Advanced reference reactor and EPR

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September 2019
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Note

In this document the references are coded by Q-numbers (e.g. Q6). Each reference has a unique number in this coding system, which is consistently used throughout all publications by the author. In the list at the back of the document the references are sorted by Q-number. The resulting sequence is not necessarily the same order in which the references appear in the text.

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Basic parameters

This study compares the specific CO_2 emissions of the full life cycles of two different nuclear power plants, both using a Pressurized Water Reactor (PWR), and both operating in the once-through mode, without recycling of uranium and/or plutonium.
On a global scale the use of MOX (MixedOXide, uranium oxide mixed with plutonium oxide as fissile material) in light-water reactors is nearly negligible and the use of MOX is not expected to increase during the next decades, the more so after the Fukushima disaster. For this reason the MOX variant is not included in this study. Closed-cycle reactors (^{238}U-^{239}Pu breeders) and thorium-fuelled reactors (^{232}Th-^{233}U breeders) are unlikely to be available for commercial application during the next decades, and are also left outside of the scope of this study.
The reference reactor is based on a PWR corresponding with the most advanced currently operating power reactors. The emissions of the advanced reference reactor is compared with those of the EPR, also a PWR. In Europe this reactor design was called European Pressurized Reactor, and the internationalised name was Evolutionary Power Reactor, but it is now simply named EPR. At the time of writing (2019) no EPR in the world has ever operated, so its performance parameters as designed are yet to be proved in practice. Some basic parameters of the reference advanced reactor and the EPR design are summarised in Table 1.

Table 1
Primary parameters of the reference advanced reactor and the EPR design. Sources primary EPR data: [UK-EPR-*Dsum* 2007] Q773, [UK-EPR 2007] Q774, [Areva 2012].

quantity	symbol	advanced reactor	EPR design	unit
net power, electric (at grid connection)	P_e	1.00	1.62	GW_e
power, thermal	P_{th}	2.94	4.50	GW_{th}
thermal efficiency	e	34	36	%
nominal burnup	B	46	60	GW_{th}.day/Mg
lifetime	T	variable	60	years
load factor	L	variable	92%	–
effective operational lifetime, full-power years	$T_{100} = T*L$	25	55	FPY (1)
tails assay of enrichment process	x_t	0.30	0.30	% U-235
fresh fuel enrichment assay	x_p	4.2	5.0	% U-235

Effective operational lifetime

Use of the unit full-power year (FPY) to quantify the lifetime useful energy production of a nuclear power station avoids ambiguities regarding the effective operational age of the reactor in calender years, load factor, availability factor and other variables. A full-power year is defined as the period in which a reactor, with a nominal power of P_e GW_e generates a fixed amount of electricity, equalling the amount if the reactor operated during a full year continually at 100% of its nominal power. The electricity produced in one FPY, J_{100} , is:

$J_{100} = P_e$ GW.year = P_e*31.536 PJ/FPY = P_e*8760*10^6 kWh/FPY

The reference advanced eactor in this study has a nominal power of P_e = 1 GW_e, so the amount of electricity corresponding with one FPY is:

J_{100} = 31.536 PJ = 8760*10^6 kWh/FPY

The EPR design has a nominal power of P_e = 1.62 GW_e, so the amount of electricity corresponding with one FPY is:

J_{100} = 51.088 PJ/FPY = 14.19*10^9 kWh/FPY

The effective operational lifetime T_{100} of a given reactor can be calculated by the following equation 1:

$$T_{100} = \frac{E_{life}}{J_{100}}$$

T_{100}	=	operational lifetime: number of full-power years	FPY
E_{life}	=	lifetime electricity production (put into the grid)	PJ
J_{100}	=	electricity production during 1 year at 100%	PJ/FPY

eq 1

In 2017 the average operational lifetime of the world nuclear power plants was estimated at 23-24 FPY, a figure that only slightly rised during the past decade. Evidently some individual reactors may have reached higher values of T_{100}. The reference advanced reactor has an assumed effective operational lifetime of T_{100} = 25 FPY, slightly higher than the world average. The EPR design, with an assumed lifetime of 60 calender years and a load factor of 92%, would have an operational lifetime of T_{100} = 0.92*60 = 55 FPY (rounded). This figure seems highly unlikely in view of the empirical evidence from the past 60 years of civil nuclear power. Not one nuclear power station in the world has ever reached an effective operational lifetime of 55 FPY.

Because global warming and CO_2 emissions are global issues, the potential contribution of nuclear power to the mitigation of the greenhouse gas emissions should be estimated on the basis of empirical world-average figures, not on hypothetical figures of one individual yet-to-be-proved concept.

