Radioactive waste management - future CO_2 emissions

Jan Willem Storm van Leeuwen
independent consultant

member of the Nuclear Consulting Group

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storm@ceedata.nl

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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Summary and results

By means of a physical/thermodynamic analysis this study assessed the energy consumption and CO_2 emission of the management and final disposal in the safest possible way of the radioactive materials originating in the industrial system needed to generate useful energy, electricity, from nuclear power.

With regard to radioactive naterials and waste management this study starts from the viewpoint that all materials generated in the nuclear process chain containing radionuclides are to be considered as radioactive waste and should be disposed of in geologic repositories. This view is based on a number of considerations, accentuated by the uncertainties, vaguenesses and ambiguities stated in the official reports on nuclear waste from the International Atomic Energy Agency (IAEA):

- Practically it is impossible to know exactly which radionuclides are present in a certain amount of materials and in each container of waste, for example long-lived alpha emitters and short-lived beta emitters. So it is impossible to determine reliably the class of risk of each amount of radioactive waste.
- Inspections are not always possible and are not always reliable.
- Human behaviour and accidents have unpredictable consequences.
- The radiological models used to classify radioactive waste have serious limitations, especially regarding long-term effects of chronic contamination by a number of radionuclides simultaneously, via inhalation and ingestion (air, dust, drinking water, food).
- Regulations for waste management are flexible under economic and political presuure.
- A low radiation level measured (what radiation is measured?) outside of an amount of waste is no guarantee that the contents of the container are harmless when they enter the body,
- Storage of radioactive materials at surface or shallow burial facilities are not safe in the long run. Materials deteriorate with time as a consequence of unavoidable Second Law phenomena. The ageing processes are ehanced in the presence of nuclear radiation. Containers certainly will go leaking, releasing radionuclides into the environment, often undetected. The risks are growing with time.
- As long as radioactive materials are stored in an accessible way within the human environment they are vulnerable to natural disasters, terrorism, intentional and unintentional actions and disruptions, releasing unmeasurable amounts of hazardous radionuclides into the environment

The CO_2 emission and energy investments of nuclear power is estimated by a physical/thermodynamic analysis of the complete life cycle of two reference reactors:

1 Advanced reference reactor, corresponding with the most advanced currently operating reactors, with an effective operational lifetime of 25 full-power years, higher than the world average of 23-24 full-power years. Lifetime electricity production is 219 billion kWh
2 The EPR design with a hypothetical effective operational lifetime of 55 full-power years. Lifetime electricity production would be 781 billion kWh.

Thermal and electric energy inputs needed to operate the processes of the nuclear energy system are kept separated in this study. The electric inputs are assumed to be provided by nuclear power and are to be balanced with the output of the nuclear power plant.
The origin of the CO_2 emissions is the burning of fossil fuels in the processes of the nuclear chain, e.g. diesel engines used in uranium mining, plus the chemical emission by the production of steel and the cement component of concrete.

CO_2 emission

Table 1

Lifetime CO_2 emissions of the contemporary processes, excluding waste management and final disposal. The uncertainty range of the uranium mining + milling figures is caused by different conditions at the operational uranium mines; the ore grade varies roughly from 0.1% to 0.05% U_3O_8 and the mineralogy varies widely, in this study simplified to 'soft ores' and 'hard ores'. 'Low' means: soft ores at a grade of 0.1% U_3O_8, and 'high' means hard ores at a grade of 0.05% U_3O_8.

process	g CO_2/kWh		total CO_2, Mg	
	advanced reactor	EPR design	advanced reactor	EPR design
uranium mining + milling, low	7.1	6.2	1551	4823
mean	32.3	28.2	7039	21965
high	57.4	50.1	12527	39106
refining + conversion	2.8	2.5	615	1911
enrichment	2.6	2.4	570	1872
reconversion + fuel fabrication, incl zircalloy	3.4	2.5	744	1926
construction	24.9	8.4	5445	6522
reactor OMR	24.4	18.1	5340	14102
sum contemporary processes - low	65.2	40.1	14265	31156
mean	90.4	62.1	19753	48298
high	115.5	84.0	25241	65439

Table 2

Lifetime CO_2 emissions of the future processes, including waste packaging and final waste disposal of the upstream processes.

	process	g CO_2/kWh		total CO_2, Mg	
		advanced reactor	EPR design	advanced reactor	EPR design
1	refining + conversion waste managem. + disposal	0.65	0.40	143	313
2	enrichment waste management + disposal	0.37	0.34	82	268
3	reconv. + fuel fabr. waste managem. +disposal	0.90	0.56	198	436
4	reactor OMR waste management + disposal	12.06	7.44	2641	5810
	sum waste managem.. + disp. upstream processes 1-4	14.0	8.74	3064	6827
5	depleted uranium conditioning + waste man. + disp.	5.7	5.06	1248	3952
6	decommissioning + dismantling + waste man. + disp.	40.9	13.61	8946	10626
7	spent fuel handing + final disposal	8.2	5.94	1797	4643
8	mine rehabilitation	4.8	4.22	1057	3295
	sum downstream processes 5-8	59.6	28.8	13048	22516
	sum future processes	73.6	57.6	16112	29343

Table 3

Summary lifetime CO_2 emissions of the complete nuclear process chain from cradle to grave

process		g CO_2/kWh		total CO_2, Mg	
		advanced reactor	EPR design	advanced reactor	EPR design
sum contemporary processes -	low	65.2	40.1	14265	31156
	mean	90.4	62.1	19753	48298
	high	115.5	84.0	25241	65439
sum future processes		73.6	37.5	16112	29343
total nuclear process chain from cradle to grave	low	138.8	77.6	30377	60499
	mean	164.0	99.6	35865	77641
	high	189.1	121.5	41353	94782

Energy investments

Table 4

Lifetime energy investments of the contemporary processes, excluding waste management and final disposal. The uncertainty range of the uranium mining + milling figures is caused by different conditions at the operational uranium mines; the ore grade varies roughly from 0.1% to 0.05% U_3O_8 and the mineralogy varies widely, in this study simplified to 'soft ores' and 'hard ores'. 'Low' means: soft ores at a grade of 0.1% U_3O_8, and 'high' means hard ores at a grade of 0.05% U_3O_8.

process		advanced reactor		EPR design	
		*E*e + *E*th PJ	*E*th PJ	*E*e + *E*th PJ	*E*th PJ
uranium mining + milling,	low	20.7	20.7	64.3	64.3
	mean	94.4	94.4	293	293
	high	168	168	521	521
refining + conversion		8.5	8.2	26.4	25.5
enrichment		10.4	7.6	27.8	25.0
reconversion + fuel fabrication		2.2	1.6	5.8	4.1
construction		80	66.2	96	79.4
reactor OMR		86	71	227	188
sum contemporary processes -	low	208	175	447	386
	mean	282	249	676	615
	high	355	323	904	843

Table 5

Lifetime energy investments of the future processes, including waste packaging and final waste disposal of the upstream processes.

	process	advanced reactor		EPR design	
		*E*e + *E*th PJ	*E*th PJ	*E*e + *E*th PJ	*E*th PJ
1	refining + conversion waste managem. + disposal	2.1	1.9	4.7	4.2
2	enrichment waste management + disposal	1.2	1.1	4.0	3.6
3	reconv. + fuel fabr. waste managem. +disposal	3.0	2.6	6.5	5.8
4	reactor OMR waste management + disposal	40.0	35.3	87.0	77.7
	sum waste managem + disposal processes 1-4	45.8	40.9	102.2	91.3
5	depleted uranium conditioning + waste man. + disp.	18.0	16.6	57.1	52.6
6	decommissioning + dismantling + waste man. + disp.	140.0	119.3	166.3	141.6
7	spent fuel handing + final disposal	26.9	21.2	69.4	51.8
8	mine rehabilitation	14.7	14.1	45.6	43.9
	sum downstream processes 5-8	199.6	171.2	338.4	289.9
	sum future processes 1-8	245	212	441	381

Table 6

Lifetime energy investments of the complete nuclear process chain from cradle to grave. 'Low' means: uranium from soft ores at a grade of 0.1% U_3O_8, and 'high' means uranium from hard ores at a grade of 0.05% U_3O_8.

process	advanced reactor		EPR design	
	*E*e + *E*th PJ	*E*th PJ	*E*e + *E*th PJ	*E*th PJ
sum contemporary processes - low	208	175	447	386
mean	282	249	676	615
high	355	323	904	843
sum future processes	245	212	441	381
total nuclear process chain from cradle to grave low	453	387	888	767
mean	527	461	1117	996
high	600	535	1345	1224

Introduction

Generation of electricity by nuclear power requires a complex system of industrial processes.A nuclear power plant is not a stand-alone system, it is just the most visible component, the pivot, of a sequence of industrial processes. The nuclear process chain has three main parts: front end, mid section and back end. The front end (also called upstream processes) comprises the industrial processes required to fabricate nuclear fuel (enriched uranium) from uranium ore as found in nature. The mid-section encompass the construction of the nuclear power plant and its operation, maintenance and refurbishments (OMR). The back end (downstream processes) includes the industrial processes needed to safely dispose of all radioactive wastes, generated by the reactor and other processes of the process chain: the nuclear legacy.
A metaphor of the complete nuclear sequence, in fact of any industrial production process, may be seen in a common daily household sequence:

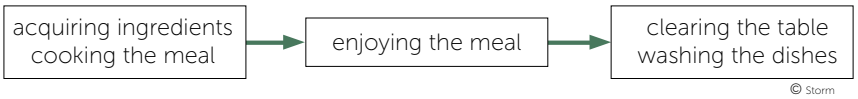

Figure 1
Metaphor of the life cycle process chain of any industrial production process, including the nuclear process chain

This study divides the industrial processes related to a given nuclear power plant (NPP) into two categories: *contemporary processes*, occurring in advance of or during operation of the NPP, and the *future processes*, that are to be performed after final closedown of the NPP. Metaphorically speaking: the future processes comprise 'clearing the table and washing the dishes'. The activities of the downstream processes are called 'future processes' because they have to occur in the future. The table is not cleared and not one dish has been washed: after more than 60 years of nuclear power all human-made radioactive materials are still piled up in the human environment in vulnerable temporary storage facilities.

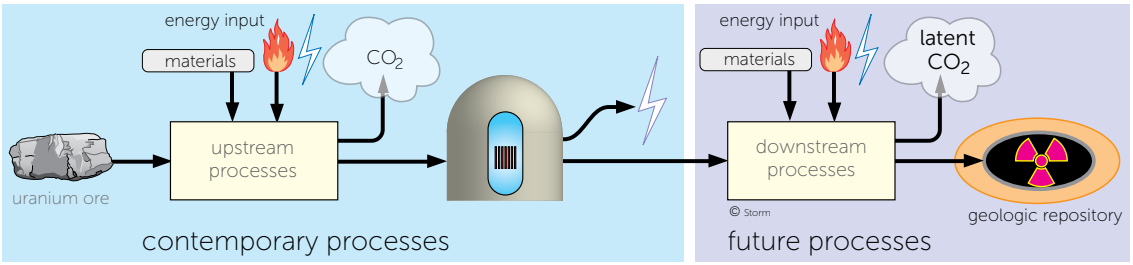

Figure 2
Simplified outline of the nuclear process chain, as it ought to be. The three main parts are the upstream processes or front end, from ore to nuclear fuel, the powerplant itself (construction, operation, maintenance & refurbishments during its operational lifetime) and the downstream processes or back end, comprising the safe and definitive sequestration of all radioactive wastes. Most activities of the downstream processes are still to be done. In 2019 not one geologic repository in the world was operational.

Each process of the nuclear chain consumes materials and energy and emits CO_2 and possibly also other greenhouse gases (GHGs). Fission of uranium in the nuclear reactor is the only process in the chain that does not emit CO_2. Emissions of other GHGs by the nuclear system are not mentioned by the nuclear industry, although a number of processes of the nuclear chain most likely do emit also other GHGs.

A nuclear power plant of 1 GWe irreversibly generates each year an amount of human-made radioactivity

equivalent to about 1000 exploded atomic bombs of about 15 kilotons (Hiroshima bomb). Each year the civil nuclear power plants of the world add more than 300000 atomic bomb equivalents to the world inventory, in 2018 amounting to roughly 12 million bomb equivalents: the nuclear legacy. These amounts of human-made radioactivity are present in spent fuel, in construction materials and in auxiliary materials. Radioactivity cannot be destroyed nor can be made harmless.
During the disasters of Chernobyl and Fukushima jointly about 0.01% of the world civil inventory of human-made radioactivity has been released into the biosphere. This corresponds with the amount of artificial radioactivity generated by one nuclear power plant of 1 GWe during one year at full power. The irreversible and harmful consequences of these disasters are noticeable on continental scales, affecting hundreds of millions of people, costing hundreds of billions of dollars, and will continue for centuriess into the future.
Adequate fulfilment of the downsteam (back-end) processes of nuclear power plants is a *conditio sine qua non* to avoid dispersion of the remaining 99.99% of the *nuclear legacy* into the biosphere and to keep vast areas on the Northern Hemisphere habitable. Fulfillment of the downstream processes may take a period of 100-150 years after closedown of the nuclear power plant, according to estimates by large nuclear institutes.

Assessment method

This study assesses by means of a physical/thermodynamic analysis the energy investments and CO_2 emissions of all processes needed to complete the processes of the nuclear chain from cradle to grave in the safest possible way. The method is discussed in detail in report **m06** *Energy analysis: the method*. The contemporary emisssions of nuclear power are assessed in report **m03** *Contemporary CO_2 emissions by nuclear power*, a summary is used in this report.
Different views on radioactive waste can be encountered in official publications: What is called 'nuclear waste'?

View of the IAEA on radioactive waste

Within the framework of its Joint Convention project the International Atomic Energy Agency (IAEA) published a series of reports *Radioactive Waste Management Data Base - Status and Trends*, [IAEA-*wmdb-st-1* 2001] Q656, [IAEA-*wmdb-st-2* 2002] Q657, [IAEA-*wmdb-st-3* 2003] Q658, [IAEA-*wmdb-st-4* 2005] Q659, discussing envisioned international agreements on waste management. In these reports the IAEA describes numerous regulations and waste classifications.
These WMDB reports do not mention contributions other than from the USA, Europe and Japan. It remains unclear wether the non-contributing countries would comply with the regulations proposed by the IAEA. The contents of the reports are dealing with formulation of possible regulations, with legal, administrative and managerial aspects and with recommendations 'what should be done'. The texts are not easily accessible and are full of new acronyms for notions and concepts that are already subject of discussions on waste management during decades. In the 60 years of its existence the IAEA apparently did not succeed in formulating unambiguous regulations for nuclear waste management.

Many, if not all definitions and recommendations given by the IAEA in the WMBD reports leave the door open for ad hoc interpretations and for adaption of regulations to economic needs. Each country and nuclear agency remains free to follow its own views. How stringent are these 'internationally agreed regulations and standards', and what safety improvements do they provide?
None of the regulations and recommendations are coupled to clear and unambiguously quantified standards, instead vague classifications of radioactivity levels are mentioned, such as: 'insignificant level' and 'acceptable level'. How are such levels defined? Who defines these levels? How are the levels measured? Who measures and how frequent? How independent are the inspections? How is the classification 'Below

Regulatory Concern' defined? Which unambiguous numerical criteria are to be applied?
In its document [IAEA-*wmdb-st-1* 2001] the IAEA uses the terms 'exclusion', 'exemption' and 'clearance'. The hardly understandable texts offer ample room for ambiguities and ad hoc interpretations. Clearing waste, classifying/managing it, or some combination of clearance and classification is likely to be a nationally based, cost-benefit decision. There are no internationally agreed definitions for clearance levels.
Dismantling wastes are not separately discussed, despite their huge volumes. Especially the amounts of waste resulting from the dismantling of reprocessing plants might be very large, probably millions of Mg, in addition to the heavy contamination of the debris by all kinds of radionuclides from spent fuel.
Noteably absent in the WMBD reports are standards based on quantified physical and chemical properties of the materials present in different waste categories; such standards are prerequisite for an unambiguous classification of radioactive wastes.

The IAEA reports seem to suggest that internationally agreed regulations are sufficient to warrant the safety of nuclear power. No recommendations are mentioned to monitor compliance with stringent regulations, such as independent international inspections and evaluations.

Radioactive waste disposal

According to [IAEA-*wmdb-st-1* 2001] there are two basic strategies for radioactive waste disposal:
- 'isolate and confine'
- 'dilute and disperse'.

The first strategy involves the emplacement of waste into a disposal facility that is intended to isolate the waste from humans and the environment and to prevent or limit releases of potentially harmful substances (toxic metals, radionuclides, organics) such that human health and the environment are protected.
The second strategy involves deliberately dispersing the waste into the environment in a manner intended to dilute harmful contaminants in the waste to levels that are considered 'acceptable' according to internationally agreed standards.

The three major options for disposal currently used or planned by IAEA Member States are:
- surface/near surface facilities
- rock cavities (at several tens of meters to a few hundreds meters depth)
- deep geologic repositories (typically at depths of more than a few hundred meters).

Surface/near surface disposal is and will most likely continue to be the most common disposal practice. No repositories for high-level waste and spent fuel are yet in operation in any Member State; this expensive option remains a major challenge in radioactive waste management.

