Materials for nuclear power

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

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PART A Outline and results

1 Assessment outline

Nuclear energy system

The nuclear process chain, the technical system making nuclear power possible, comprises a number of industrial processes, each of which requires the input of ordered materials, such as chemicals, machines and construction materials. All materials required for construction and operation of the facilities of the nuclear system will end up in the biosphere in some form at any time.
This study bases the assessment of the specific material consumption by nuclear power (counted in grams per kilowatt-hour) on the complete nuclear process chain, from cradle to grave, introduced in report m19 *Advanced reference reactor and EPR*. Figure 1 represents the outline of the complete nuclear system. This basic assumption implies that all radioactive materials generated in the nuclear chain are isolated from the biosphere in the best possible way, as described in above mentioned reports. In practice the nuclear energy system is still unfinished, after more than 60 years development and trillions of dollars spent. The cause of this fact is not a lack of advanced technology, but a paradigm based on short-term profit seeking; this issue is addressed in report m07 *Energy debt, latent CO2 emissions, latent entropy*.

A number of crucial processes of the back end of the nuclear chain, are still existing only on paper. Nevertheless the material consumption can be estimated, for those 'missing' processes are in principle conventional industrial processes.
Detailed asessment of the contemporary processes is discussed in report m03 *Contemporary CO2 emissions of advanced nuclear power*. The future processes are addressed in report m40 *Radioactive waste management - future CO2 emissions*.

Reference reactor

Parameters of the reference nuclear power plant (NPP) this assessment is based on, for more details see report L1p01 *Reference nuclear energy system*.
The lifetime-averaged load factor assumed in this study, L = 0.82, likely is a high estimate. Due to deterioration of components of the NPP with time, such as the heat exchangers, the load factor declines during the operational lifetime. This observation implies that the lifetime energy production of the reference reactor is a high estimate.
The assumed lifetimetime consumption of natural uranium in this study, m = 5212 Mg, is a low estimate. The current generation of NPPs consume some 6000 Mg of U_{nat} during the same operational lifetime. This observation implies that the actual energy production per Mg U_{nat} is some 16% lower than the reference system, or in other words, that the material input per kWh of the currently operational NPPs is higher than calculated for the reference reactor.
The assumed operational lifetime of 25 FPY is higher than world average of about 23 FPY in 2014. This observation implies that the lifetime energy production of the currently operational NPPs is lower than calculated for the reference reactor, resulting in a lower energy production per Mg material input.

nominal power capacity P = 1 GWe
operational lifespan 30 calender years = 30 reload periods, average load factor L = 0.82
effective operational lifetime T_{100} = 30•0,82 = 24.6 full-power years (FPY)
world average 2014 T_{100} = 22-23 FPY

electricity production	1 FPY = 1 GW.a = 31.56 PJ = $8.760 \bullet 10^9$ kWh
lifetime electricity production	$E = 24.6 \bullet 8.760 \bullet 10^9 = 215.5 \bullet 10^9$ kWh (gross)
lifetime enriched uranium	m = 670 Mg including first core
zirconium	m = 1340 Mg including first core
lifetime natural uranium	m = 5212 Mg including first core
lifetime uranium process loss	m = 75 Mg
depleted uranium	$m = 5212 - 75 - 670 = 4467$ Mg
spent fuel	m = 670 Mg
gross electricity per Mg U_{nat}	$E = 215.5 \bullet 10^9$ kWh/5212 Mg = $41.35 \bullet 10^6$ kWh/Mg U_{nat}
enrichment separative work	$S = (29 \bullet 0.1467 + 0.4166) \bullet 10^6 = 4.671 \bullet 10^6$ SWU (29 reloads + 1st core)

