

APPENDIXES

Appendix A: Other calculations for the mass balance of the nuclear energy systems

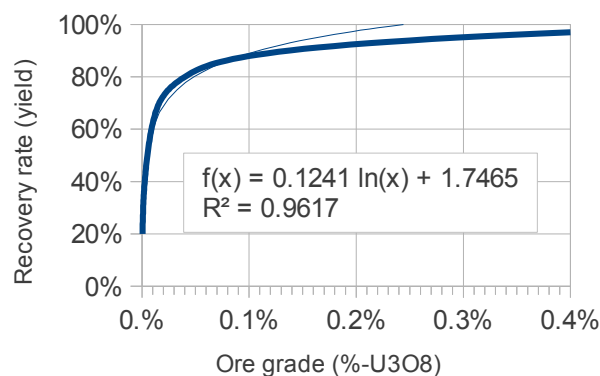


Figure A.1: Recovery rate (yield) vs. Ore grade
(source: adapted from Lenzen, 2008)

Process parameters				
Feed Assay	0.711% U-235	Feed:	264 t_{UF6}	
		Enrich. effort:		Product: (enriched)
Product Assay	3.5% U-235	120 000 SWU	→ Enrichment Plant →	38 t_{UF6}
Tails Assay	0.25% U-235			
		Tails: (depleted)		227 t_{UF6}

Table A.1: Mass balance evaluation of uranium enrichment (Case 1)
(source: adapted from WISE, 2009a)

Process parameters				
Feed Assay	0.711% U-235	Feed:	222 t_{UF6}	
		Enrich. effort:		Product: (enriched)
Product Assay	3.5% U-235	101 000 SWU	→ Enrichment Plant →	32 t_{UF6}
Tails Assay	0.25% U-235			
		Tails: (depleted)		191 t_{UF6}

Table A.2: Mass balance evaluation of uranium enrichment (Case 2)
(source: adapted from WISE, 2009a)



Plutonium recycled from spent fuel by reprocessing for use in mixed-oxide fuel (MOX)	Input:	460 kg_{Pu}/y	300 kg_{Pu}/y
		6 t_{UO2}/y	5 t_U/y
	Output:	6 t_{MOX}/y	5 t_{HM}/y
Enrichment of uranium recycled from spent fuel by reprocessing (U _{rep})	Enrich. effort:	Feed: 190 SWU → Enrichment Plant Tails: (depleted)	Product: (enriched) 0.3 t_{UF6} (rep) → 0.04 t_{UF6} 0.03 t_{UO2} 0.03 t_U
Re-enrichment of depleted uranium (U _{dep})	Enrich. effort:	Feed: 17 200 SWU → Enrichment Plant Tails: (depleted)	Product: (enriched) 190 t_{UF6} (dep) → 5 t_{UF6} 4 t_{UO2} 4 t_U

Table A.3: Mass balance evaluation for the reprocessing phase (Case 2)
(source: WISE, 2009b)



Appendix B: Detailed calculations for the electricity requirements

Phase	Parameter	Value	Unit	Source
(1) Mining	Mining, Milling and Conversion	<i>Electricity requirement negligible</i>		
(2) Enriching	Enriching	790 kWh _{el} /SWU		after Lenzen, 2008
	Fuel fab.	145 MWh _{el} /t _U		Lenzen, 2008
(3) Power plant	Construct.	<i>Electricity requirement negligible</i>		
	Operation	8.5 GWh _{el} /y		Lenzen, 2008
(4) Handling waste	Dismantling	80 MWh _{el} /t _{HLW}		Lenzen, 2008
		<i>Electricity requirement negligible</i>	MWh _{el} /t _{ILW/LLW}	
	Waste storage	<i>Electricity requirement negligible</i>		
	Waste disposal	329 MWh _{el} /t _{HLW}		Lenzen, 2008
		24 MWh _{el} /t _{ILW/LLW}		Lenzen, 2008

Table B-1: Electricity requirements (Case 1)



Phase	Parameter	Value	Unit	Source
(1) Mining	Mining, Milling and Conversion	<i>Electricity requirement negligible</i>		
(2) Enriching	Enriching	790 kWh _{el} /SWU		after Lenzen, 2008
	Fuel fab.	145 MWh _{el} /t _U		Lenzen, 2008
(3) Power plant	Construct.	<i>Electricity requirement negligible</i>		
	Operation	8.5 GWh _{el} /y		Lenzen, 2008
(4) Reprocess.	Reception and storage	<i>Electricity requirement negligible</i>		
	Reprocess.	8.5 GWh _{el} /y		
	MOX fuel fab.	145 MWh _{el} /t _{HM}		
	Urep and Udep re-enrich.	790 kWh _{el} /SWU		
	UO2-rep fuel fab.	145 MWh _{el} /t _U		
	Vitrification	8.5 GWh _{el} /y		
(5) Handling waste	Dismantling	80 MWh _{el} /t _{HLW}		Lenzen, 2008
		<i>Electricity requirement negligible</i>	MWh _{el} /t _{ILW/LLW}	
	Waste storage	<i>Electricity requirement negligible</i>		
	Waste disposal	329 MWh _{el} /t _{HLW}		Lenzen, 2008
		24 MWh _{el} /t _{ILW/LLW}		Lenzen, 2008