Retrievability or 'Long-Term Storage' versus 'Disposal'
Originally the approach of deep geological disposal was developed to remove waste from the human environment to ensure that it remains isolated from the environment and inaccessible to humans for the very time scales corresponding to the slow decay of long-lived radionuclides. The term 'storage' implies retrieval at any time in the future is intended. The term 'disposal' implies retrieval is not intended; it does not mean that retrieval is not possible. Disposal with retrievability is receiving wider attention.
Retrievability of spent fuel is a useless option. Spent fuel cannot be regarded as a potential energy source because reuse of plutonium and reprocessed uranium in breeder reactors is infeasible, based on the Second Law of thermodynamics. Reuse of plutonium in light-water reactors has a negagative energy balance: reprocessing of spent fuel is an very energy-intensive process, requiring more energy than can be generated from the recovered plutonium (see also reports **m01** *Closed-cycle reactor systems* and **m15** *Plutonium recycling in light-water reactors by MOX fuel*.

Accumulation effects

The strategy of 'dilute and disperse' ignores the effect of accumulation of radionuclides in the environment, food and drinking water. The discharges of one LWR during one year may seem innocuous and acceptable, but what about the discharges of 400 reactors during 40 years? These operating discharges come on top of the discharges due to small and large accidents and the massive discharges of reprocessing plants.
On which scientific arguments and figures are 'acceptable according to internationally agreed standards' defined? If these 'standards' are based on the background level of radioactivity a sliding scale will result, because the background level is steadily rising as a consequence of the operating discharges and the releases from large nuclear accidents.

Reprocessing plants are discharging significant amounts of fission products and actinides in the gaseous effluents (+ aerosols) and liquid effluents, year after year. Locally hazardous concentrations of radionuclides may be built up. These discharges come on top of the discharges by nuclear power plants.

In publications of the nuclear industry no mention is found of the problems evoked by the growing amounts of radioactive waste, awaiting definitive isolation from the human environment. At this moment some 12 million atomic bomb equivalents of radioactivity from civil nuclear power plus several millions bomb equivalents from military nuclear activities are piled up globally in temporary facilities, and each year more than 300 000 bomb equivalents are added to this pile.
Most of these bomb equivalents are contained in spent fuel and other contained wastes, stored at an increasing number of temporary storage sites. Due to unavoidable degrading processes (ageing) following from the Second Law, worsened by the nuclear radiation, the containment of the radioactive materials deteriorates with time. Predictable consequences of accumulation of radioactive waste combined with the ageing processes are, among other:

- increasing rate of dispersion of radioactive materials
- accumulation of dispersed radioactive materials at the storage sites and in the environment, at an increasing rate
- increasing loss of adequate knowledge of the contents of the waste packages
- increasing risks of large scale dispersion caused by natural disasters, terroristic actions and ignorance
- rising costs to maintain each nuclear bomb equivalent of radioactivity in the wastes in a 'safe' condition, and consequently application of cheaper (but less effective) 'solutions' for storage
- increasing number of repositories required, rising costs to isolate the backlog of radioactive waste in the least risky way
- increasing incentive to adapt the regulations to political and/or financial conditions, particularly relaxation of standards, for example of allowed radioactive concentrations in drinking water and food, and of clearance standards of radioactive materials for unrestricted reuse.

Viewpoint of this study on radioactive waste

With regard to radioactive naterials and waste management this study starts from the viewpoint that all materials generated in the nuclear process chain containing radionuclides are to be considered as radioactive waste and should be disposed of in geologic repositories. This view is based on a number of considerations, accentuated by the uncertainties, vaguenesses and ambiguities stated in the official reports on nuclear waste from the International Atomic Energy Agency (IAEA):

- Practically it is impossible to know exactly which radionuclides are present in a certain amount of materials and in each container of waste, for example long-lived alpha emitters and short-lived beta emitters. So it is impossible to determine reliably the class of risk of each amount of radioactive waste.
- Inspections are not always possible and are not always reliable.

- Human behaviour and accidents have unpredictable consequences.
- The radiological models used to classify radioactive waste have serious limitations, especially regarding long-term effects of chronic contamination by a number of radionuclides simultaneously, via inhalation and ingestion (air, dust, drinking water, food).
- Regulations for waste management are flexible under economic and political presuure.
- A low radiation level measured (what radiation is measured?) outside of an amount of waste is no guarantee that the contents of the container are harmless when they enter the body,
- Storage of radioactive materials at surface or shallow burial facilities are not safe in the long run. Materials deteriorate with time as a consequence of unavoidab;e Second Law phenomena. The ageing processes are ehanced in the presence of nuclear radiation. Containers will go leaking, releasing radionuclides into the environment, often undetected. The risks are growing with time.
- As long as radioactive materials are stored in an accessible way within the human environment they are vulnerable to natural disasters, terrorism, intentional and unintentional actions and disruptions, releasing unmeasurable amounts of hazardous radionuclides into the environment

See also report m37 *Message to the future*.

Parameters of the advanced reference reactor and the EPR design

The reference reactor in this study is based on a pressurized-water reactor (PWR) corresponding with the most advanced currently operating power reactors. The emissions of the 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 is operational, 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 7.

Table 7

Parameters of the reference advanced reactor and the EPR design. Sources EPR data: [UK-EPR-*Dsum* 2007] Q773, [UK-EPR 2007] Q774, [Areva 2012] Q777.

More details in report **m19** *Parameters of the reference reactors*.

quantity	advanced reactor	EPR design	unit
net power, electric (at grid connection)	1.00	1.62	GW_e
power, thermal	2.94	4.50	GW_{th}
effective operational lifetime, full-power years	25	55	FPY
lifetime electric energy production	$219*10^9$	$781*10^9$	kWh
lifetime enriched uranium in reactor	583.4	1506	Mg U_{enrich}
lifetime natural uranium consumption	5748	17880	Mg U_{nat}

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.

In 2017 the average egfective 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. The reference advanced reactor has an assumed effective operational lifetime of 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 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.

For estimation of the CO_2 emissions of nuclear power, the industrial processes comprising the nuclear process chain are divided into two categories: *contemporary processes*, occurring in advance of and during the operational lifetime of the nuclear power plant, and the *future processes*, occurring after final shutdown of the power plant. The contemporary processes encompass the upstream processes, needed to recover uranium from ore and to fabricate fuel elements for the reactor, in addition to construction of the nuclear power plant and operation, maintenance + refurbishments during the operational lifetime of the reactor. The future processes encompass the activities needed to manage all radioactive waste generated during operation of the nuclear power plant in the safest possible way and to isolate it from the biosphere.

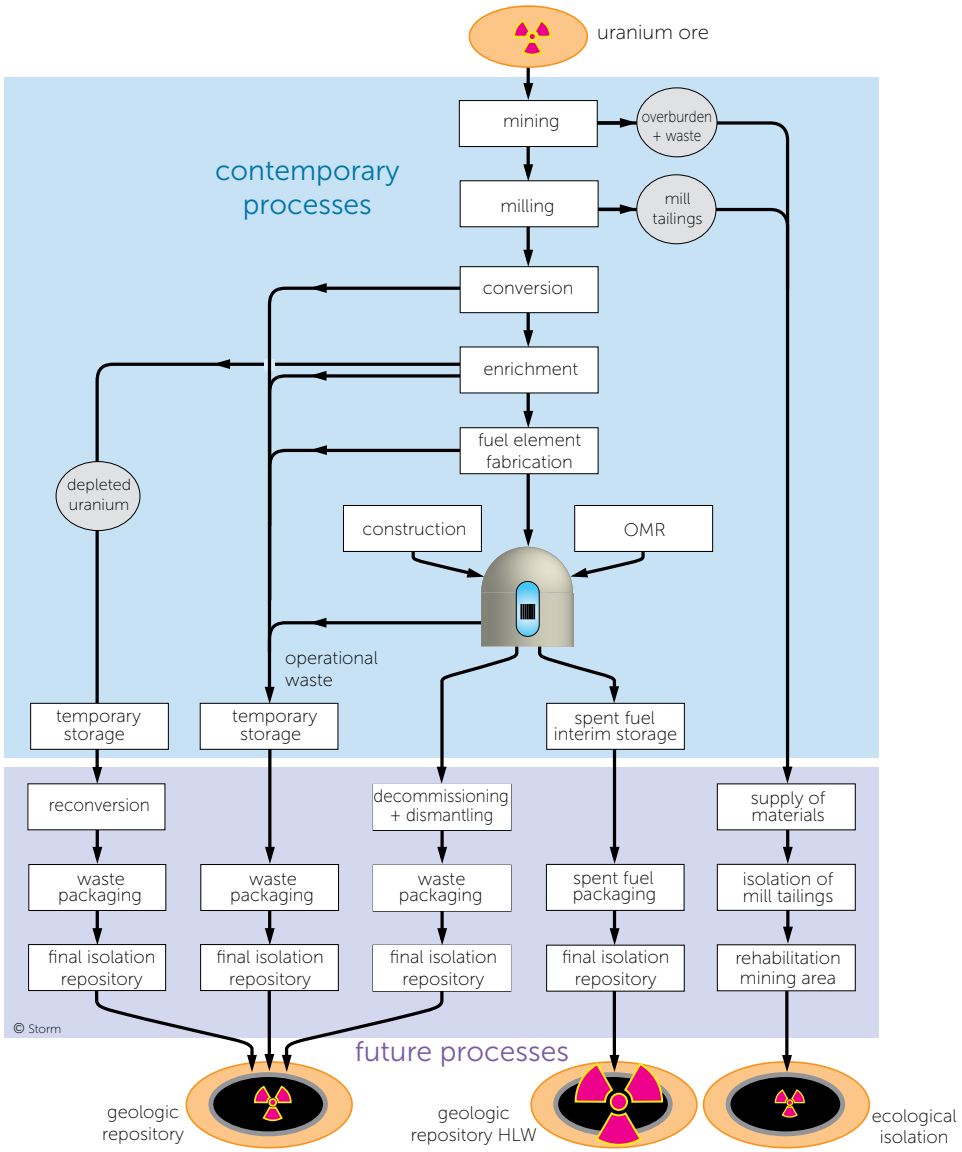

Figure 3

Complete nuclear process chain, divided into two subchains: the contemporary processes (front end or upstream processes) and the future processes (back end or downstream processes of the nuclear process chain). OMR = operation, maintenance and refurbishments. HLW = high-level waste.

Each process of the nuclear chain generates radioactive waste and non-radioactive waste. In this study the scope is limited to radioactive waste. The radioactive waste of the upstream processes, from ore to fuel, contain only naturally occurring radio-isotopes: uranium and thorium plus their decay products. During operation of the reactor the radioactivity of the involved materials rises a billionfold, caused by the generation of dozens of human-made radionuclides, in addition to uranium isotopes. This radioactivity is contained in spent fuel and in materials of the reactor plus associated installations.

Purpose of the downstream processes is to avoid dispersion of these hazardous materials into the biosphere. This study starts from the viewpoint that all radioactive materials should be isolated from the biosphere. To that end the wastes are packed in appropiate containers that are disposed of in geologic repositories. In practice not all radioactive waste of the nuclear chain can be packed in containers, that are, mining waste and radioactive effluents (authorised and unintended discharges) from the nuclear power plant during its operational lifetime.

Containers for radioactive waste

Except for the uranium mill tailings, all radioactive wastes of the nuclear energy system are to be packed in appropiate containers and isolated from the biosphere in geologic repositories.
This study assumes the use of five types of standard containers, V1 through V5, depending on the type of waste. These container concepts are among the frequently quoted types in the nuclear literature, e.g. [IAEA-349 1993] Q43 and [IAEA-355 1993] Q62.
Container V1 is not much more than a common steel drum, not suitable for permamanent disposal of radioactive waste. For that reason the V1 container is not included in the assessment of this study. In the past huge amounts of radioactive waste have been packed in this kind of drums and dumped into the sea or into shallow burial pits.
The V3 container corresponds with the German Type II container; the V4 container is not suitable for waste containing apha emitters. The four types of waste containers for permanent disposal, V2 - V5, are shown in Figure 4. The dimensions, materials, masses and specific applications of these containers are addressed in the following tables.

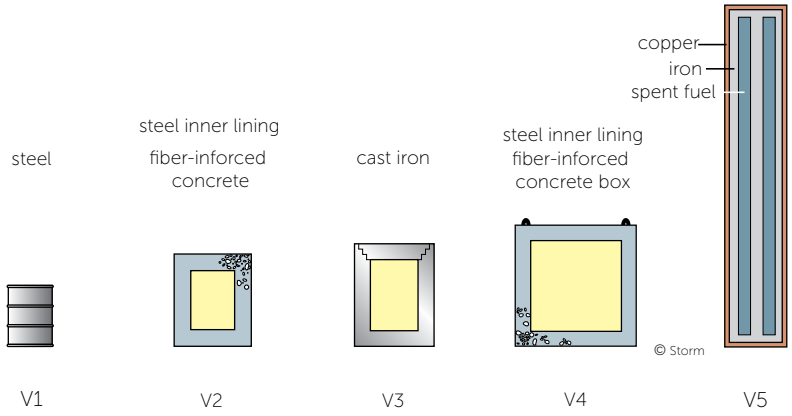

Figure 4
Containers for all categories of radioactive waste, used as reference in this study. Container V1, not much more than a common oil barrel, is not suitable for permamanent disposal and is not included in the assessment of this study. Container V5 is specificly designed for permanent storage of spent fuel elements.

Table 8
Dimensions and masses of the containers for packaging of radioactive waste.

type	outer diameter m	height m	wall thick m	external volume m^3	capacity m^3	concr. Mg	steel/ iron Mg	copper Mg	mass empty Mg
V2	1.02	1.22	0.20	1.00	0.25	1.80	0.04	-	1.84
V3	1.05	1.36	0.21	1.18	0.29	–	6.46	-	6.46
V4	1.60 x 1.60	1.60	0.20	4.10	1.73	5.68	0.137	-	5.82
V5	1.05	4.84	0.05	4.19	-	-	16.4	7.5	23.9

The average energy requirements J_v for construction, loading, handling and transport of the waste containers are assumed to be similar to the energy investments of 'new construction'. This quantity is found by means of an input/output analysis and is used to calculate the energy investments of construction and operation, maintenance + refurbishments (OMR) of the nuclear power plant (report **m39** *Construction and OMR of*

nuclear power plants) and of decommissioning + dismantling. The I/O method is explained in report m06 *Energy analysis, the method*.

$J_v = J(e) + J(th) = 80$ GJ/Mg $J(th)/J(e) = 4.8$

$J(th) = 66.2$ GJ/Mg

Assumed an average specific CO_2 emission of $\gamma = 75$ g/MJ_{th}, the specific CO_2 emission, excluding CO_2 from chemical reactions (e.g. steel and concrete production), would be:

$\gamma_V = 75 \bullet J(th) = 5.0$ Mg CO_2/Mg

Table 9

Construction data of the waste containers used as reference in this study for the packaging of radioactive wastes.

type	waste type	displaced volume m3	capacity m3	mass empty Mg	mass loaded Mg	Je + Jth constr. GJ/V#	Je GJ/V#	Jth GJ/V#	mCO2 Mg/V#
V2	LLW + ILWα	1.00	0.25	1.84	2.4 *	147	25	122	9.2
V3	HLW + α	1.18	0.29	6.46	8.0 *	517	89	428	32.3
V4	LLW + ILW	4.10	1.73	5.82	14.7 *	466	80	386	29,1
V5	spent fuel	4.19	-	23.90	26.8	4000	690	3310	248

* Assumed the content of V2 containers has an average density of $d = 2.4$ Mg/m3 (concrete) and that the V3 and V4 containers are half filled with steel scrap and the remaining volume is filled with concrete. The density of cast iron is $d = 7.3$ Mg/m3 and that of steel and stainless steel $d = 7.9$ Mg/m3.

V5 canister

Canister V5 is in accordance with the Swedish SKB-3 concept [SKB-*TR-10-14* 2010] Q675. Wall thickness of the canaister is 5.0 cm ultrapure copper, steel (iron) insert, containing 4 nuclear fuel elements, from a PWR: $m = 2.000$ Mg HM + 0.900 Mg zircalloy + control rods

Based on cost estimates by [Konings&Dodd 1999] Q57 the specific energy input for construction, handling and transport can be estimated by means of an input/output analysis - $c = 0.13$ M$(2000)/Mg, energy intensity factor $e = 12.34$ MJ/$(2000) - at:

$J(V5) = J_e + J_{th} = c*e = 1.60$ TJ/Mg HM

Assumed $J_{th}/J_e = 4.8$

A loaded V5 canister contains about 2 Mg of heavy metal (HM) - spent fuel plus control rods, excluding cladding - so the energy input for production per V5 canister is would be:

$J(V5) = 2*1.60 = 3.2$ TJ/V5

Cost estimates of new technologies are usually underestimated and spent fuel packaging and handling for definitive disposal is a new technology.

Another estimate is possible starting from the assumption that the energy intensity of the V5 production equals that of 'new construction', calculated by another version of I/O analysis, see previous section:

$J(V5) = J_e + J_{th} = 80$ GJ/Mg $J_{th}/J_e = 4.8$

Packaging the highly radioactive fuel elements and sealing off the canisters has to be done under remote control. The canisters must be fabricated from very pure materials, only exceedingly pure electrolytic copper can be uesed for the outer wall. Fabrication and handling are to be done under strict quality control with high quality specifications [SKB-*TR-10-14* 2010] Q675. In view of these considerations the specific energy requirements for construction and handling of a V5 canister may be estimated at:

$J(V5) = J_e + J_{th} = 4.0$ TJ/V5 $J_{th}/J_e = 4.8$

This value, slightly higher than found according to the first estimate, is used throughout this study. Probably the value of 4.0 TJ/V5 is a low estimate. In practice the cost and energy input might become significantly higher. In view of the electrolytic materials and remote control the energy input of production and handling of V5 canisters might show a high electric component, corresponding with a lower ratio of *J*(th)/*J*(e) than assumed in this study.