Secondary parameters

Table 2

Secondary parameters of the reference advanced reactor and the EPR design.

quantity	symbol	advanced reactor	EPR desigm	unit
enrichment feed/product ratio	F/P	9.51	11.46	–
specific separative work	S_{spec}	5.66	7.20	SWU/kg U
lifetime separative work	S_{life}	3352	11004	MSWU
nominal burnup	B	3.974	5.184	PJ_{th}/Mg U_{enrich}
full power thermal energy production rate	J_{100} (th)	92.75	141.9	PJ_{th}/FPY
full power electric energy production rate	J_{100} (e)	8.760E9	1.419E10	kWh/FPY
lifetime thermal energy production	E_{th} (life) = J_{100} (th) * T_{100}	2319	7805	PJ_{th}
lifetime electric energy production	E_e (life) = J_{100} (e) * T_{100}	$219*10^9$	$781*10^9$	kWh
lifetime enriched uranium in reactor	$m_0 = E_{th}$ (life)/B	583.4	1506	Mg U_{enrich}
lifetime natural uranium consumption (1)	m_3	5748	17880	Mg U_{nat}
average specific electricity generation	$J_e = E_e / m_3$	3.810E7	4.365E7	kWh/ Mg U_{nat}
specific enriched uranium consumption	m_0/kWh	0.002664	0.001930	g U_{enrich}/kWh
specific natural uranium consumption	m_3/kWh	0.0262	0.02291	g U_{nat}/kWh

(1) see section uranium balance

Enrichment

In the enrichment process natural uranium is separated into two fractions: one small fraction is enriched in fissile uranium-235, the other, larger fraction is depleted in U-235.

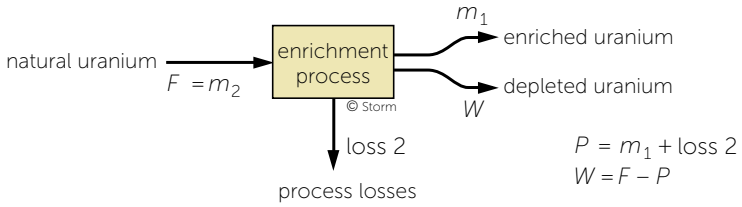

Figure 1
In the enrichment process the feed *F* of natural uranium is separated into the product fraction *P* (enriched uranium) and the waste fraction *W* (depleted uranium)

The ratio of feed mass *F* and product mass *P* depends on the product assay and tails assay and can be calculated by equation 2:

$$\frac{F}{P} = \frac{x_p - x_t}{x_f - x_t}$$

F	=	feed mass uranium	kg
P	=	product mass uranium	kg
x_f	=	feed assay	fraction U-235
x_p	=	product assay	fraction U-235
x_t	=	tails assay	fraction U-235

eq 2

Separative work *S* (unit: SWU) can be calculated by equation 3 [DOE/EIA 1997] Q64. If *F* and *P* are given in kg, de unit is SWU/kg U.

$$S = P \bullet V(x_p) - F \bullet V(x_f) + (F - P) \bullet V(x_t)$$

$$V(x) = (2x - 1) \bullet \ln\left(\frac{x}{1 - x}\right)$$

S = separative work kg SWU = separative work unit

eq 3

In this study a tails assay of $x_t = 0.0030$ (fraction U-235) is assumed. A tails assay of 0.30% U-235 is common practice at low uranium prices, according to [MIT 2003-2009] Q280.
Feed assay, natural uranium $x_f = 0.0071$,
product assay of reference advanced reactor $x_p = 0.042$,
product assay of EPR design $x_p = 0.050$.

Uranium mass balance

In the front-end processes uranium as found in nature is converted into nuclear fuel to be placed into a reactor. To assess the energy equirements and specific CO_2 emissions of the front-end processes the mass balance of uranium of the nuclear energy system during its operational lifetime has to be calculated.