Table B-2: Electricity requirements (Case 2)



Phase	Parameter	Value	Unit	Source
(1) Mining	Mining	<i>Electricity requirement negligible</i>		
(2) Cleaning	Sulfur removal	<i>N/A</i>		
(3) Handling waste		<i>N/A</i>		

Table B-3: Electricity requirements (Case 3)

Phase	Parameter	Value	Unit	Source
(1) Mining	Mining	<i>Electricity requirement negligible</i>		
(2) Cleaning	Sulfur removal	<i>Electricity requirement negligible</i>		
(3) Handling waste	Capture	<i>Electricity requirement negligible</i>		
	Compress. and transport	111 kWh _{el} /t _{captured}		Koomneef et al., 2008
	Injection	7 kWh _{el} /t _{captured}		Koomneef et al., 2008

Table B-4: Electricity requirements (Case 4)



Appendix C: Detailed calculations for the fossil-fuel requirements

(1) Mining	Mining	844 GJ/t _U	after Lenzen, 2008
	Milling	1153 GJ/t _U	after Lenzen, 2008
	Conversion	276 MWh _{th} /t _U	after Lenzen, 2008
(2) Enriching	Enriching	19.7 kWh _{th} /SWU	after Lenzen, 2008
	Fuel fab.	1403 GJ/t _U	Lenzen, 2008
(3) Power plant	Construct.	3136 GWh _{th}	after Lenzen, 2008
	Operation	332 GWh _{th} /y	after Lenzen, 2008
(4) Handling waste	Dismantling	5.2 PJ	after Lenzen, 2008
	Waste storage	600 MWh _{th} /t _{HLLW}	Lenzen, 2008
		400 MWh _{th} /t _{LLW}	Lenzen, 2008
	Waste disposal	119 MWh _{th} /t _{HLLW}	Lenzen, 2008
		1 MWh _{th} /t _{ILW/LLW}	Lenzen, 2008

Table C-1: Indirect fossil-fuel (oil) requirements (Case 1)



(1) Mining	Mining	844 GJ/t _U	after Lenzen, 2008
	Milling	1153 GJ/t _U	after Lenzen, 2008
	Conversion	276 MWh _{th} /t _U	after Lenzen, 2008
(2) Enriching	Enriching	19.7 kWh _{th} /SWU	after Lenzen, 2008
	Fuel fab.	1403 GJ/t _U	Lenzen, 2008
(3) Power plant	Construct.	3136 GWh _{th}	after Lenzen, 2008
	Operation	332 GWh _{th} /y	after Lenzen, 2008
(4) Reprocess.	Reception and storage	600 MWh _{th} /t _{HLLW}	
	Reprocess.	332 GWh _{th} /y	
	MOX fuel fab.	1403 GJ/t _{HM}	
	Urep and Udep re-enrich.	19.7 kWh _{th} /SWU	
	UO2-rep fuel fab.	1403 GJ/t _U	
	Vitrification	332 GWh _{th} /y	
(5) Handling waste	Dismantling	5.2 PJ	after Lenzen, 2008
	Waste storage	600 MWh _{th} /t _{HLLW}	Lenzen, 2008
		400 MWh _{th} /t _{LLW}	Lenzen, 2008
	Waste disposal	119 MWh _{th} /t _{HLLW}	Lenzen, 2008
		1 MWh _{th} /t _{ILW/LLW}	Lenzen, 2008

Table C-2: Indirect fossil-fuel (oil) requirements (Case 2)



Phase	Parameter	Value	Unit	Source
(1) Mining	Mining		1.2 Mt/y	see Table 4-3
(2) Cleaning	Sulfur removal	N/A		
(3) Handling waste		N/A		

Table C-3: Direct fossil-fuel (coal) requirements (Case 3)

Phase	Parameter	Value	Unit	Source
(1) Mining	Mining		0.1 MJ/kWh _{el}	after Spath et al., 1999
(2) Cleaning	Sulfur removal	<i>Oil requirement negligible</i>		
(3) Handling waste		N/A		

Table C-4: Indirect fossil-fuel (oil) requirements (Case 3)

Phase	Parameter	Value	Unit	Source
(1) Mining	Mining		1.5 Mt/y	see Table 4-4
(2) Cleaning	Sulfur removal	N/A		
(3) Handling waste	Capture	N/A		
	Compress., transport and storage	N/A		

Table C-5: Direct fossil-fuel (coal) requirements (Case 4)