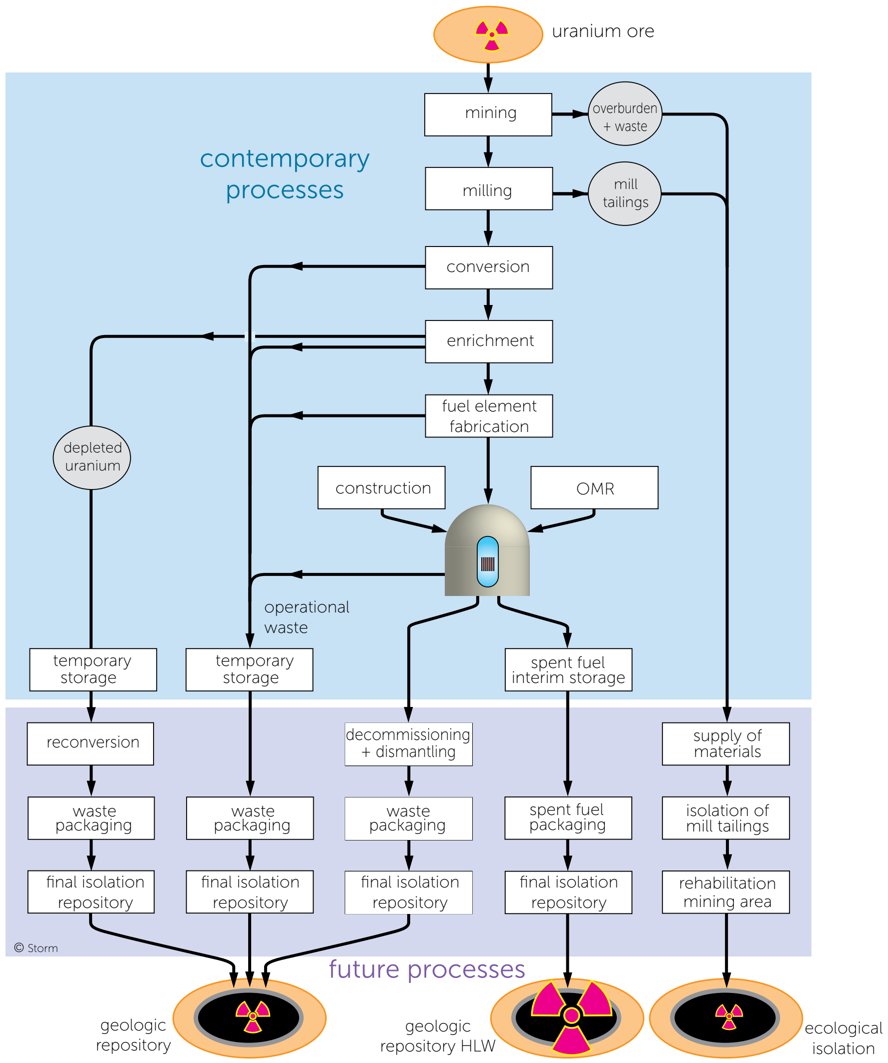

Figure 1

Full process chain of a light-water reactor (LWR) nuclear power plant in the once-through mode. Calculations in the reports on this website are based on this full chain. In practice a number of processes of the back end, including the sequestration of the wastes, are still existing only in cyberspace, despite countless discussions and publications during the past several decades.

Input of materials

Broadly, the following categories of material inputs of the nuclear system can be discerned:

- Ordered materials
  Materials that have been processed by industrial processes outside of the nuclear energy system:
  – construction materials of the nuclear power plant and other facilities of the nuclear chain: concrete, steel, other metals and non-metal materials
  – construction materials for production of the waste containers needed to pack the radioactive wastes for permanent disposal
  – ordered materials needed to perform the industrial processes of the nuclear chain: chemicals, auxiliary materials, machines, zirconium to fabricate nuclear fuel elements, etcetera.
- Fresh water
  – process water
  – cooling water
- Raw materials
  Materials needed to isolate radioactive wastes in geologic repositories from (ground)water flows and human intrusion , chiefly sand and bentonite
- Uranium ore
  The primary energy source of the system.
- Waste rock and soil
  The nuclear system displaces massive amounts of soil and rock during mining activities for uranium recovery and for construction of geologic repositories.

Output of materials

All materials entering the nuclear energy system are extracted from the environment and all materials leaving the nuclear system will end up in that same environment sooner or later.
During operation the nuclear system generates tremendous amounts of radioactivity: a billionfold of the radioactivity of the nuclear fuel which is used in the reactor. The human-made radioactivity is mainly contained in the spent fuel elements, but a part of it leaves the nuclear system dispersed over large volumes of construction materials, as a consequence of neutron irradiation and contamination with radionuclides. In addition to the generation of human-made radioactivity the nuclear system mobilises vast amounts of natural radionuclides from the uranium ore (see report m41 *Uranium mine rehabilitation*). During operation and thereafter the nuclear system discharges radioactive and non-radioactive materials into the environment, see for example m17 *Pathways of radioactive contamination*.

The material flows leaving the nuclear system can be divided into several categories:

- Recyclable materials
  – construction materials of builidings and equipment, e.g. steel and other metals, that remained free of radioactivity can reenter the economic production system after dismantling of the non-radioactive parts of nuclear installations
  – non-radioactive wastes, such as concrete rubble and non-radioactive chemical waste are here considered to be partially recyclable.
- Discharges into the biosphere
  The nuclear system unavoidably discharges radioactive and non-radioactive materials into the human environment, intentionally and unintentionally:
  – gaseous effluents into the atmoshpere
  – liquid effluents into groundwater, rivers and sea
  – solid discharges dispersed on soil and into water.