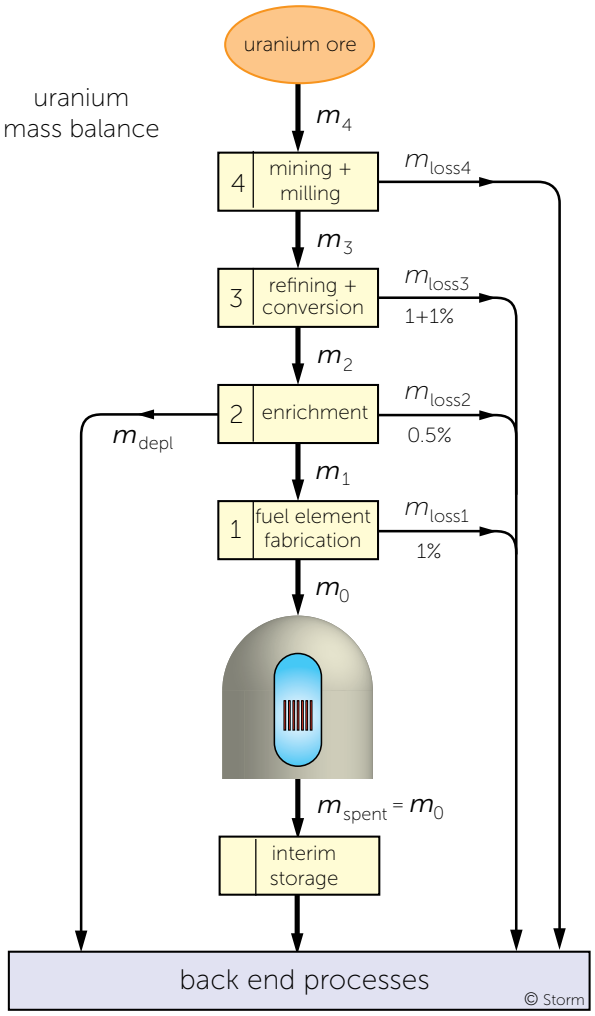

Figure 2

Mass balance of uranium to be processed in the front end, including the losses of each process. Process losses derived from: [Jan & Krug 1995] Q29, [Scheidt 1995] Q30, [DOE/EIA 1997], [ERA 2006] Q320 and [ERA-*AR* 2005] Q321.

The mass of enriched uranium consumed by the reactor during its operational lifetime, indicated by m_0 in Figure 2, can be calculated from the lifetime thermal energy production and the nominal burnup of the nuclear fuel. In practice the effective burnup averaged over the operational lifetime may be lower than the nominal burnup rate.

Table 3 summarises the figures of the uranium mass balances of the advanced reference reactor and the EPR design.

Table 3

Lifetime uranium mass balances of the advanced refrence reactor and the EPR design in the once-through mode. Assumed recovery yield of the uranium mining and milling $Y = 90\%$, grade of the processed ore $G = 0.085\%$ U.

process	symbol	unit	advanced reactor $x_p = 4.2\%$	EPR design $x_p = 5.0\%$
processed ore	m_{ore}	Tg	7.514	23.37
input mining+milling	m_4	Mg U_{nat}	6387	19867
loss mining + milling	$\Delta = m_4 - m_3$	Mg U_{nat}	639	1987
input refining + conversion	m_3	Mg U_{nat}	5748	17880
loss refining and conversion	$\Delta = m_3 - m_2$	Mg U_{nat}	115	358
enrichment feed	$m_2 = F$	Mg U_{nat}	5633	17522
feed/product ratio	F/P	-	9.51	11.46
enrichment product	P	Mg U_{enr}	592	1529
depleted uranium	$m_{depl} = W$	Mg U	5041	15993
specific separative work	S (kg)	SWU/kg U_{enr}	5.66	7.20
lifetime separative work	S (life)	MSWU	3352	11009
loss enrichment	$\Delta = P - m_1$	Mg U_{enr}	3	8
fuel element fabrication	m_1	Mg U_{enr}	589	1521
loss fuel fabrication	$\Delta = m_1 - m_o$	Mg U_{enr}	6	15
lifetime input reactor	m_o	Mg U_{enr}	583	1506
uranium utilization ratio *	R (U-235)	% of U-235	60	59
fissioned fraction *	$R_{fission}$	% of U_{nat}	0.50	0.54

* see sections below

Uranium-235 utilisation ratio

The uranium-235 utilisation factor $R_{(U\text{-}235)}$ is in this study defined as the ratio of the mass of the uranium-235 entering the reactor over the mass of the mass of uranium-235 in the natural uranium leaving the mine:

$$R_{(U\text{-}235)} = \frac{\text{mass U-235 into reactor}}{\text{mass U-235 leaving mine}} = \frac{m_{0\,(U\text{-}235)}}{m_{3\,(U\text{-}235)}} \qquad \text{eq 4}$$

$$m_0\,(U\text{-}235) = x_p * m_0$$
$$m_3\,(U\text{-}235) = x_f * m_3 = 0.0071 * m_3$$

advanced eactor:

$m_0\,(U\text{-}235) = 0.042 * 583.4 = 24.50$ Mg
$m_3\,(U\text{-}235) = 0.0071 * 5748 = 40.81$ Mg
$R\,(U\text{-}235) = 24.50/40.81 = 0.6003 = 60\%$

EPR design:

$m_0\,(U\text{-}235) = 0.050 * 1506 = 75.30$ Mg
$m_3\,(U\text{-}235) = 0.0071 * 17880 = 126.95$ Mg
$R\,(U\text{-}235) = 75.30/126.95 = 0.5931 = 59\%$

These results mean that 40% respectively 41% of the U-235 recovered from the earth's crust in natural uranium is lost in the waste streams of the front-end processes and is not placed into the reactor.