CO_2 emission from construction materials

To the energy consumption and the coupled CO_2 emission of construction of the waste containers, as listed in Table 2, should be added the energy consumption and CO_2 emission of the production of the used construction materials concrete, steel and electrolytic copper (embodied energy and CO_2 emission).

Table 10

Specific embodied energy and CO_2 emission of the construction materials of the waste containers. Sources for steel and concrete: [IAEA-TecDoc-753 1994] Q148, [IPCC 2006] Q215, [NRMCA 2012] Q216, for copper: [White 1998] Q299.

quantity	unit	steel/iron	concrete	electrotytic copper
specific thermal energy input	MJ/kg	29.54	1.83	1612
specific CO_2 emission	Mg CO_2/Mg	2.41	0.139 *	97.15

* Portland cement: 927 kgCO_2/Mg cement. Assumed the high quality concrete used for nuclear applications contains 15% cement, then the chemical specific emission of concrete would be 139 kgCO_2/Mg concrete.

Table 11

Embodied CO_2 emission of the construction materials concrete, steel/iron and copper of the waste containers.

type	mass concrete Mg	mass steel Mg	mass copper Mg	mass total Mg	*m*CO2 concrete Mg	*m*CO2 steel Mg	*m*CO2 copper Mg	*m*CO2 materials Mg
V2	1.80	0.04	–	1.84	0.250	0.006	–	0.26
V3	–	6.46	–	6.46	-	15.6	–	15.6
V4	5.68	0.137	–	5.82	0.790	0.019	–	0.81
V5	–	16.40	7.50	23.90	–	39.52	728.6	768.1

Table 12

Specific energy investment and CO_2 emission of the waste containers.

type	*J*e + *J*th construction GJ/V#	*J*e + *J*th materials GJ/V#	*J*e + *J*th total GJ/V#	*J*th total GJ/V#	*m*CO2 construction Mg/V#	*m*CO2 materials Mg/V#	*m*CO2 total Mg/V#
V2	147	4.47	152	127	9.2	0.26	9.46
V3	517	191	708	619	32.3	15.6	47.9
V4	466	14.4	480	400	29,1	0.81	29.9
V5	4000	12600	16600	3792	248	768	1016

Uranium mine rehabilitation

In the front end processes of the nuclear chain, from uranium ore to nuclear fuel, only naturally occurring radioactivity is involved: uranium and its decay daughters. At the mine uranium is separated from its radioactive decay products and other elements present in the ore, that end up in the waste streams of the mine (mill tailings), together with a part of the uranium, because separation processes never go to completion. All these radionuclides are in chemically mobile and reactive form. This waste stream of mobilised natural radioactivity is discharged into the biosphere. The radionuclides enter the groundwater and are also dispersed as dust and fine particulate matter, blown by the wind over vast distances. Apart from their radiological toxity uranium and its decay products are also chemically toxic. Often uranium ores contain also thorium and its radioactive decay products, and tese radionucldes are also released into the environment.
Mine rehabilitation can only be done after depletion of the mine. This moment is not directly coupled to the operation of a given nuclear power plant. This study assesses the rehabilitation of an average uranium mine and attibutes a proportional part of the material and energy investments to the reference nuclear power station. For details of the rehabilitation activities see report **m41** *Uranium mine rehabilitation*.

Total specific energy input of uranium mine rehabilitation

The total specific energy input, directly + indirectly, of mine rehabilitation according to the concept of this study can be calculated based on following figures:

excavation + haulage	J_{th} = 26	MJ/Mg rock or tailings
	γ = 2.0	kg CO_2/Mg rock or tailings
auxiliary materials	J_{th} = 1.747	GJ/Mg tailings
	J_e = 75	MJ/Mg tailings
	γ = 131	kg CO_2/Mg tailings

The total energy input of rehabilitation strongly depends on the characteristics of the mine, especially the ore grade, overburden ratio, and location (transport distances).
The assessment of this study is based on an average uranium mine, assuming an overburden ratio of S = 3 and a haulage distance of d = 5 km. For many uranium mines haulage distances are in practice considerably more than 5 km and overburden ratios are often much higher than 3, overburden ratios of 50 are reported.
Transport distance of the supply of auxiliary materials is assumed to be 10000 km, by truck, train and/or ship, likely including several transfers from one to another.
Above estimate of input of energy and materials does not include:

- treatment of waste water, containing a number of toxic chemicals
- rendering organic chemicals (solvents, complexing agents) non-noxious
- restoring the top soil and indigeneous vegetation.

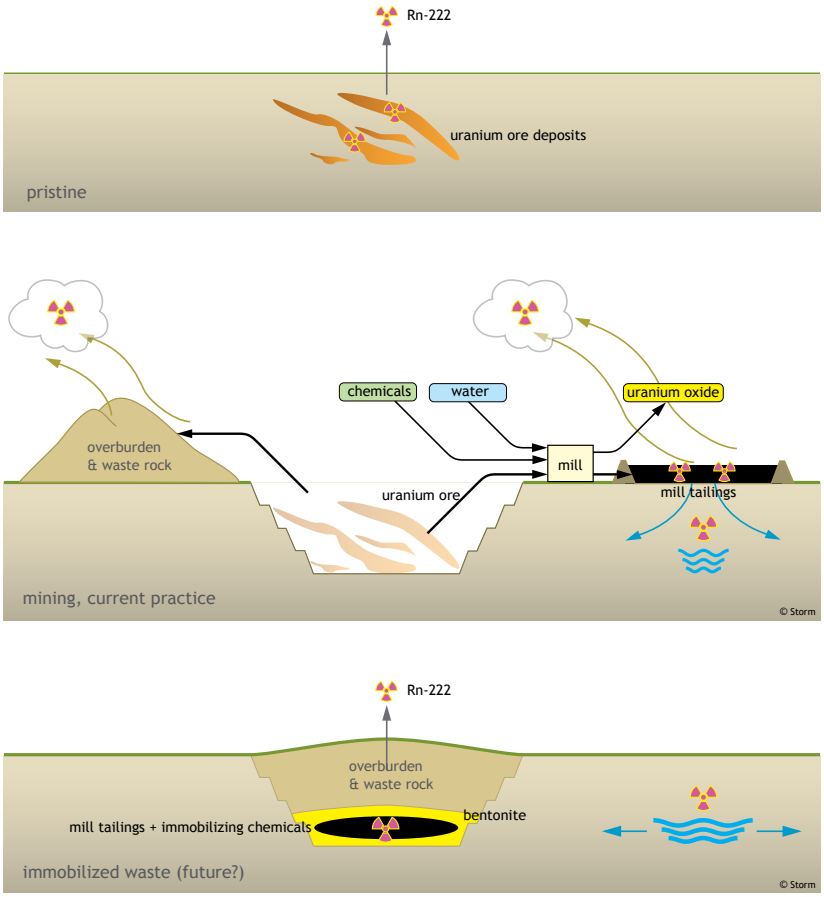

Figure 5

Schematic representation of uranium mining, the first step of the nuclear process chain. The area directly disturbed by the mining operations of a large uranium mine may come to some 100 km². The indirectly disturbed area, by wind-blown dust and contaminated groundwater, may run into hundreds of thousands of square kilometers. When the ore is exhausted, the dangerous mill tailings should be immobilised and the mine and its surrounding area should be restored to the original situation, a process called mine rehabilitation or reclamation. The ground water table remains contaminated permanently.

Mine rehabilitation for the advanced reference reactor and the EPR

From the uranium balance of the reference reactors, see report **m19** *Reference reactor and EPR*, follows the figures listed in Table 13.

Table 13

Masses of materials involved in uranium mine rehabilitation for the advanced reacror and EPR design

quantity	unit	advanced reactor	EPR
lifetime natural uranium consumptiom	Tg	5.748	17.880
processed ore, G = 0.1% U_3O_8, Y = 0.90	Tg	7.514	23.37
mill tailings	Tg	7.6	23.7
waste rock (overburden ratio = 3)	Tg	30.4	94.8
required bentonite (60 kg/Mg tailings)	Tg	0.456	1.42

Assumed ore grade G = 0.1% U_3O_8 (0.085% U) and the extraction yield Y = 0.90.
Mass of the mill tailings includes the added chemicals for processing the ore and the chemicals needed to neutralize the tailings and rendering toxic heavy metals from the ore immobile.
With an overburden ratio of 3 the mass of waste rock + tailings to be hauled back into the mining pit is four times the mass of rock mined.
Specific mass of bentonite needed to isolate the tailings is $m_{bentonite}$ = 60 kg/Mg tailings.

Table 14A

Energy investments and CO_2 emission of uranium mine rehabilitation for the advanced reference reactor

process advanced reference reactor	mass Tg	*E*e + *E*th input TJ	*E*th input TJ	*m*CO_2 Gg	CO2 g/kWh
excavation + haulage waste rock + taiings	30.4	790	790	59	0.27
supply materials for isolation tailings	0.456	13 870	13 300	998	4.56
sum	30.9	14 660	14 090	1057	4.83

The specific CO_2 emission of mine rehabilitation for the advanced reference reactor, with a lifetime electricity production of E_{life} = 219*10^9 kWh, becomes:

γ = 1057*10^9/219*10^9 = 4.83 gCO_2/kWh

Table 14B

Energy investments and CO_2 emission of uranium mine rehabilitation for the EPR design

process EPR design	mass Tg	*E*e + *E*th input TJ	*E*th input TJ	*m*CO_2 Gg	CO2 g/kWh
excavation + haulage waste rock + taiings	94.8	2465	2465	190	0.24
supply materials for isolation tailings	1.42	43181	41404	3105	3.98
sum	96.2	45 646	43 869	3295	4.22

The specific CO_2 emission of mine rehabilitation for the EPR design, with a hypothetical lifetime electricity production of E_{life} = 781*10^9 kWh, becomes:

γ = 3295*10^9/781*10^9 = 4.22 gCO_2/kWh

Waste packaging of upstream processes

Refining + conversion

The uranium compound delivered by the uranium mine is refined, followed by conversion of the purified uranium into uranium hexafluoride UF_6, needed for the following process.

Enrichment

Enrichment by ultracentrifuge (UC) has a lower direct energy consumption than by diffusion, but costs of operation and maintenance are higher, because of the relative short technical life of the centrifuges. The UC process produces more waste than the diffusion process [INFCE-2 1980] Q142, [Crossley 1980] Q143, [Becker et al. 1982] Q60. The net difference in specific energy consumption, including construction, operation and maintenance, with the gas diffusion process is not large. According to [Crossley 1980] Q143 both processes cost roughly the same per SWU. The US Department of Energy expected that UC would prove more competitive in the future.

Enrichment for the advanced reference reactor and the EPR is assumed to be done exclusively by UC.

By the enrichment process uranium hexafluoride is separated into two fractions, one enriched in the fissile isotope uranium-235 and another fraction with a lower content of U-235 (depleted UF_6).

Lifetime separative work for the advanced reference reactor S_{life} = 3.352 million separative work units (MSWU), see report **m19** *Reference reactor and EPR*. At an operational lifetime of 25 FPY this corresponds with 0.134 MSWU/FPY. Waste generation of enrichment by ultracentrifuge (UC) 230 m³/MSWU. Sources: [Kistemaker 1975] Q182, [DOE/EIA1997] Q64, ERDA-76-1] Q109, Rotty et al. 1975] Q95. The specific volume of the enrichment waste generation amounts to V = 31 m³/FPY.

Lifetime separative work for the EPR design is S_{life} = 11.009 million SWU. At an operational lifetime of 55 FPY this corresponds with 0.2002 MSWU/FPY and a waste generation of V = 46 m³/FPY.

Reconversion + fuel fabrication

In this step of the nuclear chain the enriched UF_6 is converted into uranium oxide UO_2; fuel fabrication comprises packing UO_2 pellets into zircalloy tubes; zircalloy is an alloy of very pure zirconium with a few percent tin or nickel added. The production of zircalloy is included in this assessment.

Reactor operation, maintenance and refurbishments (OMR)

During its operation a nuclear power station generates radioactive waste, from purification activities of air and water cleaning of equipment, replacement of components, etcetera, see report **m39** *Construction and OMR of nuclear power plants*.

Construction

Construction of the nuclear power plant does not generate radioactive waste, and is left outside the scope of this assessment..

Mining waste

During mining and milling of uranium ore millions of tons of radioactive waste are generated, Although its activity is relatively low, the waste contains numerous hazardous radionuclides (uranium and thorium plus their decay products), toxic non-radioactive elements and toxic chemicals used in the extraction processes. Isolation of the mining waste is discussed in the previous section.

Sum upstream processes, except uranium recovery

This study assumes that the radioactive wastes generated by the upstream processes, classified as LLW + ILW + alpha emitters, are packaged in V2 containers, that are to disposed of in a geologic repository.
Table 7 summarises for the advanced reference reactor and the EPR design the quantities of radioactive waste that are produced during normal operation of the upstream processes, also called the contemporary processes, including decommissioning and dismantling of the facilities of each process, except the nuclear part of the nuclear power station. Sources: [IAEA-293 1988] Q36, [Orita 1995] Q23-14, [IAEA-377 1995] Q44.

V2 waste containers

Specific energy investment of the production of the V2 waste containers, including embodied energy in concrete and steel:

$E_e + E_{th} = 152$ GJ/V2

$E_{th} = 127$ GJ/V2

Total CO_2 emission, including CO_2 from the chemical reactions of the production of concrete and steel:

$m(CO_2) = 9.46$ Mg/V2

Displaced volume, needed in repository:

$V = 1$ m³/V2

The numerical value of the displaced volume in a repository for definitive disposal of the wastes equals the number of V2 containers.

Table 15A

Waste containers, all type V2, needed to condition radioactive wastes (classified as LLW + ILW + alpha-emitters) from the contemporary processes for the advanced reference reactor, excluding uranium mining +milling. Operational lifetime of the advanced reference reactor is 25 full-power years (FPY). OMR = operation, maimtenance, refurbishments.

process advanced reference reactor	waste generation m³/FPY	lifetime waste volume m³	number of V2 containers	displaced volume m³
refining + conversion	54	1350	5400	5400
enrichment	31	775	3100	3100
reconversion + fuel fabrication	75	1875	7500	7500
reactor OMR	1000	25000	100 000	100 000
sum	1160	29 000	116 000	116 000

Table 15B

Waste containers, all type V2, needed to condition radioactive wastes (classified as LLW + ILW + alpha-emitters) from the contemporary processes for the EPR design, excluding uranium mining +milling. Hypothetical operational lifetime of the EPR design is 55 full-power years (FPY). OMR = operation, maimtenance, refurbishments.

process EPR design	waste generation m³/FPY	lifetime waste volume m³	number of V2 containers	displaced volume m³
refining + conversion	54	2970	11 880	11 880
enrichment	46	2530	10 120	10 120
reconversion + fuel fabrication	75	4125	16 500	16 500
reactor OMR	1000	55 000	220 000	220 000
sum	1175	64625	258 500	258 500

Table 16A

Energy investment and CO_2 emission of the containers V2 for packaging the lifetime contemporary process wastes of the advanced reference reactor.

process advanced reference reactor	number of V2 containers	$E_e + E_{th}$ input TJ	E_{th} input TJ	mCO_2 Gg	specific emission gCO_2/kWh
refining + conversion	5400	821	686	51	0.23
enrichment	3040	462	386	29	0.13
reconvonversion + fuel fabrication	7500	1140	953	71	0.32
reactor OMR	100 000	15200	12 700	946	4.32
sum	116 000	17623	14 725	1097	5.01

Specific CO_2 emission:

$\gamma = 1097*10^9/219*10^9 = 5.01\ gCO_2/kWh$

Table 16B

Energy investment and CO_2 emission of the containers V2 for packaging the lifetime contemporary process wastes of the EPR design.

process EPR design	number of V2 containers	$E_e + E_{th}$ input TJ	E_{th} input TJ	mCO_2 Gg	specific emission gCO_2/kWh
refining + conversion	11 880	1806	1509	112	0.14
enrichment	10 120	1538	1285	96	0.12
reconvonversion + fuel fabrication	16 500	2508	2096	156	0.20
reactor OMR	220 000	33440	27940	2081	2.66
sum	258 500	39 292	32 830	2445	3.13

Specific CO_2 emission:

$\gamma = 2445*10^9/781*10^9 = 3.13\ gCO_2/kWh$

Reconversion of depleted uranium plus waste packaging

The enrichment tails, consisting of depleted uranium, still contains some 0.2% of U-235, the rest being U-238. Depleted uranium is stored as uranium hexafluoride UF_6 in metal containers above ground, with most being outdoors. If these containers lose their integrity they pose a health risk because contact of UF_6 with water results in the release of toxic fluorine-bearing compounds. Apart from the fluorine compounds, uranium itself is a highly toxic element.
Over long times the decay progeny increases to sigificant levels. The depleted uranium can produce a continuous source of radon if reasonable disposal methods are not employed. In the long run, the main concerns are ^{226}Ra and ^{210}Pb (from the decay of ^{238}U) and ^{231}Pa, a daughter of ^{235}U (NRC 1996 [Q16]).
A part of the depleted UF_6 is converted into the uranium metal, for use as radiation shielding, ballast in airplanes and in anti-armor munition. By using the depleted uranium in munition, the element effectively is released into the environment and becomes unretrievable.