Phase	Parameter	Value	Unit	Source
(1) Mining	Mining		0.1 MJ/kWh _{el}	after Spath et al., 1999
(2) Cleaning	Sulfur removal	<i>Oil requirement negligible</i>		
(3) Handling waste	Capture, Compress., transport and storage	<i>Oil requirement negligible</i>		

Table C-6: Indirect fossil-fuel (oil) requirements (Case 4)



Appendix D: Detailed calculations for the CO₂ emissions

CO ₂ emitted from oil used (diesel)		3.4 t _{CO₂} /toe
Direct emissions	Power plant operation	3.2 toe/GWh _{el}
Indirect emissions	Fuel cycle process	4.6 toe/GWh _{el}

Table D-1: CO₂ emissions (Case 1)

CO ₂ emitted from oil used (diesel)		3.4 t _{CO₂} /toe
Direct emissions	Power plant operation and reprocess.	3.2 toe/GWh _{el}
Indirect emissions	Fuel cycle process	10.2 toe/GWh _{el}

Table D-2: CO₂ emissions (Case 2)

CO ₂ emitted from oil used (diesel)		3.4 t _{CO₂} /toe
Direct emissions	Power plant operation	2.7 Mt _{CO₂} /y
Indirect emissions	Fuel cycle process	2.9 toe/GWh _{el}

Table D-3: CO₂ emissions (Case 3)

CO ₂ emitted from oil used (diesel)		3.4 t _{CO₂} /toe
Direct emissions	Power plant operation	0.3 Mt _{CO₂} /y
Indirect emissions	Fuel cycle process	2.9 toe/GWh _{el}

Table D-4: CO₂ emissions (Case 4)



Appendix E: Detailed calculations for the CO₂ emissions

Country	Production Employment (pers/y)	Production (tU/y)	Average grade (%- U ₃ O ₈)
Brazil	128	272	0.108
Canada	972	11607	17.584
Kazakhstan	1280	2822	0.065
Namibia	782	2333	0.030
Niger	1348	3080	0.412
Russian Federation	5000	2850	0.188
Productivity	2.41 (tU/pers)		3.06% (U₃O₈)

Table E-1: Uranium mining productivity (Cases 1 and 2)
(source: after OECD/IAEA, 2004)



Phase	Parameter	Value	Unit	Source
(1) Mining	Productivity		80 t _{ORE} /man-year (av.)	after OECD/IAEA, 2004
(2) Enriching	Centrifuge		80 man-year	after Rothwell, 2009
	Fuel fabrication		40 man-year	after Rothwell, 2010
(3) Power plant	Construct.	18 700 man-year		after NEI, 2010
	Operation	400 man-year		NEI, 2010
(4) Handling waste	Dismantling (45% of construct.)	8 400 man-year		
	Waste storage and disposal of HLW	<i>Labor requirement not included</i>		
	Waste storage and disposal of ILW/LLW (France)		200 man-year	ANDRA, 2008
			43 000 t _{ILW/LLW} /y	ANDRA, 2008
	Average working hours	1 800 h/y		OECD, 2008

Table E-2: Labor requirements (Case 1)



Phase	Parameter	Value	Unit	Source
(1) Mining	Productivity		80 t _{ORE} /man-year (av.)	after OECD/IAEA, 2004
(2) Enriching	Centrifuge		70 man-year	after Rothwell, 2009
	Fuel fabrication		30 man-year	after Rothwell, 2010
(3) Power plant	Construct.	18 700 man-year		after NEI, 2010
	Operation	400 man-year		NEI, 2010
(4) Reprocess.	French reproces. plant of La Hague – staff	6 000 man-year		Schneider and Marignac, 2008
	French reproces. plant of La Hague – capacity	1 700 t _{USED} /y		Schneider and Marignac, 2008
(5) Handling waste	Dismantling (45% of construct.)	8 400 man-year		
	Waste storage and disposal of HLW	<i>Labor requirement included in Reprocess.</i>		
	Waste storage and disposal of ILW/LLW (France)	200 man-year		ANDRA, 2008
		43 000 t _{ILW/LLW} /y		ANDRA, 2008
	Average working hours	1 800 h/y		OECD, 2008

Table E-3: Labor requirements (Case 2)



Phase	Parameter	Value	Unit	Source
(1) Mining	Productivity		14 t/h (Surface)	Darmstadter, 1999
			5 t/h (Underg.)	Darmstadter, 1999
			8 t/h (av.)	
(2) Cleaning		<i>Labor requirement negligible</i>		
(3) Handling waste		<i>N/A</i>		

Table E-4: Labor requirements (Case 3)

Phase	Parameter	Value	Unit	Source
(1) Mining	Productivity		14 t/h (Surface)	Darmstadter, 1999
			5 t/h (Underg.)	Darmstadter, 1999
			8 t/h (av.)	
(2) Cleaning		<i>Labor requirement negligible</i>		
(3) Handling waste		<i>Labor requirement negligible</i>		

Table E-5: Labor requirements (Case 4)

