5% management 1/3 core*		ATB = 41.2 GWd/tHM E = 3.7% management 1/4 core*		ATB = 50.05 GWd/tHM E = 4.2% management 1/5 core*	
	Mass (kg)		**Mass** (kg)		**Mass** (kg)
U	955.2	U	945	U	935
Pu	9.73	Pu	10.85	Pu	12.00
Np	0.42	Np	0.55	Np	0.72
Am	0.37	Am	0.53	Am	0.66
Cm	0.02	Cm	0.06	Cm	0.11
(ΣMA:	0.815)	(ΣMA:	1.14)	(ΣMA:	1.25)
ΣFP	33.74	ΣFP	42.25	ΣFP	51.3
including:		including:		including:	
^{79}Sc	0.005	^{79}Sc	0.006	^{79}Sc	0.007
^{93}Zr	0.715	^{93}Zr	0.87	^{93}Zr	1.05
^{99}Tc	0.823	^{99}Tc	1.00	^{99}Tc	1.2
^{107}Pd	0.20	^{107}Pd	0.27	^{107}Pd	0.34
^{126}Sn	0.02	^{126}Sn	0.03	^{126}Sn	0.03
^{129}I	0.17	^{129}I	0.21	^{129}I	0.26
^{135}Cs	0.35	^{135}Cs	0.46	^{135}Cs	0.59
(ΣLLFP:	2.28)	(ΣLLFP:	2.85)	(ΣLLFP:	2.89)
	Activity (TBq)		**Activity** (TBq)		**Activity** (TBq)
• Heavy nuclides		• Heavy nuclides		• Heavy nuclides	
α activity	2.4×10^{2}	α activity	4.3×10^{2}	α activity	6.6×10^{2}
β activity	4.3×10^{3}	β activity	5.2×10^{3}	β activity	5.9×10^{3}
• FP		• FP		• FP	
β activity	1.75×10^{4}	β activity	2.13×10^{4}	β activity	2.46×10^{4}

*: Four years after discharge from reactor.
E: Initial enrichment in ^{235}U
ATB: Average thermal burn-up
MA: Minor actinides
FP: Fission products
LLFP: Long-lived fission products
TBq: Terabecquerel (10^{12} Bq)
Source: CEA/DRN/SPRC

Table E.3 **Changes in radioactive properties of MOX fuels as a function of burn-up (Expressed per ton of initial heavy metal)**

ATB = 33 GWd/tHM average Pu content: 5.3%*		ATB = 43.5 GWd/tHM average Pu content: 5.2%*	
	Mass (kg)		Mass (kg)
U	924	U	873
Pu	38.4	Pu	57.5
Np	0.14	Np	0.16
Am	2.90	Am	4.83
Cm	0.50	Cm	0.92
	(ΣMA: 3.54)		(ΣMA: 5.91)
ΣFP	33.2	ΣFP	49.1
	Activity (TBq)		**Activity (TBq)**
• Heavy nuclides		• Heavy nuclides	
α activity	2.5×10^3	α activity	4.8×10^3
β activity	21.8×10^3	β activity	31.6×10^3
• FP		• FP	
β activity	17.9×10^3	β activity	21.4×10^3

*: Four years discharge exit from reactor.

Source: CEA/DRN/SPRC

Table E.4 **Radioactive properties of UOX and MOX fuels (Expressed per TWhe)**

UOX, ATB = 41.2 GWd/tHM initial enrichment: 3.7%*		MOX, ATB = 43.5 GWd/tHM average Pu content: 8.2%*	
	Mass (kg)		**Mass** (kg)
U	2946	U	2578
Pu	33.8	Pu	169.8
Np	1.71	Np	0.47
Am	3.12	Am	14.27
Cm	0.1	Cm	2.72
	(ΣMA: 3.55)		(ΣMA: 17.46)
ΣFP	132	ΣFP	145
	Activity (TBq)		**Activity** (TBq)
• Heavy nuclides		• Heavy nuclides	
α activity	1.3×10^3	α activity	1.4×10^3
β activity	16.2×10^3	β activity	9.3×10^3
• FP		• FP	
β activity	66.4×10^3	β activity	63.2×10^3

*: Four years discharge exit from reactor.

Table E.5 **Main long-lived or parent radionuclides present in irradiated fuels**

Radionuclide	Half-life (year)
Uranium	
^{234}U	2.46×10^{5}
^{235}U	7.04×10^{8}
^{236}U	2.34×10^{7}
^{238}U	4.47×10^{9}
Actinides (α emitters)	
^{238}Pu	87.7
^{239}Pu	24 100
^{240}Pu	6 560
^{241}Pu	14.35
^{242}Pu	3.74×10^{5}
^{237}Np	2.14×10^{6}
^{241}Am	432.7
^{243}Am	7 368
^{245}Mc	8.5×10^{3}
^{246}Mc	4.73×10^{3}
Fission products (β/γ emitters)	
^{79}Se	6.5×10^{5}
^{93}Zr	1.5×10^{6}
^{99}Tc	2.13×10^{5}
^{107}Pd	6.5×10^{6}
^{126}Sn	1×10^{5}
^{129}I	1.57×10^{7}
^{135}Cs	2.3×10^{6}
Activation products (β/γ emitters)	
^{14}C	5 715
^{59}Ni	7.6×10^{4}
^{63}Ni	100
^{93}Zr	1.53×10^{6}
^{94}Nb	2.03×10^{4}

Table E.6 **Change in isotopic composition of actinides with burn-up (4 years after discharge from reactor)**