In the current practice a small portion of depleted UF_6 is converted into uranium metal for military applications. Another small portion of depleted UF_6 is converted into UO_2 and mixed with plutonium or highly enriched uranium (HEU) from military inventories to fabricate nuclear fuel for power reactors. These two applications of depleted UF_6 are not very significant on global scale and will become less in the future. Large scale utilisation of depleted uranium as nuclear fuel by mixing with plutonium, as envisioned in the breeder concept turned out out to be based on unfeasible concepts, apart from the fact that the energy balance of such a system would be negative (see for example report **m01** *Uranium-plutonium breeder systems*. In view of this observation depleted uranium has to be classified as radioactive waste, and has to be isolated from the human environment in the best possible way.

Generally depleted uranium is stored as UF_6 in special vessels, often at facilities in the open air. UF_6 is a volatile compound and chemically very reactive. Evidently this way of storage cannot be a permanent one, in view of deteriorating and leaking vessels and increasing chances for accidents or terroristic actions. For that reasons this study assumes that the depleted uranium hexafluoride originating from the enrichment process is reconverted into uranium oxide U_3O_8 , packed in durable containers and permanently disposed of in a geologic repository.
It should be noted that the processes of reconversion of depleted uranium and subsequently safe disposal of the depleted uranium oxide are lacking in previous studies. The ISA study [Lenzen et al. 2006] Q325 has adopted the approach of this study.

Reconversion process

Conversion assumed by reaction with limestone $CaCO_3$:

$UF_6 + 3\ CaCO_3 \rightarrow UO_3 + 3\ CaF_2 + 3\ CO_2$

$3\ UO_3 \rightarrow U_3O_8 + 1/2\ O_2$

sum reaction:

$UF_6 + 3\ CaCO_3 \rightarrow 1/3\ U_3O_8 + 1/6\ O_2 + 3\ CaF_2 + 3\ CO_2$

Stoichiometric mass ratios:

$m(UF_6) : m(CaCO_3) = M(UF_6) : 3*M(CaCO_3) = 352 : 300 = 1.173$

$m(CaF_2) : m(UF_6) = 3*M(CaF_2) : M(UF_6) = 234 : 352 = 0.6648$

$m(U) : m(U_3O_8) = M(U) : 1/3*M(U_3O_8) = 238 : 842/3 = 238 : 281$

$m(U) : m(CO_2) = M(U) : 3*M(CO_2) = 238 : 132$

In practice excess limestone is needed for complete chemical conversion, assume:

$m(UF_6) : m(CaCO_3) = 1 : 2$

densities $d(CaF_2) = 3.18$ Mg/m3
$d(CaCO_3) = 2.7$ Mg/m3
$d(U_3O_8) = 11$ Mg/m3

Advanced reference reactor

Lifetime mass of depleted uranium from the advanced reference reactor:

$m = 5041$ Mg U

depleted UF_6 $m = 352/238*5041 = 7456$ Mg UF_6

lime consumption $m = 2*7456 = 14912$ Mg $CaCO_3$

excess limestone $m = (2 - 1.173)*14912 = 0.827*14912 = 12332$ Mg $CaCO_3$
$V(CaCO_3) = 12332/2.7 = 4567$ m3

calcium fluoride formed $m(CaF_2) = 0.6648*7456 = 4957$ Mg
$V(CaF_2) = 4957/3.18 = 1559$ m3

uranium oxide formed:

$m = 281/238*5041 = 5952$ Mg U_3O_8

$V(U_3O_8) = 5952/11 = 541$ m3

mass of CO_2 formed in conversion reaction:

$m = 132/238*5041 = 2796$ Mg CO_2

Energy consumption

Assumed that the reconversion of UF_6 into U_3O_8 consumes as much energy as the conversion of yellow cake into UF_6, the first process of the nuclear process chain after uranium mining and milling, the specific energy consumption is according to [ERDA-76-1] Q109:

$J_e + J_{th} = 1.478$ TJ/Mg U $J_{th} / J_e = 27$

$E_{th} = 1.425$ TJ/Mg U

Total energy input of the reconversion process:

$E_e + E_{th} = 1.478*5041 = 7451$ TJ

thermal input:

$E_{th} = 1.425*5041 = 7183$ TJ

mass of CO_2 from thermal energy input:

$m = 75*7183 = 538725$ Mg CO_2

Total CO_2 production:

$m = 538725 + 2796 = 541521$ Mg $CO_2 = 542$ Gg CO_2

Specific CO_2 emission:

$\gamma = 542*10^9/219*10^9 = 2.47$ gCO_2/kWh

EPR design

Lifetime mass of depleted uranium from the advanced reference reactor:

$m = 15\,993$ Mg U

depleted UF_6 $m = 352/238*15993 = 23654$ Mg UF_6

lime consumption $m = 2*23654 = 47308$ Mg $CaCO_3$

excess limestone $m = (2 - 1.173)*47308 = 0.827*47308 = 39124$ Mg $CaCO_3$
$V(CaCO_3) = 39124/2.7 = 14490$ m3

calcium fluoride formed $m(CaF_2) = 0.6648*23654 = 15725$ Mg
$V(CaF_2) = 15725/3.18 = 4945$ m3

uranium oxide formed :

$m = 281/238*15993 = 18882$ Mg U_3O_8

V (U_3O_8) = 18882/11 = 1717 m3
mass of CO_2 formed in conversion reaction:
m = 132/238*15993 = 8870 Mg CO_2

Energy consumption
Total energy input of the reconversion process:
$E_e + E_{th}$ = 1.478*15993 = 23638 TJ
thermal input:
E_{th} = 1.425*15993 = 22790 TJ
mass of CO_2 from thermal energy input:
m = 75*22790 = 1 709 252 Mg CO_2
Total CO_2 production:
m = 1 709 252 + 8870 = 1 718 122 Mg CO_2 = 1718 Gg CO_2
Specific CO_2 emission:
γ = 1718*10^9/781*10^9 = 2.20 gCO_2/kWh

Temporary storage of depleted UF_6

No data are found in the open literature on the actual consumption of materials needed to construct and maintain the containers and facilities currently used for storage of uranium hexafluoride UF_6. For this reason the energy investments and CO_2 emission of the production and maintenance during many decades of the temporary storage containers and facilities of depleted UF_6 are not included in this assessment. This neglect might result in a significant underrating of the required energy investments and CO_2 emission.

Waste packaging

The chemical wastes of the reconversion process are contaminated with radionuclides from the depleted uranium and should be classified as radioactive waste. This study assumes that the contaninated waste is packed in V2 containers, as well as the depleted uranium oxide U_3O_8.

Advanced reference reactor

Waste containers V2 for packing depleted uranium oxide U_3O_8

number	N (V2) = 541/0.25 = 2164	
displaced volume	V = 2164*1.00 = 2164 m3	
construction materials	m = 2164*1.84 = 3982 Mg	(steel+concrete)

chemical waste contaminated with U compounds

excess $CaCO_3$	m =12332 Mg	
	V = 4567 m3	
formed CaF_2	m = 4957 Mg	
	V = 1559 m3	

waste containers V2 for packing contaminated chemical waste

number	N = (4567 + 1559)/0.25 = 24 504
displaced volume	V = 24 504 m3
mass steel+concrete	m = 24 504*1.84 = 45087 Mg

total waste containers V2

number	N = 2164 + 24504 = 26 668
displaced volume	V = 26 668 m3

mass (steel+concrete) m = 26 668*1.84 = 49 069 Mg = 49.1 Gg
mass of contents $m = m(U_3O_8) + m((CaCO_3)) + m(CaF_2)$ =
= 5952 + 12332 + 4957 = 23 241 Mg = 23.2 Gg
total mass loaded containers m = 49.1 + 23.2 = 72.3 Gg

EPR design

waste containers V2 for packing depleted uranium oxide U_3O_8
number N (V2) = 1717/0.25 = 6868
displaced volume V = 6868 m3
construction materials m = 6868*1.84 =12637 Mg = 12.6 Gg (steel+concrete)
chemical waste contaminated with U compounds
excess $CaCO_3$ m =39 124 Mg
V = 14 490 m3
formed CaF_2 m = 15725 Mg
V = 4945 m3
waste containers V2 for packing contaninated chemical waste
number N = (14490 + 4945)/0.25 = 77 740
displaced volume V = 77 740 m3
mass (steel+concrete) m = 77 740*1.84 = 24304 Mg = 143.0 Gg

total waste containers V2
number N = 6868 + 77 740 = 84 608
displaced volume V = 84 608 m3
mass (steel+concrete) m = 84608*1.84 = 1556779 Mg = 155.7 Gg
mass of contents $m = m(U_3O_8) + m((CaCO_3)) + m(CaF_2)$ =
= 18882 + 39124 + 15725 = 73731 Mg =73.7 Gg
total mass loaded containers m = 155.7 + 73.7 = 229.4 Gg

Energy investment and CO_2 emission of the waste containers

Advanced reference reactor

Energy investment of the production of the waste containers, including embodied energy in concrete and steel:
$E_e + E_{th}$ = 26668*152 GJ = 4053536 GJ = 4054 TJ
E_{th} = 26668*127 GJ = 3387 TJ
CO_2 emission, including CO_2 from the production of concrete and steel:
$m(CO_2)$ = 26668*9.46 Mg = 252.3 Gg
Specific CO_2 emission:
γ = 252.3*10^9/219*10^9 = 1.15 gCO_2/kWh

EPR design

Energy investment of the production of the waste containers, including embodied energy in concrete and steel:
$E_e + E_{th}$ = 84608*152 GJ = 12860 TJ
E_{th} = 84608*127 GJ = 10745 TJ
CO_2 emission, including CO_2 from the production of concrete and steel:
$m(CO_2)$ = 84608*9.46 Mg = 800.4 Gg
Specific CO_2 emission:
γ = 800.4 *10^9/781*10^9 = 1.02 gCO_2/kWh

Table 17A

Energy investments and CO_2 emission of depleted uranium reconversion and packaging in V2 waste containers for the advanced reference reactor

process advanced reference reactor	number of V2 containers	*E*e + *E*th input TJ	*E*th input TJ	mCO_2 Gg	CO2 g/kWh
reconversion depleted UF_6 –› U_3O_8	-	7451	7183	539	2.47
waste packaging in V2 containers	26 668	4054	3387	252	1.15
sum	26 668	11 505	10 570	791	3.62

Table 17B

Energy investments and CO_2 emission of depleted uranium reconversion and packaging in V2 waste containers for the EPR design

process EPR design	number of V2 containers	*E*e + *E*th input TJ	*E*th input TJ	mCO_2 Gg	CO2 g/kWh
reconversion depleted UF_6 –› U_3O_8	-	23 638	22 790	1718	2.20
waste packaging in V2 containers	84 608	12 860	10 745	800	1.02
sum	84 608	36 498	33 535	2518	3.22

Decommissioning and dismantling of a nuclear power plant

Complete sequence of decommissioning and dismantling

The thermodynamic analysis of this study is based on complete dismantling of each nuclear power plant. The site is to be restored to conditions needed for unrestricted reuse. The UK Nuclear Decommissioning Authority has published detailed plans for the decommissioning and dismantling of closed-down nuclear power plants and other nuclear facilities [NDA 2006] Q365, [NDA 2009] Q501, [NDA 2015] Q646. The outline of the NDA plans correspond with the general outline from earlier publications. Starting from these publications this study assumes that the full sequence of decommissioning and dismantling of a nuclear power plant would comprise the following phases:

Phase 1. Clean-out
After final shutdown, the spent fuel is removed from the reactor and transferred to an interim storage facility. The reactor and associated systems are prepared for the next stage, e.g. draining the liquid systems, disconnecting most operating systems and controlling the atmosphere within the containment building. This phase may take 2-5 years to complete.

Phase 2. Decontamination, or decommissioning
After removal of fuel elements and other removable components, the reactor vessel and the connected cooling system are to be chemically and mechanically cleansed, to remove as much radioactive contamination as possible. The contaminating material is sometimes called CRUD, Corrosion Residuals & Unidentified Deposits, it contains activated corrosion products from the reactor and cooling system, fission products and actinides from leaking fuel pins and from uranium oxide contamination on the outside of the fuel pins.
After decontamination, which may take 5-20 years to complete, the reactor, the biological shield and other radioactive equipment within the containment is sealed for a cooling period.
Non-radioactive ancillary buildings of the plant, e.g. offices and buildings not needed for the safe store period, are demolished and removed from the site during this phase.

Phase 3. Safe-guarded cooling period, or safe enclosure, or safestor
During the cooling period following the decontamination, the nuclear island of the power plant is put into care and maintenance and has to be kept under surveillance. Operations and maintenance ensure that the plant remains in a safe condition. This cooling period may range from several years to more than a century. In many studies a minimum cooling period of 30 years or longer is considered, in which most of the short-lived activation products decay. After this period, the radioactive inventory is dominated by long-lived nuclides. It should be noted that little is known on the radionuclide composition and radioactivity of the parts to be demolished, for no commercial nuclear power plant has ever been dismantled after an average operating lifetime, 23 full-power years.

Phase 4. Dismantling, or demolition
The radioactive parts of the power plant are to be dismantled, cut into pieces and packed in containers for final disposal. Many of these activities have to be carried out with remotely controlled equipment, due to high radiation levels and the presence of radioactive dust.
Phase 4 may take 5-10 years. NDA suggests that this phase may start some 80-100 years after final shutdown.

Phase 5. Waste packaging and site clearance
In the current decommissioning & dismantling projects the wastes are usually stored in temporary facilities at the site of the NPP. Actually phase 5 should coincide with phase 4: immediately after release the radioactive

rubble and scrap should be packaged in suitable containers, removed from the site and transported to a geologic repository and sealed off from the biosphere definitively. Temporary storage should be avoided as much as possible to prevent illicit trafficking and other unwanted happenings.
All contaminated materials are to be removed from the site, including foundations and underground structures. In a unknown number of cases also large volumes of contaminated soil have to be removed and disposed of in a geologic repository.

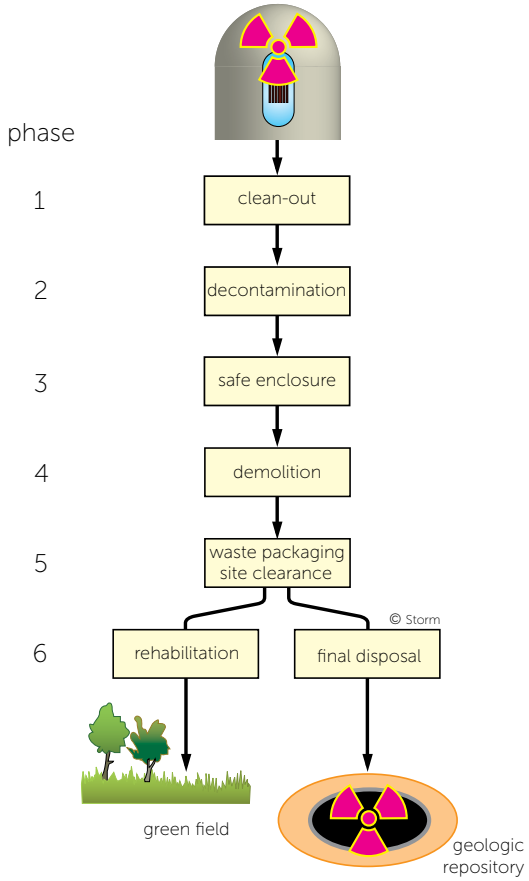

Figure 6
Sequence of activities of decommissioning and dismantling a nuclear power plant; the timescale may be as long as one century, according to [NDA 2015] Q646. The last three processes, waste packaging, final disposal of the dismantling wastes and site rehabilitation, are not included in the NDA scenarios.

Phase 6. Final disposal of wastes and rehabilitation of the site
The packaged wastes, spent fuel and decommissioning wastes, are transported to a geological repository and sealed off from the biosphere definitively.
Few, if any, of the known studies include the packaging and final disposal of the dismantlings waste. The analysis of this study includes the activities needed to isolate all radioactive waste from the biosphere indefinitely in a geological repository.
Rehabilitation, restoring the site to greenfield condition after removal of all radioactive materials and contaminated soil, comprises returning fresh top soil to the site and replanting the site with indigenous vegetation.
Groundwater may turn out to be contaminated by artificial radionuclides beyond tolerable levels. It is not clear what could be done to remediate this kind of contamination. It is conceivable that a site could not be released for unrestricted reuse.

Energy investment

As far as known not one decommissioning + dismantling sequence of a nuclear power station, as represented by Figure 4, has ever been completed. Reported cost figures are often unclear with regard to the phases of the sequence that were included and which were not. In most cases the sequence was performed no further than phase 3: safe enclosure. In some cases the reactor vessels of small and experimental NPPs were transported to temporary storage sites. Also it remains unclear wether the total cost are mentioned or only the part that one of the stakeholders had to pay.

Few studies mentioned the (expected) energy investment, for example: [Ecoinvent 2003] Q333 estimated it at 0.2 PJ, [WNA-eroi 2017] Q155 at 0.9 PJ, [Vattenfall 2005] Q152 at 4.4 PJ. In view of the long timescale of the full decommissioning + dismantling sequence, possibly about a century, and the unexplained wide range of reported estimates, this study concludes that the reported figures are underestimates of the actual energy investment.
For those reasons this study bases its estimate of the energy consumption of decommissioning + dismantling on the estimated cost,according to the same method as the construction cost.