Fissioned fraction of natural uranium

The fissioned fraction is in this study defined as the fraction of the natural uranium, U-235 + U-238, leaving the mine that is actually fissioned in the reactor.

The average specific heat generation by fission of fissile nuclides $J_{fission}$ is:

$J_{fission}$ = 81.08 GJ/g = 81.08 PJ/Mg

The total mass of the nuclides fissioned during the lifetime of the reactor can be found by equation 5:

$$m_{fission} = \frac{\text{gross lifetime heat generation}}{\text{specific fission heat generation}} = \frac{E_{th(life)}}{J_{fission}} \qquad \text{eq 5}$$

The lifetime fissioned fraction $R_{fission}$ is given by equation 6:

$$R_{fission} = \frac{\text{mass of fissioned U}}{\text{mass of U leaving mine}} = \frac{m_{fission}}{m_3} \qquad \text{eq6}$$

advanced reference reactor:

$m_{fission}$ = 2319/81.08 = 28.60 Mg

$R_{fission}$ = 28.60/5748 = 0.004976 = 0.50%

EPR design:

$m_{fission}$ = 7805/81.08 = 96.26 Mg

$R_{fission}$ = 96.26/17880 = 0.005384 = 0.54%

These results mean that in the currently available advanced light-water reactors not more than about 0.5% of the uranium nuclei in natural uranium can be fissioned for useful energy generation.

References

Q29
Jan & Krug 1995
Jan R von & Krug H,
'Brennelemente für den weltweiten Einsatze', (in German),
ATW 40. Jg (1995), Heft 3, März, pp 164 166.

Q30
Scheidt 1995
Scheidt S vom,
'Kohärenz zwischen Brennstoff Auslegung und –Fertigung',
ATW 40, Heft 3, März, pp. 167 169, Jg 1995.

Q64
DOE/EIA 1997
Nuclear power generation and fuel cycle report 1997,
DOE/EIA 0436(97),
Energy Information Administration, September 1997.

Q280
MIT 2003-2009
Deutch J et al.,
The Future of Nuclear Power. An Interdisciplinary MIT Study,
Massachusetts Institute of Technology, Cambridge MA, USA,
2003
ISBN 0-615-12420-8
http://www.mit.edu/afs/athena/org/n/nuclearpower/pdf

Update 2009 /2015(?)
http://web.mit.edu/nuclearpower/
retrieved Nov 2018

Q320
ERA 2006
Energy Resources of Australia Ltd (ERA),
Ranger Operation,
2006,
http://www.energyres.com.au

Q321
ERA-AR 2005
Energy Resources of Australia Ltd (ERA),
ERA 2005 Annual Report,
Chairman's and Chief Executive Report,
2006
http://www.energyres.com.au

Q773
Q777.-Dsum 2007
UK-EPR. Fundamental safety overview. Volume 2: Design and safety. Chapter D: Reactor and core. Sub-chapter D-1 Summary description of the core and fuel assemblies.
not dated, presumably 2007
‹ 2.D.1- Summary Description - v2.pdf ›
http://epr-reactor.co.uk/ssmod/liblocal/docs/V3/Volume%202%20-%20Design%20and%20Safety/2.D%20-%20Reactor%20and%20Core/2.D.1%20-%20Summary%20Description%20-%20v2.pdf
accessed 20 Jan 2018

Q774
UK-EPR 2007
UK-EPR. Fundamental safety overview. Volume 1: Head Document. Chapter A: EPR design description.
AREVA NP & EDF, 2007
‹ 1.A - EPR Design Description - v3.pdf ›
http://www.epr-reactor.co.uk/ssmod/liblocal/docs/V3/Volume%201%20-%20Overview/1.A%20-%20EPR%20Design%20Description/1.A%20-%20EPR%20Design%20Description%20-%20v3.pdf
accessed 20 Jan 2018

Q777
Areva 2012
The EPR reactor. The reference for New Build,
Areva, December 2012.
‹ Areva-8p-EPR-09112012-16.pdf ›
(brochure, 8 pages)
http://www.epr-reactor.co.uk/scripts/ssmod/publigen/content/templates/show.asp?P=198&L=EN
download 20180119