- Water
  All water flows entering the nuclear system end up in the biosphere, most of it contaminated with radionuclides
  – cooling water of primary circuit of the reactor, primary and secondary cooling water from the reactor and cooling pools are contaminated by tritium and other radionuclides which are difficult to extract
  – cooling water of secondary circuit of the reactor, cooling pools and other installations;
  – process water of uranium milling, heavily contaminated by processing chemicals, toxic non-radioactive elements and toxic radionuclides from the uranium ore.
- Materials lost forever
  – materials that became radioactive: construction materials, chemicals, equipment, etcetera; to be removed from the human environment forever by sequestration in geologic repositories
  – materials (e.g. concrete, steel, lead, copper) for construction of the waste containers
  – uranium mine mill tailings
  – bentonite and sand needed for isolation of mill tailings and for geologic repository fillup.
- Waste rock
  – rock displaced during the uranium mining activities.
  – rock excavated for construction of geologic repositories.

More details are discussed in reports m26 *Uranium mining + milling*, m41 *Uranium mine rehabilitation* and m40 *Radioactive waste management - future CO2 emissions*.

The distinction between contaminated (radioactive) and non-contaminated is arbitrary and depends on the economic situation at a given place and time, see for example reports m34 *Conflict of interests, flexibility of regulations*.

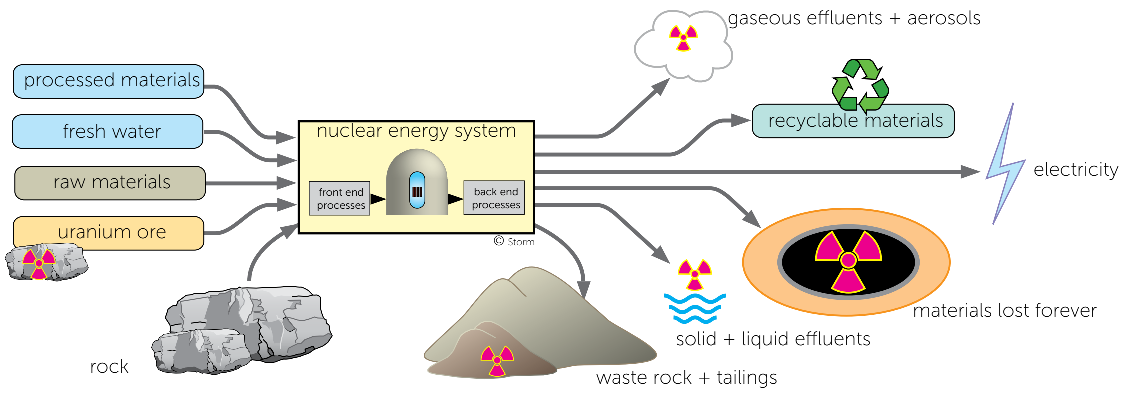

Figure 2
Outline of the flows of materials of the complete nuclear energy system as it should be from cradle to grave. All radioactive materials are assumed to be sequestered definitively in geologic repositories, except the intentional (including the complete fresh water input) and unintentional (leaks, accidents) discharges into the environment. In the current practice all radioactive waste is still present in mobile condition within the human environment.

Method

The material consumption of the processes of the nuclear chain are assessed as far as possible, using data from the open literature. Due to the secrecy of most processes estimation of many quantities of consumed and dischaged materials is hardly possible. In case of packing and definitive storage of radioactive waste estmates are based on analogue non-nuclear industrial processes
Consumption of materials other than discussed in this report are not included in this assessment,

consequently the sum of the lifetime material consumption of the nuclear system is low estimate and includes a list of unknown items. In addition various material inputs of the nuclear system are not taken into account, to make the results of this assessment comparable with the material assessment of other energy systems, i.e. renewable systems. In this report nuclear power is compared with wind power.

A basic issue in this assessment is the fact that the nuclear energy system is still unfinished. The most important processes of the back end of the chain, such as packing and definitive sequestration of spent fuel and other radioactive waste, are still not in existence, as pointed out above. However, the main part of the material input of these missing processes can be estimated with reasonable accuracy. So it is possible to estimate the cradle-to-grave material consumption of nuclear power.

The future activities, that are not included in in the material balance of the current practice, are a *conditio sine qua non* to keep vast and densily inhabited areas habitable in the future.