Cost figures reported in the open literature vary widely: from a fraction of the construction cost to more than the construction cost, see for instance [NDA 2006] Q365, [NDA 2015] Q646, [SWI 2011c] Q649, [IPOL 2013] Q842. Even after a few full-power days, a nuclear reactor becomes so radioactive, that dismantling costs may rise to as much as about 60% of the construction costs, e.g. Niederaichbach [Schwald et al. 1995] Q25, [Liebholz 1995] Q32, [Komorowski & Meuresch 1995] Q33, [NEA 1996] Q61.

First-of-a-kind projects often enjoy subsidies by governments (sometimes hidden), certainly when strategic important technologies are involved.
For instance, the radioactive components of Elk River, Shippingport and Maine Yankee have been transported intact by barge to state-owned disposal facilities. The cost of packaging and final disposal of that dangerous material obviously is not included in the published dismantling costs.

A bookkeeping method may trouble the discussion about the real energy requirements of decommissioning and dismantling. If in 2019 an amount of $100 million is invested at an average 4% interest, for decommissioning after 100 years, one may argue: after 100 years the capital will be 100M$ • 1.04^{100} = 5.05 G$, in the year 2119. Apart from the unusual long term and the large uncertaintities regarding the value of a fund 100 years from now (who cares today about shares from 1919?), an amount of 5.05 billion in dollars of 2119, if available, surely will not have the same 'work potential' as 5.05 G$ in 2019. The financial reserves mentioned in [IPOL 2013] Q842 may have less significance than suggested.

Using energy units the method would not work. An activity requiring 80 PJ in 2019 will need atleast the same in 2119. Requirements of energy, materials and manpower do not inflate. These quantities will not change by bookkeeping concepts, subsidies or by deferring the moment of dismantling beyond a certain cooling period.
After a cooling period of a several decades the activity of the short-lived nuclides Fe-55, Co-60 has decayed to a low level, but what is 'low'? What level is 'negligible? After the first decades the radioactivity of the construction will decrease very slowly. Unknown is the activity of the radionuclides that are not measured. The risks of dispersion of radioactive materials into the biosphere, by inevitable physical/chemical deterioration processes and by human behaviour, increase with time. The entropy of the radioactive waste irrevocably will increase over time by spontaneous processes, according to the Second Law. Consequently the energy requirements of the safe isolation of the waste from the biosphere will increase over time.

The cost of decommissioning and dismantling the US West Valley reprocessing plant - that operated

between 1966 and 1972 and reprocessed 640 Mg of spent fuel - is estimated at about $16bn [UCS 2007] Q421, 100 times the construction cost, excluding final disposal of the radioactive waste and contaminated soil. If all goes well the sequence may be finished by about 2050. These figures are not reassuring when decommissioning and dismantling of other, larger reprocessing plants, e.g. Sellafield (UK) and The Hague (France), come into the picture. [NDA 2015] Q646 estimated the cost of decommissioning Sellafield in 2014 at £ 80bn, and the estimates are still rising.

Advanced reference reactor

Based on the available evidence this study assumes a cost of decommissioning + dismantling of the advanced reference reactor equal to the average construction cost:

c = 6.5 G$(2000)/GWe

From the cost figure the specific energy investment and CO_2 emission can be estimated using the energy/cost ratio of construction, e = 12.34 MJ/$(2000):

$E_{decom+dism} = c*e = 6.5*10^9*12.34 = E_{th} + E_e$ = 80 PJ $\quad J_{th}/J_e = 4.8$

The thermal component of the energy consumption is:

$E_{th} = (4.8/5.8)*80 = 66.2$ PJ

CO_2 emission:

$m = 66.2*10^9*75 = 4966$ Gg CO_2

specific CO_2 emission:

$\gamma = 4966*10^9/219*10^9 = 22.7$ gCO_2/kWh

These figures include:

- clean up
- decontamination of the nuclear components
- operation and maintenance during safeguarded period after final shutdown
- actual demolition of the radioactive components
- site clearance,

but excludes waste packaging and final disposal of the dismantling waste.

Evidently this is a rough estimate of the energy investment of decommissioning + dismantling. In view of the long history of sizeable cost escalations within the nuclear industry and especially with regard to new technologies, the above figure might be not overestimated. At the time of writing (2019) few, if any, decommissioning + dismantling sequences in the world have been completed, and vrtually no empirical data are pubished. Large cost escalations are intrinsic to new technology projects according to [RAND 1981] Q126:

"Severe underestimation of capital costs is the norm for *all* advanced technologies."

According to [RAND 1979] Q127 escalations in cost estimates of energy process plants with factors 2-5 are not uncommon.

EPR design

This study assumes construction mass of the EPR design of 1.2 times that of the advanced reactor, due to its double containment and other features to

$E_{th} + E_e = 96$ PJ $\quad J_{th}/J_e = 4.8$

$E_{th} = (4.8/5.8)*96 = 79.4$ PJ

CO_2 emission:

$m = 79.4*10^9*75 = 5959$ Gg CO_2

specific CO_2 emission:

$\gamma = 5959*10^9/781*10^9 = 7.6$ gCO_2/kWh

Packaging decommissioning and dismantling waste

The part of the construction materials of a nuclear power plant that become radioactive waste, depends partly on the cumulative neutron flux during the operational life and therefore on the thermal power and the full-power time of the reactor. Higher power and longer operational lifetime will result in larger volumes of radioactive materials materials, which will be more heavily activated and contaminated.

According to [IAEA-293 1988] Q36 10.7% of the construction steel mass (including reinforcing steel) will become radioactive waste and 8.0% of the concrete, by activation reactions and contamination. If the total fraction of radioactive materiPackaging decommissioning and dismantling wasteal would remain constant at 8.8%, independent of higher construction masses, the amount of radioactive waste released from a reactor with a construction mass of 1000 Gg would be about 88 Gg.

Thierfeldt 1995 [Q41] cites percentages of 2-3% of the mass becoming radwaste and 6% of the construction mass becoming materials for restricted reuse after decontamination. The last phrasing is an euphemism for low-radioactive materials of unknown radioisotopic composition, which may be reused in other nuclear facilities. The figures of Thierfeldt are based on the dismantling of Niederaichbach, a 100 MWe plant with a full-power time of only a few weeks.

Reuse of contaminated and/or activated concrete and steel, by mixing it with fresh steel or concrete, seems incompatible with any sustainability principle. The potentially hazardous isotopic composition and specific activity of the dismantling debris will largely remain unknown. Moreover, such a policy would introduce a very high risk of uncontrolled trade in radioactive materials, already an underrated problem today. This assessment assumes that all radioactive dismantling waste is packed in containers that are permanently stored in a geologic repository.

No large commercial nuclear power station has ever been completely dismantled, including packaging the waste for final disposal, and it is still unclear how the nuclear industry will manage the dismantling waste. Data are exceedingly scarce in the open literature. The concept used in this study is based on [IAEA 293 1988] Q36 and [Berg & Görtz 1995] Q46. The publication years of these studies show how old these concepts are and also that during the past three decades virtually no progress has been made with this aspect of the nuclear legacy.

An unanswered question is what to do with the radioactive coolant and off-gas. By way of approximation, this study assumes that only the coolant present in the reactor system at final shutdown, will be immobilized and packed for final disposal. The tritiated cooling water (HTO or T_2O) will be fixed in cement and packed in appropriate containers. A problem may become the pressure build-up of the helium-3 decay product in the tritiated concrete.

In this study the coolant, water containing tritium, other radionuclides and added chemicals, is immobilized in cement, with about 25 mass-% water [IAEA-203 1981] Q74. With a density of the resulting hardened cement of d = 2.7 Mg/m3, 1 m3 water can be fixed in 1.5 m3 cement.

In this study no cooling water will be immobilized during operation. This assumption means that virtually all of the tritium and carbon-14 generated in the coolant of the reactor during its operational lifetime, together with low quantities of other radionuclides (see e.g. [IAEA-377 1985] Q44 and [NRC 1996] Q16) will be discharged into the environment, as is the present practice. This means a non-sustainable situation in the sense that an unknown but irreversible harm is being inflicted on the environment.

Other unknowns exist about the amounts of contaminated soil and the extent of contamination of the foundations of the nuclear power plant. Experience from the past learns that always leaks occur in the technical system of a nuclear power plant during its operation, often unnoticed. A complete dismantling process must include removal of the foundations of the nuclear power plant in order to achieve adequate site clearance. Based on the scarce information available only rough estimates are possible with regards to the amounts of dismantling waste. This study assumes that 10% of the concrete of an average nuclear power plant, or 85 Gg, becomes radioactive by contamination and that 10 000 m3 of contaminated soil has to be removed from the site.

The waste containers for decommissioning waste in the [Ecoinvent 2003] Q333 study are large concrete boxes (wall thickness 10 cm) with a steel liner: height 2.4 m, width 2.5 m and length 4.5 m. The displaced volume is 27 m3 and the internal volume (waste capacity) is 21.6 m3. The loaded mass of this type of container would be some 70 Mg. This type of container might be difficult to handle, it would require specialized heavy transporters, vulnerable to mishaps and not very appropiate to be transported into a deep geologic repository. For that reason this study assumed that the dismantling waste would be packed in containers of type V3 and V4. The way of packaging and the number of resulting waste containers are summarized in Table 18A for the advanced reference reactor and Table 18B for the EPR design. The total volumes and masses of packaging the dismantling waste of the reference nuclear power plant are summarised in Tables 19A and 19B. Tables 20A and 20B summarise the energy input and CO_2 emission of the decommissioning + dismantling and the waste packaging.

Table 18A

Categories of dismantling waste from the advanced reference reactor and needed containers

material	mass waste Mg	volume waste m3	assumed waste class	type container	number of containers	displaced volume m3
decontamination	7500	5000	HLW	V3	17241	20345
steel/ stainless steel	3000	380	HLW	V3	1309	1545
steel	10000	1266	LLW	V4	732	3000
other materials	1000	500	LLW	V4	289	1185
coolant	1000	1500	LLW	V4	867	3555
concrete	85000	35417	LLW	V4	20472	83935
contaminated soil	20000	10000	LLW	V4	5780	23699
sum	127 500	54 063			46691	137265

Table 18B

Categories of dismantling waste from the EPR design and needed containers

material	mass waste Mg	volume waste m3	assumed waste class	type container	number of containers	displaced volume m3
decontamination	9000	6000	HLW	V3	20690	24414
steel/ stainless steel	3600	456	HLW	V3	1571	1854
steel	12000	1519	LLW	V4	878	3600
other materials	1200	600	LLW	V4	347	1422
coolant	1200	1800	LLW	V4	1040	4266
concrete	102000	42500	LLW	V4	24566	100723
contaminated soil	20000	10000	LLW	V4	5780	23699
sum	149000	62875			54873	159978

Table 19A

Containers for dismantling wastes from the advanced reference reactor numbers, displaced volume, energy input and CO_2 emission

container type	number of containers	displaced volume m^3	Ee + Eth input TJ	Eth input TJ	mCO2 Mg
V3	18600	21900	13134	11 513	888568
V4	28100	115400	13507	11 240	841391
sum	46700	137300	26641	22753	1729977

Table 19B

Containers for dismantling wastes from the EPR design numbers, displaced volume, energy input and CO_2 emission

container type	number of containers	displaced volume m^3	Ee + Eth input TJ	Eth input TJ	mCO2 Mg
V3	22261	26268	15761	13044	1066303
V4	32612	133710	15654	12955	975103
sum	54873	159978	32415	25999	2041406

Table 20A

Energy investments and CO_2 emission of decommissioning + dismantling the advanced reference nuclear power plant and packaging the waste in appopriate containers.

process advanced reference nuclear power plant	*E*e + *E*th input TJ	*E*th input TJ	mCO_2 Gg	CO2 g/kWh
decommisioning + dismantling	80 000	66 000	4966	22.67
waste packaging in V3 and V4 containers	26641	22048	1650	7.53
sum	106600	88048	6616	30.20

Specific CO_2 emission of packaging the radioactive waste from decommissioning and dismantling:

$\gamma = 1650*10^9/219*10^9 = 7.53\ gCO_2/kWh$

Table 20B

Energy investments and CO_2 emission of decommissioning + dismantling the advanced reference nuclear power plant and packaging the waste in appopriate containers.

process advanced reference nuclear power plant	*E*e + *E*th input TJ	*E*th input TJ	mCO_2 Gg	CO2 g/kWh
decommisioning + dismantling	96 000	79 448	5959	7.63
waste packaging in V3 and V4 containers	31415	25999	1950	2.50
sum	127 415	105 447	7909	10.13

Specific CO_2 emission of packaging the radioactive waste from decommissioning and dismantling:

$\gamma = 1950*10^9/781*10^9 = 2.50\ gCO_2/kWh$

Spent nuclear fuel

By far the largest part of the anthropogenic radioactivity is confined within the spent fuel elements. The highly dangerous spent nuclear fuel is unloaded from the reactor and transported to cooling ponds, usually on the site of the nuclear power plant. The decay of the radioactivity to levels comparable with an uncontaninated environment takes millons of years. Because of its heat generation and extremely high radioactivity spent fuel has to be cooled for decades, in order to avoid melting, hydrogen explosions and consequently release of its contents, as happened in Fukushima.

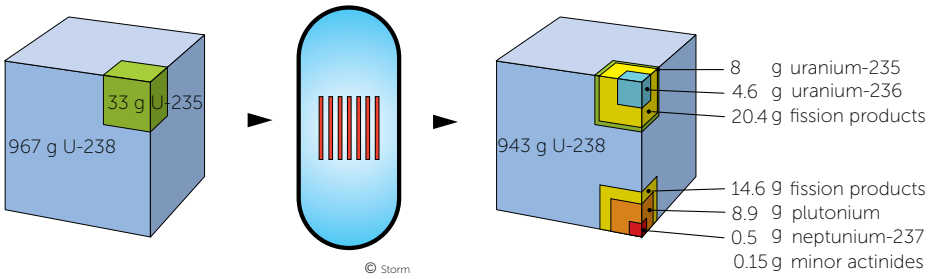

Figure 7

Composition of fresh and spent nuclear fuel. Fresh nuclear fuel consists of very pue uranium, enriched in the fissile uranium-235 isotope. During operation of the reactor a part of the U-235 nuclides are fissioned. a part is converted into non-fissile U-236 and a part has not fissioned when the fission process is no longer sustainable and the fuel has to be removed from the reactor. By neutron capture - the neutrons coming from fissioning nuclides – a small part of the non-fissile U-238 isotope are converted into fissile and non-fissile plutonium isotopes. A part of the formed plutonium is fissioned and so contributes to the energy production. Another part of the plutonium is converted into the minor actinides: nuclides with a higher atomic number than plutonium, having nasty properties. The radioactivity of 1 kg spent fuel is a billion times higher than of 1 kg fresh fuel.

In reality the constituents of fresh and spent nuclear fuel are mixed on atomic scale, so it is not possible to cut out a few pieces from spent fuel to obtain all fission products, plutonium and minor actinides in separate blocks. Separation of these materials requires a complicated sequence of processes, called reprocessing.

Table 21

Annual discharges of spent fuel for three common reactor types. This assumes a reactor of 1 GWe operating at 90% capacity. GWd/tHM is the amount of thermal energy (heat) in gigawatt-days released per metric ton of heavy metal (HM) in the fuel. Source: IPFM 2011 [Q513].

reactor type	typical burn-up (GWd/tHM)	annual discharge of spent fuel (Mg)
LWR (light-water moderated)	50	20
CANDU (heavy-water moderated)	7	140
RBMK (graphite moderated)	15	65

The radioactivity of spent fuel at a given moment in an operating reactor is largely set by the fission products. During the fission process some thousand different nuclides are formed and a significant part of these are radioactive. During the first months after the fission process stopped the radioactivity of spent fuel decreases sharply, due to the decay of very short-lived fission products. After some 300 years the radioactivity of spent

fuel is chiefly set by the actinides.

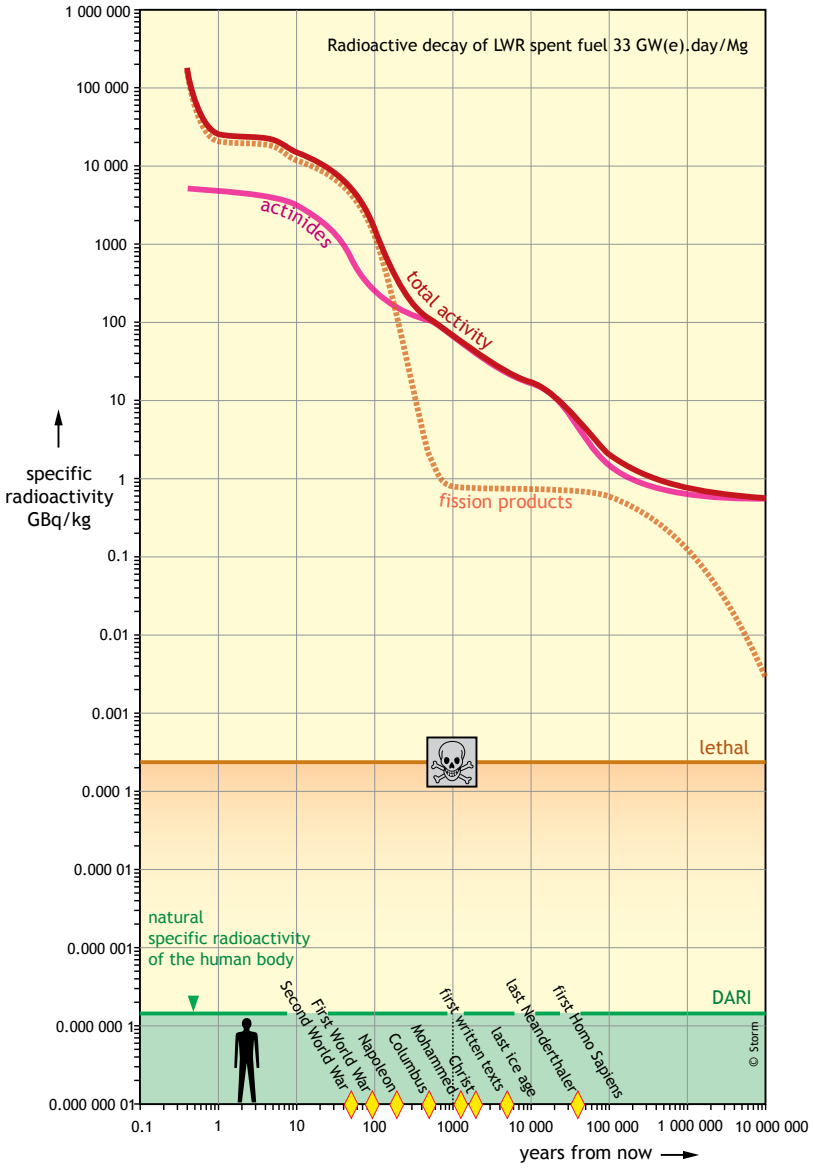

Figure 8

Specific radioactivity, in gigabecquerel per kilogram (GBq/kg), of spent nuclear fuel at a burnup of 33 GWe.day/Mg (gigawatt electric per metric tonne uranium) with time. Nuclear fuel from current types of nuclear reactors usually has higher burnup (40-50 GWe.day/Mg) than the fuel this diagram is based on and consequently its specific radioactivity is higher. The contributions of tritium and carbon-14 are not included in these curves. Note that both axes have logarithmic scales. Each scale division denotes a factor ten. With linear time scales the horizontal axis would be about 100 kilometers long and the vertical axis some 100 million km.