(A) UO_2 fuels

Isotope	ATB = 33 GWd/tHM E = 3.5%	ATB = 41.2 GWd/tHM E = 3.7%	ATB = 50 GWd/tHM E = 4.2%
^{238}Pu	1.7%	2.5%	3.5%
^{239}Pu	58.8%	54.2%	51.9%
^{240}Pu	22.8%	23.8%	23.8%
^{241}Pu	11.7%	12.6%	12.9%
^{242}Pu	5.0%	6.8%	7.9%
^{241}Am	72.6%	63.8%	58.1%
^{242}Am	0.2%	0.2%	0.2%
^{243}Am	27.2%	36.0%	41.7%
^{242}Cm	0.1%	–	–
^{243}Cm	1.3%	1.0%	0.8%
^{244}Cm	92.9%	92.2%	91.2%
^{245}Cm	4.9%	5.7%	6.5%
^{246}Cm	0.8%	1.1%	1.5%

ATB: Average thermal burn-up (GWd/tHM)
E: Initial enrichment in ^{235}U

(B) MOX fuels

Isotope	ATB = 33 GWd/tHM average Pu* = 5.3%	ATB = 43.5 GWd/tHM average Pu** = 8.2%
^{238}Pu	3.1%	4.4%
^{239}Pu	40.8%	37.4%
^{240}Pu	30.6%	31.1%
^{241}Pu	14.9%	14.5%
^{242}Pu	10.6%	12.6%
^{241}Am	61.0%	61.1%
^{242}Am	0.4%	0.7%
^{243}Am	38.6%	38.2%
^{242}Cm	0.07%	0.07%
^{243}Cm	1.2%	1.5%
^{244}Cm	88.5%	86.8%
^{245}Cm	9.6%	10.9%
^{246}Cm	0.7%	0.7%

* Initial Pu from UOX1 fuel 33 GWd/tHM (E = 3.5%) reprocessed after 3 years.
** Initial Pu from UOX2 fuel 45 GWd/tHM (E = 3.7%) reprocessed after 4 years.

Table E.7 **Mass proportion of long-lived fission product isotopes at the time of reprocessing (4 years after discharge from the reactor)**

Isotope	UOX (ATB = 41.2 GWd/tHM)	MOX (ATB = 43.5 GWd/tHM)
^{79}Se	8.6%	10%
^{93}Zr	20%	19.6%
^{99}Tc	100%	100%
^{107}Pd	16%	19%
^{126}Sn	40%	41%
^{129}I	81%	76%
^{135}Cs	14%	25%

Table E.8 **Mean inventory of radioactive nuclides in high-burn-up UO_2 fuel per GWe-year (45-50 GWd/tHM, 5 years cooling)**

Significant fission products

Nuclide	Isotope (kg/GWe-year)	Element (kg/GWe-year)	Activity (Bq/GWe-year)	Half-life (year)	Radiation energy (MeV)
^{90}Sr	15.03	26.04 (Sr)	8.1×10^{16}	28.78	0.54 (β)
^{99}Tc	26.6	26.6 (Tc)	1.57×10^{13}	2.13×10^{5}	0.29 (β)
^{93}Zr	23.1	117.8 (Zr)	2.4×10^{12}	1.53×10^{6}	0.06 (β)
^{129}I	5.8	7.1 (I)	3.9×10^{10}	1.57×10^{7}	0.15 (β)
^{135}Cs	12.5	85.7 (Cs)	$4\text{-}6\times10^{11}$	2.3×10^{6}	0.21 (β)
^{137}Cs	35.8	85.7 (Cs)	1.17×10^{17}	30.07	0.51 (β)

Actinide inventory of spent UO_2 fuel per GWe/year at 47.5 – 50 GWd/tHM

Nuclide	Isotope (kg/GWe-year)	Element (kg/GWe-year)	Activity (Bq/GWe-year)	Half-life (year)	Radiation energy (MeV)
^{234}U	3.7 – 5.2	20 685 (U)	$6.2 – 8.7\times10^{11}$	2.46×10^{5}	4.85 (α)
^{235}U	138 – 173		$1.3 – 1.7\times10^{10}$	7.04×10^{8}	4.68 (α)
^{236}U	118 – 136		3×10^{11}	2.34×10^{7}	4.57 (α)
^{238}U	20 424		2.7×10^{11}	4.47×10^{9}	4.27 (α)
^{237}Np	15.6 – 16	16 (Np)	4.2×10^{11}	2.14×10^{6}	4.95 (α)
^{238}Pu	7.46 – 8.65	240 (Pu)	$4.2 – 5.5\times10^{15}$	87.7	5.50 (α)
^{239}Pu	125.3		3.3×10^{14}	2.41×10^{4}	5.15 (α)
^{240}Pu	60.8 – 71.2		$5.1 – 5.9\times10^{14}$	6.56×10^{3}	5.15 (α)
^{241}Pu	26.3 – 30.3		3.1×10^{12}	14.35	5.14 (α) 0.02 (β)
^{242}Pu	17.6 – 19.8		$2.6 – 3\times10^{12}$	3.74×10^{5}	4.98 (α)
^{241}Am	9.3 – 11.6	12.8 – 16.4 (Am)	$1.1 – 1.3\times10^{17}$	432.7	5.64 (α)
^{243}Am	3.5 – 4.72		$2.6 – 3.5\times10^{13}$	7.36×10^{3}	5.44 (α)
^{243}Cm	0.012	1.745 (Cm)	3.62×10^{13}	29.1	6.16 (α)
^{244}Cm	1.557		$4.6 – 5.8\times10^{15}$	18.1	5.9 (α)
^{245}Cm	0.075		$4.7 – 8.8\times10^{11}$	8.532×10^{3}	5.62 (α)
^{246}Cm	0.100		$1.1 – 3.5\times10^{11}$	4.73×10^{3}	5.47 (α)