On the horizontal axis a reverse historic timescale is indicated, to give an idea of the time frames involved. The green line indicates the natural radioactivity of the human body (143 Bq/kg). Sources: [Bell 1973] Q264, [Hollocher 1975]Q262, [JPL-77-69 1977] Q263, [Charpak & Garwin 2002] Q300.

Spent nuclear fuel management options

The bulk of the human-made radioactivity is contained in the spent fuel removed from the nuclear reactor. In principle there are two options to deal with spent fuel:

- direct disposal as radioactive waste
- reprocessing.

During the fission process in an advanced light-water reactor (LWR) not more than 0.5% of the uranium nuclei (U-235 + U-238 via Pu-239) can be fissioned. A small part of the uranium-238 nuclei are transformed into plutonium by neutron capture. In a reprocessing plant spent fuel is separated into three fractions: fission products, plutonium and uranium.
According to the nuclear industry the recovered plutonium and uranium could be used for more energy generation per kg uranium than possible in LWRs by means of MOX fuel in LWRs or in breeder reactors. MixedOXide fuel consists of uranium oxide and plutonium oxide, see m15 *Plutonium recycling in light-water reactors* and m01 *Uranium-plutonium breeder systems*. Use of MOX fuel in LWRs has a negative energy balance: more energy is cconsumed to reprocess spent fuel and to fabricatie MOX fuel elements than can be extracted from those elements. Breeder reactors use plutonium as fissile material and depleted or natural uranium as fertile material, from which new plutonium can be formed by neutron capture. Plutonium to start up the first generation breeders would have to be extracted from spent fuel of the present generation nuclear reactors by reprocessing

Reprocessing would also make waste reduction possible by vitrification of only high-level radioactive component of spent fuel and/or by partitioning and transmutation. According to a popular view within the nuclear industry the latter two technical concepts, vitrification and P&T, could reduce the high-level waste problem to a routine job, see for example [MacKay 2009] Q399. Both concepts may seem plausible at a first glance. However, on closer examination these concepts prove to be unfeasible as radioactive waste reduction strategies. Contrary to assertions of the nuclear industry vitrification of high-level radioactive waste greatly increases the volumes of radioactive waste to be sequestered in gelologic repositories. Partitioning and transmutation of long-lived radionuclides from spent fuel is an infeasible concept, due to phenomena governed by the Second Law of thermodynamics. see reports m16 *Partitioning and transmutation*, m20 *Reprocessing of spent fuel* and m30 *Vitrification of radioactive waste*.

Permanent storage in a geologic repository without any treatment other than packing in durable containers, is the least dangerous way to isolate the radioactivity in spent fuel from the human environment. The next section addresses technical aspects of direct disposal of spent fuel. By leaving the spent fuel elements intact, the volume containing the radioactivity remains minimal and the contents are in least unstable form. Consequently the chances of dispersion of the radioactivity into the environment remain minimal. The less activities involving the spent fuel, the less chances of accidents and releases of the radioactive contents. In addition, the energy consumption of this option is less than of the other options, all involving reprocessing of spent fuel.
The other options depend on succesful reprocessing of spent fuel, a highly energy-intensive and polluting process, see report m20 *Reprocessing of spent fuel*.

Direct disposal of spent fuel

After shutdown of the reactor spent fuel generates enough heat to melt it within a short time. The residual heat generation slowly decays.
Therefore the first step in the management of spent fuel is a cooling period of 30-60 years, to let decay the residual heat, in water-filled cooling pools or dry casks. This so-called interim storage period poses serious

public health risks, because the facilities are vulnerable to natural disasters and terrorism.
The second step to an effective isolation is an appropriate packing of the spent fuel. The containers should be resistant to water for long periods, a demanding task, for most materials rapidly deteriorate in the presence of water and strong radiation fields and at elevated temperatures.
The third step is the construction of a facility for permanent disposal of the waste containers. In view of the geologic timescales (millions of years) the waste has to be isolated, the final storage facility should be embedded in a geologically very stable formation, a deep geologic repository.
The last step is placing the waste containers into the geologic repository and back filling the remaining galleries definitively.

The spent fuel in the containers generates heat for long periods after removal from the reactor, so each spent fuel container has to be placed into a separate hole in the floor of a gallery to avoid melting and cracking. Each hole is filled up with bentonite. When the holes of one gallery are occupied, which has to be done with robotic equipment because of the high radiation fields, the gallery itself is back filled with a bentonite-sand mixture and permanently closed. Bentonite is a clay mineral that swells by absorption of water and so forms a poorly permeable mass. Ion migration through bentonite is very slow.
This scenario is based on the Swedish KBS-3 concept, one of the farthest developed designs of a geologic repository for direct disposal of spent fuel, see next section.

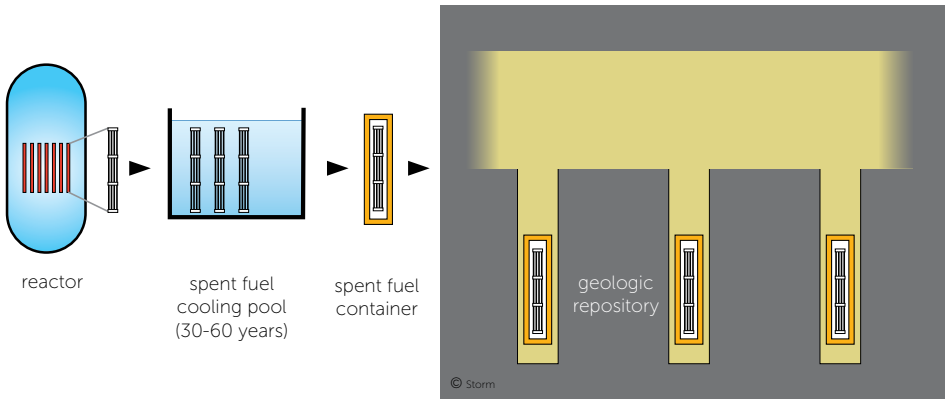

Figure 9
Outline of the sequence of activities needed for direct disposal of spent fuel. After removal from the reactor the spent fuel elements are stored in cooling basins for extended periods, before packed in a special container. These containers are placed in a deep geologic repository by means of robotic equipment. If a deep geologic repository is available, it may take 30-60 years before a spent fuel element is effectively isolated from the biosphere, as far as possible.

Several other concepts have been published for final disposal of high-level waste and spent fuel, such as deep boreholes, see for example [IAEA NW 2018] Q843, [CTECH 2003] Q824, [Smith 2008] Q823, [SKB P-10-47 2010] Q836. This study bases its assessment on the KBS-3 design.

Residual heat generation

Spent fuel is extremely radioactive and generates much heat, due to the radioactive decay of its contents. The material has to be cooled in spent fuel pools for many years to prevent melting and consequently the release of the contents into the environment. The greatest part of the human-made radioactivity generated during fission is contained in the spent fuel elements.

After shutdown of the reactor the spent fuel generates so much heat, due to the radioactive decay of the fission products and actinides, that the fuel elements will melt within a very short time if not effectively cooled. The residual heat generation falls to less than 1% during the first year and slowly decays thereafter. A 100 years after removal from the reactor it is still 100-200 watt/Mg. For that reason spent fuel has to be cooled actively during many years after removal from the reactor, before it can be processed for final storage or other purposes. Even then the residual heat generation requires precautionary measures.

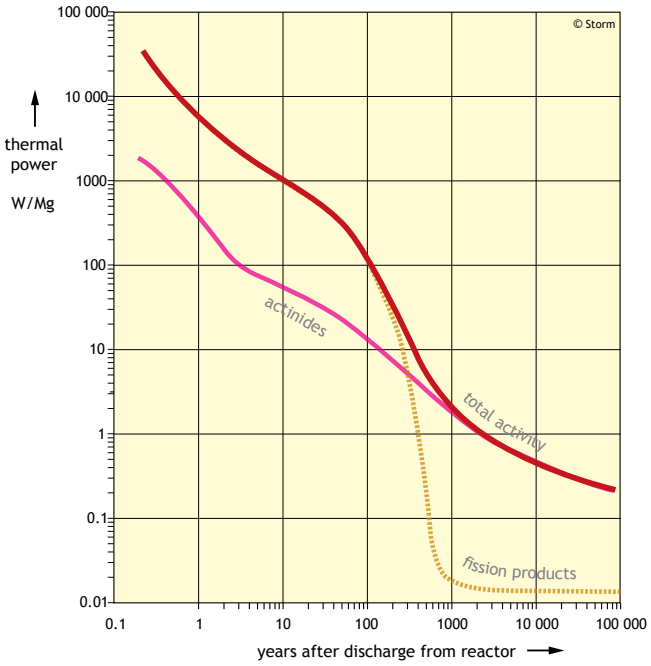

Figure 10

Residual heat generation of spent fuel (burnup B = 33 GWday/Mg) as function of cooling time. At the moment of reactor shutdown, the fuel radiates about 8 MW/Mg (not shown in the diagram). Source: [Hollocher 1975] Q262.

Note that both axes of this diagram have logarithmic scales: each division marks a factor of ten. Spent fuel from current nuclear power plants generally has a higher fuel burnup (B = 40-50 GWday/Mg) and has a about two times higher residual heat generation [IPFM 2011] Q513.

Cooling pools

After removal from the reactor spent fuel elements are stored in water-filled cooling pools for a long period, this is called interim storage. After some 30 years interim storage in cooling ponds the heat production has decayed sufficiently to handle the fuel elements for further processing. Interim storage may become a source of inadvertent emission of radioactivity.

Operation and maintenance of the interim storage facilities are expensive. The water in the pools has to be actively cooled and decontaminated during a period of at least 30 years. The spent fuel of the new generation of reactors with a high fuel burnup, such as the EPR, may have to be cooled for much longer periods. The basins deteriorate and may go leaking, as happened at several occasions in the past, and have to be replaced. In addition the condition of the fuel elements unavoidably degrades over time, due to a number of natural mechanisms, such as ageing of spent fuel. The integrity of the fuel elements deteriorates inevitably over time, so unplanned releases of radioactivity into the environment increase over time as well as the risks of the occurrence of large accidents.
Activities related to interim storage of spent fuel do not generate financial profits for the company which operated the nuclear power plant during its productive life. Does that company still exist 30-60 years after closedown of the plant?

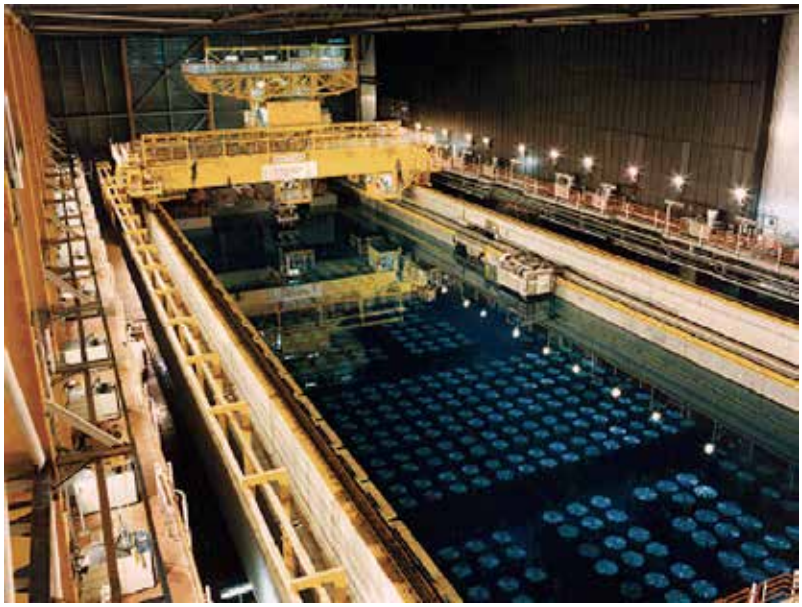

Figure 11
Storage basin (cooling pool) for spent fuel in the British reprocessing plant THORP at Sellafield. The basin is filled with demineralised water, which has to be cooled and purified continuously. The spent fuel elements give off a blue glare caused by the interaction of the nuclear radiation with water (Cherenkov effect). The cooling pools of nuclear power plants have a similar construction, but are smaller. Photo WNA.

Dry casks

In the United States during the late 1970s and early 1980s, the need for alternative storage of spent fuel began to grow when pools at many nuclear reactors began to fill up with stored spent fuel. Utilities began looking at options such as dry cask storage for increasing spent fuel storage capacity. Designers of nuclear power plants anticipated that the spent fuel would be reprocessed, with usable portions of the fuel to be recycled and the rest to be disposed as waste. However, commercial reprocessing was never successfully developed in the United States, and a permanent waste repository has not yet been developed. As a result, many of the spent fuel pools at commercial nuclear power plants are nearing capacity [NRC 2012a] Q510. A similar development may be expected also in other countries.

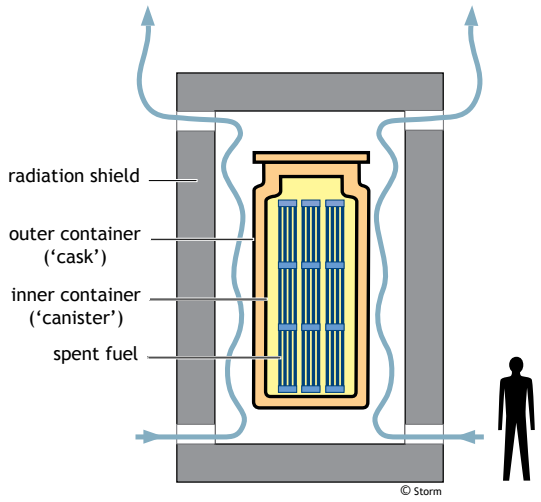

Figure 12

Dry storage of spent fuel elements. The residual heat has to be removed by convection and natural circulation of air around the steel vessels containing the heat generating spent fuel.

Figure 13

Dry cask storage facility of spent nuclear fuel. Source: US Nuclear Regulatory Commission (retrieved from wikipedia).

Spent fuel is typically cooled at least 5 years in the spent fuel pool at the reactor site before transfer to cask; the industry norm is 10 years. In the United States nearly 63000 Mg (metric tons) of commercial spent fuel accumulated at the end of 2009. Of that total nearly 49000 Mg (~78%) were in pools and nearly 14000 Mg were stored in dry casks. The total amount of spent fuel increases by 2000-2400 Mg annually in the US.
U.S. nuclear utilities are operating dry-storage facilities for used fuel that are licensed for operating periods of up to 60 years. The fuel in these facilities and the used fuel that will be discharged in the foreseeable future may need to remain in storage for much longer periods. Some have suggested that this period could extend to as long as 300 years [NRC 2012c] Q512.
In Europe the reprocessing option is still kept open and large numbers of spent fuel elements are stored in pools at the reactor sites and in large pools at the sites of the reprocessing plants, La Hague in France and Sellafield in the UK.

After an initial cooling period in a cooling pool the spent fuel elements could be placed in double-walled

steel containers. These containers, casks in nuclear jargon, are placed vertically inside concrete cilinders as radiation shields, or horizontally into a concrete bunker.
During dry storage the spent fuel elements have to be cooled by natural air circulation. This implies that the steel containers inside the concrete outer cask (radiation shielding) has to stay constantly in direct contact with air and that the heat transfer from the fuel elements to the outside air has to be sufficient to keep the temperature of the fuel elements at a safe level.

Energy consumption and CO_2 emission

Spent fuel interim storage involves three phases of the storage facilities (cooling pools and/or dry casks):
- construction of the facility or casks
- maintenance and security guarding during 30-60 years, or even longer
- decommissioning and dismantling of the storage facility.

As a result of ageing and other unavoidable processes the fuel elements deteriorate and radioactive materials escape into the cooling water and environment, a phenomenon that increases with storage time. The cooling water becomes contaminated by radionuclides from leaking fuel pins and has to be purified continuously. Dry casks have a limited lifetime, corrosion goes fast due to the presence of nuclear radiation, and would to be replaced by new ones after a certain period. Replacement is precarious, if not impossible, due to the release of hazardous radionuclides from the leaking fuel elements.
Interim storage facilities for spent fuel are vulnarable to terroristic actions.

No data could be found in the open literature on the energy consumption of these three phases. In this study the estimate of the energy input is based on the cost from the German study [atw-7 1997] Q40:

c = 267 $(2000)/kg HM

ftom this would result an estimate of the specific energy investment of:

$J_{interim}$ = $c \bullet e$ =267 $/kg•12.34 MJ/$ =
= 3.3 TJ/Mg spent fuel J_{th}/J_e = 4.8

It is not clear from the literature wether the cited cost figure refers to the annual cost of operation and maintenance of the storage facility, or to the full 30-60 years cooling period. Likely the full cooling period is not accounted for, so the final cost figures may turn out significantly higher. Most likely the decommissioning and dismantling cost are included neither. To stay on the safe side this study assumes a total specific energy investment of:

$J_{interim} = J_{th} + J_e$ = 6 TJ/Mg spent fuel J_{th}/J_e = 4.8

This figure includes the three phases of the complete interim storage operation with a coolng period of 30 years. The thermal component is:

J_{th} = 5 TJ/Mg spent fuel

Table 22

Energy investment and CO_2 emission of interim storage of spent fuel from the advanced reference reactor and the EPR design, during 30 years.

reactor	mass spent fuel Mg	$E_e + E_{th}$ input TJ	E_{th} input TJ	mCO_2 Gg	specific emission gCO_2/kWh
advanced reference reactor	583.4	3500	2917	219	1.0
EPR design	1506	9036	7530	565	0.72

Spent fuel conditioning for final disposal

After a cooling period of 30 years, or longer, the spent fuel elements are to be packed in V5 canisters, that are to be disposed of in a special deep geologic repository.
Estimates of the energy requirements and CO_2 emission in this study are based on the Swedish SKB-3 concept. A V5 canister has a loaded mass of 26.8 Mg and contains 2 Mg spent fuel from the reference PWR + its cladding and control rods. Based on this data the energy input per Mg spent fuel of the conditioning process can be estimated; see Table 9 for specific energy input and CO_2 emission.

$J_e + J_{th}$ = 16.6 TJ/V5 canister => $J_e + J_{th}$ = 8.3 TJ/Mg spent fuel

J_{th} = 3.8 TJ/V5 canister => J_{th} = 1.9 TJ/Mg spent fuel

specific CO_2 emission

m = 1016 Mg CO_2 /V5 canister

Table 23

Energy investment and CO_2 emission of packaging spent fuel from the advanced reference reactor and the EPR design.

reactor	mass spent fuel Mg	number of V5 canisters	$E_e + E_{th}$ input TJ	E_{th} input TJ	mCO_2 Gg	specific emission gCO_2/kWh
advanced reference reactor	583.4	292	4847	1107	297	1.36
EPR design	1506	753	12 500	2855	765	0.98

Deep geologic repository for spent nuclear fuel

KBS-3 concept

A good example of a geologic repository for permanent storage of spent fuel is the KBS-3 concept designed by SKB (Svensk Kärnbränslehantering AB, Swedish Nuclear Fuel and Waste Management Co). The KBS-3 project started in 1973 and has been presented in 1983 by the Nuclear Fuel Safety project KBS: [Papp 1998a] Q37, [Papp 1998b] Q38, [IAEA-349 1993] Q43, [Thegerstrom 2010] Q453, [SKB 2006a] Q176a, [SKB 2006b] Q176b, [SKB P-10-47 2010] Q836. The design, which is similar to the design described in [INFCE-7 1980] Q277, has been approved in 1984 by the Swedish government. SKB expects to start disposal of spent fuel canisters by 2020, 47 years after the start of the KBS project.
The KBS-3 concept is envisioned as a system of galleries in a granitic formation or in very stable rock strata some 500-700 meters below the surface. The spent fuel elements would be packed in containers of cast iron, clad by a thick layer of very pure copper. The designers assume this combination of materials to be resistant to (sea)water for thousands of years. However this assumption may be optimistic in view of the elevated temperatures and the presence of nuclear radiation. There are also doubts regarding the sealing function of bentonite under the extreme conditions to be expected in the repository.
The spent fuel canisters are placed in boreholes in the floor of the galleries by remotely piloted vehicles. The holes are to be filled up with bentonite, and the gallery itself would be backfilled with a bentonite-sand mixture after filling the holes. The canister must remain subcritical with sufficient certainty in the rare cases where highly enriched uranium or uranium mixed with plutonium has to be placed in an individual canister, even if water penetrates into the canister.

There are three main phases of spent fuel final disposal:
- construction of the repository
- operation of the facility during 60 years, sequestering the spent fuel canisters
- definitive closure of the repository.

The complete sequence of these activities may take a period of a century.

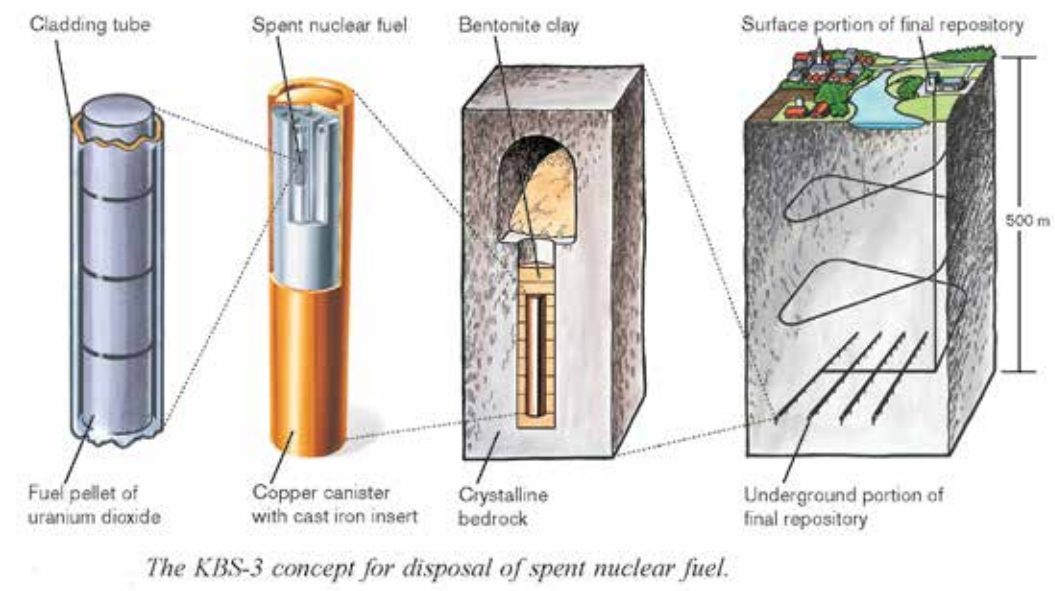

Figure 14
Swedish KBS-3 concept for deep geological disposal of spent nuclear fuel. Source: [SKB 2006a] Q176a.

Each canister in the KBS-3 concept holds 2 Mg of spent fuel. Assume a modern nuclear power plant of 1 GWe power generates 20 Mg spent fuel a year, and assuming the distance between the holes for the canisters in the gallery floor to be 6 m, then 60 m of gallery plus holes have to be constructed per reactor per year.

If the current global nuclear capacity of some 470 GWe would consist of reference reactors, then 9400 Mg of spent fuel would be generated per year. The actual production of spent fuel is much higher because the majority of the currently operating reactors discharge spent fuel at lower burnup than the reference reactor, so we assume for convenience that 10000 Mg of spent fuel is generated annually worldwide.
A large geologic repository at a capacity of 40000 Mg of spent fuel would comprise 100 km of galleries, excluding the access tunnels. This would imply that every four years a repository with 100 km of galleries 500 m below level in a geologically stable formation has to be opened to dispose of the global generation of spent fuel at the current rate. To dispose of the existing backlog of more than 60 years civil nuclear power, some 368 000 Mg at the end of 2013 [IAEA-NW 2018] Q843, more than nine of such large repositories would be needed.

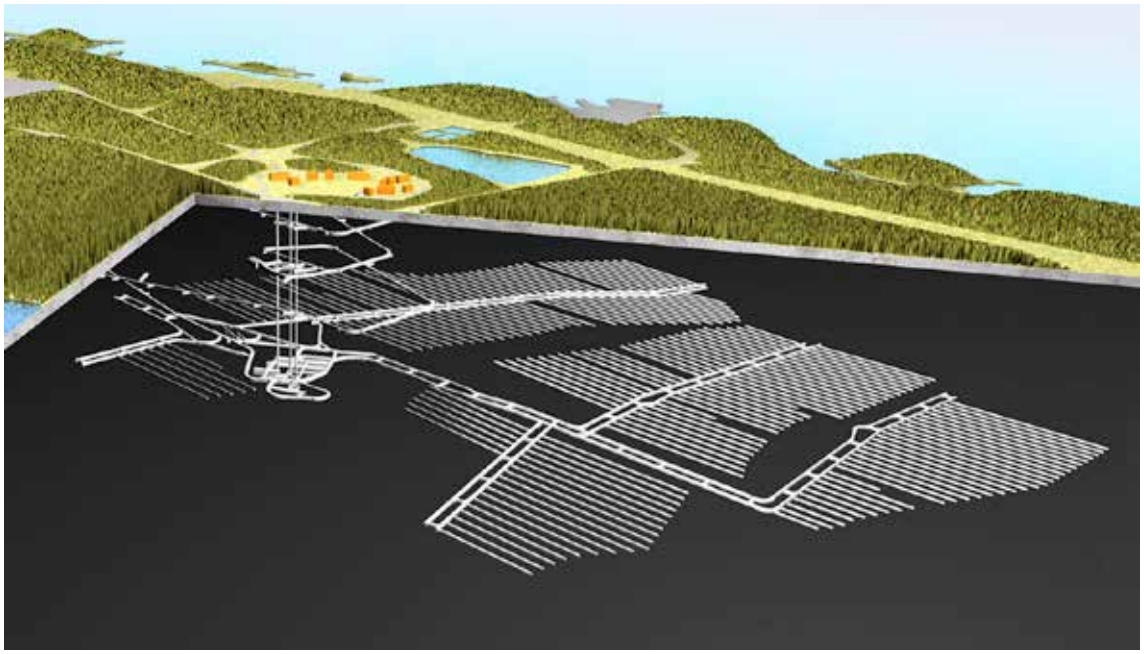

Figure 15
Spent nuclear fuel disposal repository at Olkiluoto (Finland), according the KBS-3 concept. The current plans involve excavation of the repository on one level at about 400-450 m depth. Deposition holes will be bored in the floors of the deposition tunnels for inserting the canisters. The canisters will be completely surrounded by bentonite blocks that will swell considerably when becoming wet. The repository will be expanded as the disposal operations progress by excavation of more disposal and central tunnels. Source: Posiva Oy [www.posiva.fi/en/media/image_gallery].

Construction

Numerical data on the energy investment and CO_2 emission of the final disposal of spent fuel are not found in the open literature. To store 7000 Mg spent fuel, about $5.8*10^6$ m^3 granite has to be mined, according to [Papp-1 1998] Q37.
The specific repository volume per Mg spent fuel then would be:

V_{rep} = 829 m^3/Mg

This figure is adopted in this study to estimate the energy investment and CO_2 emission of the onstruction of the repository.

Papp cites a total cost of DM 8.5bn in 1998 for a repository with a capacity of 7000 Mg spent fuel, one of the very few cost estimates found. This estimate, concerning only the construction phase, is based on a mining cost of 600 DM/m3 and a bentonite cost of 3000 DM/m3.
From these figures follows per Mg spent fuel:

c = 1.21*10^6 DM/Mg in 1998 = 0.63*10^6 $(2000)/Mg spent fuel

In practice the construction cost and corresponding energy investment might be higher. At the time of writing (2019) not one deep geologic repository in the world is operational, so no empirical data exist. Large cost escalations are intrinsic to new technology projects according to [RAND 1981] Q126:

"Severe underestimation of capital costs is the norm for *all* advanced technologies."

According to [RAND 1979] Q127 escalations in cost estimates of energy process plants with factors 2-5 are not uncommon. The nuclear industry provides ample examples of this rule and of the observations mentioned in both publications.

The specific energy investment of the construction of the KBS-3 repository in granite can be estimated by comparison with underground mining in hard rock. A specific figure of mining hard rock can be found based on a process analysis of the Ranger mine in Australia (see report **m26** *Uranium mining and milling*):

$J_{mining} = J_e + J_{th}$ = 1.1 GJ/m3 rock $J_{th}/J_e = 8$

The thermal energy input then is:

J_{th} = 0.98 GJ/m3 rock

Both bentonite and sand, needed to backfill the access tunnels and galleries, have to be mined, prepared and transported to the repository. From a process analysis (see report **m41** *Uranium mine rehabilitation*) follows a specific thermal energy consumption of:

J_{th} = 20 GJ/Mg bentonite

At an average density of d =2.15 Mg/m3 this corresponds with:

J_{th} = 43 GJ/m3 bentonite

Assumed that the backfill consists of a 1:1 mixture of sand and bentonite and neglecting the energy consumption of the sand component, the energy input of the backfill per m3 of repository would be:

$J_{bentonite} = J_{th}$ = 21.5 GJ/m3 repository

The total thermal energy investment of the construction of the repository, including the supply of bentonite, but excluding the backfilling operation would be:

J_{th} = 22.5 GJ/m3 repository

Per Mg spent fuel:

J_{th} = 22.5*829 = 18.6 TJ/Mg spent fuel

The electric component is small compared with the thermal component (less than 1%) and is neglected in this assessment.

Sequestering and backfilling

Estimation of the cost and energy investments of the operational phase (handling and sequestering the spent fuel canisters) and closure (backfilling the galleries and access tunnels) during the 60+ years following the construction may be compared with operation + maintenance of a nuclear power plant. Many operations have to be remotely piloted, due to high radiation levels.in the disposal galleries.
From the figures given by [Papp-1 1998] Q37 follows per Mg spent fuel:

c = 1.21*10^6 DM/Mg in 1998 = 0.63*10^6 $(2000)/Mg spent fuel

From the cost figure the specific energy investment and CO_2 emission can be estimated using the energy/cost ratio of new construction, e = 12.34 MJ/$ (2000):

$J_{rep.sf} = c*e$ = 0.63*10^6*12.34 = 7.8 TJ/Mg spent fuel $J_{th}/J_e = 4.8$

This study assumes an annual operation cost of 2% of the construction cost, or:

$c = 0.02*0.63*8.5*10^9$ $(2000)/a = $ $107*10^6$ $(2000)/a$

Assumed that phase 2 (sequestering) will takes 60 years and phase 3 (final closure) 10 years, the total cost would become:

$c = 70*107*10^6 = 7.49*10^9$ $(2000)

Per Mg spent fuel :

$J_e + J_{th} = c*e = 1.07*10^6*12.34$ =13.2 TJ/Mg spent fuel $\quad J_{th}/J_e = 4.8$

The thermal component is:

J_{th} = 10.9 TJ/Mg spent fuel

Complete sequence

The specific energy investment per Mg spent fuel is:

$J_e + J_{th}$ = 18.6 + 13.2 = 31.8 TJ/Mg spent fuel

The specific thermal energy investment per Mg spent fuel is:

J_{th} = 18.6 + 10.9 = 29.5 TJ/Mg spent fuel

The specific CO_2 emission is:

$m = 29.5*10^6 *75$ = 2200 Mg CO_2/Mg spent fuel

The lifetime figures of the reference reactor are:

Energy investment:

$E_e + E_{th} = 31.8*583.4$ = 18552 TJ

$E_{th} = 29.5*583.4$ = 17 210 TJ

CO_2 emission:

$m = 2200*583.4$ = 1283000 Mg CO_2

The corresponding specific CO_2 emission is:

$\gamma = 1283*10^9/219*10^9$ = 5.86 gCO_2/kWh

Table 24

Energy investment and CO_2 emission of the final disposal of spent fuel from the advanced reference reactor and the EPR design.

reactor	mass spent fuel Mg	number of V5 canisters	$E_e + E_{th}$ input TJ	E_{th} input TJ	mCO_2 Gg	specific emission gCO_2/kWh
advanced reference reactor	583.4	292	18 552	17 210	1283	5.86
EPR design	1506	753	47 891	44 427	3313	4.24

Deep geologic repository for other radioactive waste

This study starts from the idea that all radioactive waste produced by the nuclear system has to be disposed of in a geologic repository. Radioactive waste other than spent fuel has to be stored in a separate repository. Temporary or even permanent storage in above-ground facilities or shallow burial sites, such as in France [ANDRA-*solutions* 2014] Q757 is no option in the long run, in the view of this study.
Estimates of energy investments and CO_2 emission are based on the Swedish SFR concept [IAEA-349 1993] Q43, [Vattenfall 2005] Q152, [Sjöland 2014] Q704, for the same reasons as for the spent fuel repository concept. The waste containers are stored in large caverns, mined in a stable rock formation. In the extended SFR concept 6.33 m^3 rock has to be mined for each m^3 of packaged waste [SKB 2018] Q839, or 17.5 Mg rock per m^3 waste (density of granite d = 2.76 Mg/m^3).

Figure 16
The existing SFR on the right, the new section on the left. After extension the SFR will be three times bigger than it is today. Source: [SKB 2018] Q839.

Assumed that the specific energy investment of the construction of the SFR repository, including the supply of bentonite, but excluding the backfilling operation would be the same as for the KBS-3 spent fuel repository:

J_{th} = 22.5 GJ/m^3 repository

Sequestering + closure per m^3 repository:

J_{th} = 13.2 TJ/Mg spent fuel/829 m^3 repository/Mg spent fuel = 15.9 GJ/m^3 repository J_{th}/J_e = 4.8 (see SKB-3)

The total energy investment of construction + sequestering + closure:

$J_e + J_{th}$ = 22.5 + 15.9 = 38.4 GJ/m^3 repository

The thermal component of sequestering + closure is:

J_{th} = 13.2 GJ/m^3 repository

The total thermal energy investment of construction + sequestering + closure then becomes:

J_{th} = 22.5 + 13.3 = 35.7 GJ/m^3 repository

Per m3 waste:

J_{th} = 35.7*6.33 = 226 GJ/m3 waste

The corresponding specific CO_2 emission is:

γ = 226*75 = 16950 kgCO_2/m3 waste

The total energy investment and CO_2 emission of the final disposal of the radioactive wastes from the nuclear process chain of the advanced reference reactor, except spent fuel and uranium mine tailings, would become:

thermal component:

J_{th} = 61,3 PJ

electric component:

J_e = 4,63 PJ

and the specific CO_2 emission per kilowatthour:

γ = 4594*10^9/219*10^9 = 21.0 gCO_2/kWh

Table 25A

Data on the final disposal of the radioactive waste other than spent fuel from the upstream processes of the advanced reference reactor

process advanced refer. reactor	number of containers	displaced volume m3	repository volume m3	E_e+E_{th} input TJ	E_{th} input TJ	mCO_2 Gg	specific CO_2 g/kWh
refining + conversion	5400	5400	34 182	1313	1220	91.53	0.42
enrichment	3100	3100	19 623	754	701	52.55	0.24
reconv. + fuel fabr.	7500	7500	47 475	1823	1695	127	0.58
reactor OMR	100 000	100 000	633 000	24307	22 600	1695	7.74
sum 1 upstream	116 000	116 000	734 280	28 196	26 216	1966	9.0
reconverted depleted U	26668	26668	168808	6482	6027	452	2.06
decomm. + dismantling	46700	137 300	869109	33 374	31 030	2327	10.63
sum 2 downstream	73368	163 968	1 037 917	39 856	37 057	2779	12.7
total sum 1 + sum 2	189 368	279 968	1 772 197	68 052	63 273	4745	21.7

Table 25B

Data on the final disposal of the radioactive waste other than spent fuel from the upstream processes of the EPR design

process advanced refer. reactor	number of containers	displaced volume m3	repository volume m3	E_e+E_{th} input TJ	E_{th} input TJ	mCO_2 Gg	specific CO_2 g/kWh
refining + conversion	11880	11880	75 200	2888	2685	201	0.26
enrichment	10120	10120	64 060	2460	2287	172	0.22
reconv. + fuel fabr.	16500	16500	104 445	4011	3729	280	0.36
reactor OMR	220 000	220 000	1 392600	53576	49720	3729	4.77
sum 1 upstream	258 500	258 500	1 636305	62834	58521	4382	5.6
reconverted depleted U	84608	84608	535 569	20566	19121	1434	1.84
decomm. + dismantling	54873	159 978	1 012661	38886	36155	2712	3.47
sum 2 downstream	139481	244 586	1 548229	59452	55276	4146	5.3
total sum 1 + sum 2	397 981	503 086	3 184534	122286	113 697	8527	10.9

Overview energy consumption and CO_2 emission nuclear chain

Advanced reference reactor

Figures of the energy input and specific CO_2 emission of the complete process chain of the advanced reference reactor are listed in Tables 26A - 29A.

Table 26A

Lifetime energy input and CO_2 emission of the upstream processes, including waste packaging and final waste disposal.

process advanced reference reactor		$E_e + E_{th}$ input TJ	E_{th} input TJ	mCO_2 Gg	specific CO_2 g/kWh
refining + conversion	process	8495	8191	614	2.81
	waste pack	821	686	51	0.23
	disposal	1313	1220	92	0.42
	sum	10 629	10097	757	3.46
enrichment	process	10 392	7600	570	2.60
	waste pack	462	386	29	0.13
	disposal	754	701	53	0.24
	sum	11608	8687	652	2.97
reconversion + fuel fabrication	process	2234	1596	744	3.40
	waste pack	1140	953	71	0.32
	disposal	1823	1695	127	0.58
	sum	5197	4244	942	4.30
reactor OMR	process	86000	71200	5340	24,4
	waste pack	15200	12700	946	4.32
	disposal	24 307	22 600	1695	7.74
	sum	125 507	106 500	7981	36.46
sum processes		107 121	88 587	7268	33.20
sum waste packaging + disposal		45 820	40941	3064	13.98
sum total		152 941	129528	10 332	47.18

Table 27A

Lifetime energy input and CO_2 emission of the contemporary processes, excluding uranium mining + milling and excluding waste management

process advanced reference reactor	$E_e + E_{th}$ input TJ	E_{th} input TJ	mCO_2 Gg	specific CO_2 g/kWh
refining + conversion	8495	8191	615	2.81
enrichment	10 392	7600	570	2.60
reconversion + fuel fabrication	2234	1596	744	3.40
construction	80 000	66 200	5445	24.9
reactor OMR	86 000	71 200	5340	24,4
sum upstream processes	187 121	154 787	12 714	58.1

Table 28A

Advanced reference reactor lifetime energy input and CO_2 emission of the upstream processes, including waste packaging and final waste disposal.

process advanced reference reactor		$E_e + E_{th}$ input TJ	E_{th} input TJ	mCO_2 Gg	specific CO_2 g/kWh
depleted uranium	process	7451	7183	542	2.47
	waste pack	4054	3387	354	1.16
	disposal	6482	6027	452	2.06
	sum	17 987	16 5978	1248	5.70
decommissioning + dismantling	process	80 000	66 200	4965	22.67
	waste pack	26 641	22 048	1654	7.55
	disposal	33 374	31 030	2327	10.63
	sum	140015	119 278	8946	40.85
spent fuel	interim store	3500	2897	217	1.00
	canisters	4847	1107	297	1.36
	disposal	18 552	17 210	1283	5.86
	sum	26 899	21 214	1797	8.22
mine rehabilitation	supply mat.	13 870	13 300	998	4.56.
	disposal	790	790	59	0.27
	sum	14 660	14 090	1057	4.83
sum processes		87 451	73 383	5507	25.15
sum waste packaging + disposal		112 110	97 796	7541	34.45
sum total		199 561	171 179	13 048	59.60

Table 29A

Advanced reference reactor lifetime energy input and CO_2 emission of the future processes: waste packaging + final waste disposal of the upstream processes. plus the complete downstream processes.

process advanced reference reactor	$E_e + E_{th}$ input TJ	E_{th} input TJ	mCO_2 Gg	specific CO_2 g/kWh
refining + conversion into UF_6 waste management	2134	1906	143	0.65
enrichment waste management	1216	1087	82	0.37
reconversion + fuel fabrication waste managem.	2963	2648	198	0.90
reactor OMR waste management	39507	35 300	2641	12.06
sum waste management upstream processes	45 820	40 941	3064	13.98
depleted uranium conditioning + waste man.	17 987	16 597	1248	5.70
decommissioning + dismantling + waste man.	140 015	119 278	8946	40.85
spent fuel handing + final disposal	26 899	21 214	1797	8.22
mine rehabilitation	14 660	14 090	1057	4.83
sum remaining downstream processes	199 562	171 179	13 048	59.60
sum total	245 381	212 120	16 612	73.6

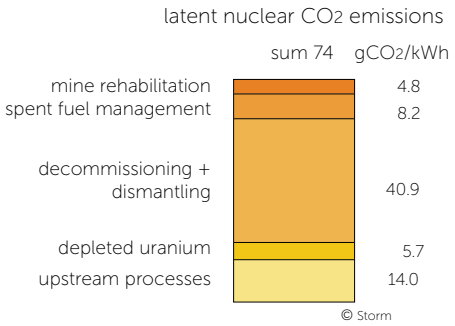

Figure 17

Latent (future) CO_2 emission of nuclear power, based on the advanced reference reactor

EPR design

Figures of the energy input and specific CO_2 emission of the complete process chain of the EPR design are listed in Tables 26B - 29B.

Table 26B

Hypothetical lifetime energy input and CO_2 emission of the upstream (contemporary) processes, including waste packaging and final waste disposal of the EPR design.

process EPR design		$E_e + E_{th}$ input TJ	E_{th} input TJ	mCO_2 Gg	specific CO_2 g/kWh
refining + conversion	process	26 424	25 480	1911	2.45
	waste pack	1806	1509	112	0.14
	disposal	2888	2685	201	0.26
	sum	31 118	29 674	2224	2.85
enrichment	process	34 130	24960	1872	2.40
	waste pack	1538	1285	96	0.12
	disposal	2460	2287	172	0.22
	sum	38 128	28 532	2140	2.74
reconversion + fuel fabrication	process	5770	4120	1920	2.46
	waste pack	2508	2096	156	0.20
	disposal	4011	3729	280	0.36
	sum	12 289	9945	2356	3.02
reactor OMR	process	227 000	188 000	14 102	18.06
	waste pack	33 440	27 940	2081	2.66
	disposal	53578	49 720	3729	4.77
	sum	314 018	265 660	19 912	25.50
sum processes		293 324	242 560	19 805	25.36
sum waste packaging + disposal		102 229	91 251	6827	8.74
sum total		395 553	333 811	26 632	34.10

Table 27B

Hypothetical lifetime energy input and CO_2 emission of the contemporary processes, excluding uranium mining + milling and excluding waste management of the EPR design.

process EPR design	$E_e + E_{th}$ input TJ	E_{th} input TJ	mCO_2 Gg	specific CO_2 g/kWh
refining + conversion	26 424	25 480	1911	2.45
enrichment	34 130	24960	1872	2.40
reconversion + fuel fabrication	5770	4120	1920	2.46
construction	96 000	79 400	6522	8.35
reactor OMR	227 000	188 000	14 102	18.06
sum upstream processes	389 324	321 960	26 327	33.71

Table 28B

EPR design lifetime energy input and CO_2 emission of upstream (future) processes, including waste packaging and final waste disposal.

process EPR design		$E_e + E_{th}$ input TJ	E_{th} input TJ	mCO_2 Gg	specific CO_2 g/kWh
depleted uranium	process	23 638	22 790	1718	2.20
	waste pack	12 860	10 745	800	1.02
	disposal	20 566	19 121	14334	1.84
	sum	57 064	52 656	3952	5.06
decommissioning + dismantling	process	96 000	79 400	5955	7.62
	waste pack	31 415	25 999	1959	2.51
	disposal	38 886	36 155	2712	3.47
	sum	166 301	141 554	10 626	13.61
spent fuel	interim store	9036	7530	565	0.72
	canisters	12 500	2855	764	0.98
	disposal	47 891	41 427	3313	4.24
	sum	69 427	51 812	4643	5.94
mine rehabilitation	supply mat.	43 181	41 404	3105	3.98
	disposal	2465	2465	190	0.24
	sum	45 646	43 869	3295	4.22
sum processes		119 638	102 190	7673	9.82
sum waste packaging + disposal		218 800	187 701	14 843	19.01
sum total		338 438	289 891	22 516	28.83

Table 29B

EPR design lifetime energy input and CO_2 emission of the future processes: waste packaging + final waste disposal of the upstream processes. plus the complete downstream processes..

process EPR design	$E_e + E_{th}$ input TJ	E_{th} input TJ	mCO_2 Gg	specific CO_2 g/kWh
refining + conversion waste managem. + disposal	4694	4194	313	0.40
enrichment waste management + disposal	3998	3572	268	0.34
reconv. + fuel fabr. waste managem. +disposal	6519	5825	436	0.56
reactor OMR waste management + disposal	87018	77660	5810	7.44
sum waste managem + disposal upstream processes	102229	91251	6827	8.74
depleted uranium conditioning + waste man. + disp.	57 064	52 656	3952	5.06
decommissioning + dismantling + waste man. + disp.	166 301	141 554	10 626	13.61
spent fuel handing + final disposal	69 427	51 812	4643	5.94
mine rehabilitation	45 646	43 869	3295	422
sum remaining downstream processes	338 438	289 891	22 516	28.83
sum total	440 667	381 142	29343	37.57

Summary cradle-to-grave CO_2 emissions

Figures of uranium mining + milling and other upstream processes, excluding waste management of the processes. are taken from report **m03** *Contemporary CO2 emissions*,

Table 30

Lifetime CO_2 emissions of the contemporary processes, excluding waste management and final disposal. The uncertainty range of the uranium mining + milling figures is caused by different conditions at the operational uranium mines; the ore grade varies roughly from 0.1% to 0.05% U_3O_8 and the mineralogy varies widely, in this study simplified to 'soft ores' and 'hard ores'. 'Low' means: soft ores at a grade of 0.1% U_3O_8, and 'high' means hard ores at a grade of 0.05% U_3O_8.

process	g CO_2/kWh		total CO_2, Mg	
	advanced reactor	EPR design	advanced reactor	EPR design
uranium mining + milling, low	7.1	6.2	1551	4823
mean	32.3	28.2	7039	21965
high	57.4	50.1	12527	39106
refining + conversion	2.8	2.5	615	1911
enrichment	2.6	2.4	570	1872
reconversion + fuel fabrication, incl zircalloy	3.4	2.5	744	1926
construction	24.9	8.4	5445	6522
reactor OMR	24.4	18.1	5340	14102
sum contemporary processes - low	65.2	40.1	14265	31156
mean	90.4	62.1	19753	48298
high	115.5	84.0	25241	65439

Table 31

Lifetime CO_2 emissions of the future processes, including waste packaging and final disposal of the upstream processes.

	process	g CO_2/kWh		total CO_2, Mg	
		advanced reactor	EPR design	advanced reactor	EPR design
1	refining + conversion waste managem. + disposal	0.65	0.40	143	313
2	enrichment waste management + disposal	0.37	0.34	82	268
3	reconv. + fuel fabr. waste managem. +disposal	0.90	0.56	198	436
4	reactor OMR waste management + disposal	12.06	7.44	2641	5810
	sum waste managem.. + disp. upstream processes 1-4	14.0	8.74	3064	6827
5	depleted uranium conditioning + waste man. + disp.	5.7	5.06	1248	3952
6	decommissioning + dismantling + waste man. + disp.	40.9	13.61	8946	10626
7	spent fuel handing + final disposal	8.2	5.94	1797	4643
8	mine rehabilitation	4.8	4.22	1057	3295
	sum downstream processes 5-8	59.6	28.8	13048	22516
	sum future processes	73.6	57.6	16112	29343

Table 32

Summary lifetime CO_2 emissions of the complete nuclear process chain from cradle to grave

process		g CO_2/kWh		total CO_2, Mg	
		advanced reactor	EPR design	advanced reactor	EPR design
sum contemporary processes -	low	65.2	40.1	14265	31156
	mean	90.4	62.1	19753	48298
	high	115.5	84.0	25241	65439
sum future processes		73.6	37.5	16112	29343
total nuclear process chain from cradle to grave	low	138.8	77.6	30377	60499
	mean	164.0	99.6	35865	77641
	high	189.1	121.5	41353	94782

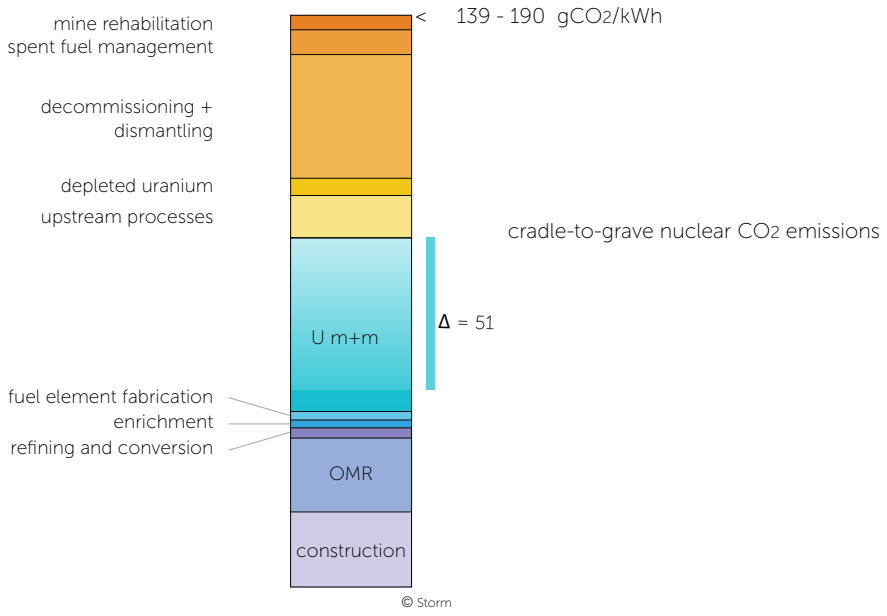

Figure 18

Lifetime CO_2 emission of nuclear power, based on the advanced reference reactor: contemporary + latent CO_2. OMR = operation, maintenance + refurbishments of the nuclear power plant. U m+m = uranium mining + milling; the large value range (Δ = 51 gCO_2/kWh) is caused by widely diverging conditions at the currently operational uranium mines.

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