2 Summary of material balances

Material inputs excluded from the assessment

Not included in the material balances of this assessment are:

- Materials required for construction of the facilities of the nuclear chain, other than the nuclear power plant. So construction materials required for construction of temporary and final storage facilities of radioactive waste are not included.
- Materials required for processing the materials required for construction of the facilities of the nuclear chain. Special materials meeting very high quality standards are frequently used in nuclear installations, for example the reactor vessel.
- Transport of materials other than the raw materials transported during mining, mine rehabilitation and excavation of the repositories.
- Materials needed for construction of machines and other equipment used in the nuclear chain.
- Materials needed for maintenance and refurbishments of the nuclear power plant and other nuclear facilities.
- Materials needed for construction of waste containers and geologic repository of radioactive waste resulting from decommissioning + dismantling of nuclear intallations other than the NPP.
- Cooling water for nuclear power plant and spent fuel storage facilities.
- Materials required for construction and maintenance of the electricity distribution grid.

In addition to the above listed material inputs left out of account there are a number on unknown material inputs of the nuclear energy system, indicated by Σx in the summary tables below.

Lifetime energy production of the reference NPP

lifetime consumption of natural uranium	m = 5.212 Gg => m = 0.0242 g/kWh
lifetime electricity production	$E = 24.6 \bullet 8.760 \bullet 10^9 = 215.5 \bullet 10^9$ kWh (gross)
gross electricity per Mg U_{nat}	$E = 215.5 \bullet 10^9$ kWh/5212 Mg = $41.35 \bullet 10^6$ kWh/Mg U_{nat}

Material balance of nuclear power from cradle to grave

See chapter 12 for more details.

Table 1

Material balance of the complete nuclear system from cradle to grave

Input	Gg	g/kWh	g/kWh (rounded)
ordered materials	2449 + Σx *	11.364 + y **	12 + y
raw materials	4529	21.016	21
fresh water (mining only)	3670	17.030	17
uranium ore	5610	26.032	26
total input	16 258 + Σx	75.442 + y	76 + y
rock excavated	27 866	129.309	130

* $\Sigma x = x_1 + x_2 + \ldots x_{12}$ (unknown inputs)

** $y = \Sigma x$ Gg/$215.5 \bullet 10^9$ kWh

Output	Gg	g/kWh	g/kWh (rounded)
recyclable construction materials	982	4.557	5
ordered materials lost forever	1467 + Σ*x*	6.807	7 + y
raw materials lost forever	4529	20.993	21
contaminated fresh water (mining only)	3670	17.030	17
mill tailings, lost forever	5610	26.032	26
total output	16 260 + Σ*x*	75.454 + *y*	76 + y
waste rock	27 860	129.281	130

Material balance of nuclear power in current practice

See chapter 12 for more details.

Table 2

Material balance of the unfinished nuclear system as operating in the current practice

Input	Gg	g/kWh	g/kWh (rounded)
ordered materials	1629 + Σ*x* *	7.559 + *y* **	8 + *y*
raw materials	–	–	
fresh water (mining only)	3670	17.030	17
uranium ore	5610	26.032	26
total input	10 909 + Σ*x*	50.622 + *y*	51 + *y*
rock excavated	22 440	104.130	104

* $\Sigma x = x_1 + x_2 + \ldots x_{12}$ (unknown inputs)

** $y = \Sigma x$ Gg/215.5•10^9 kWh

Output	Gg	g/kWh	g/kWh (rounded)
recyclable construction materials	982	4.557	5
ordered materials lost forever	647 + Σ*x*	3.002	3 + y
contaminated fresh water (mining only)	3670	17.030	17
mill tailings, lost forever	5610	26.032	26
total output	10 909 + Σ*x*	54.459 + *y*	51 + y
waste rock	22 440	104.130	104

For reason of the many unknown excluded material inputs (see list above) the numerical results of this assessment are certainly too low.

3 Wind power system

Offshore windfarm

The reference offshore wind power system consists of 200 windturbines of 5 MWe nominal power capacity each.
Assumed an operational lifespan of 20 calender years and an average load factor of $L = 0.33$.
Figures of $L = 0.51$ that are also mentioned in the literature for currently installed offshore wind farms. Onshore wind farms have lower load factors, usually in the range of $L = 0.26$-0.30.

operational lifetime	$T_{100} = 20 \cdot 0.33 = 6.6$	full-power years FPY
lifetime electricity production	$E = 57.82 \cdot 10^6$	kWh per MWe power capacity *
assumed construction mass	$m = 1500$	Mg per wind turbine
specific construction mass	$m_p = 300$	Mg/MWe
specific construction material input	$m_e = 5.19$	g/kWh

* $E = 1000 \cdot 20 \cdot 0.33 \cdot 8760 = 57.82 \cdot 10^6$ kWh

Onshore windfarm

The reference onshore wind power system consists of 200 windturbines of 5 MWe nominal power capacity each.
Assumed an operational lifespan of 20 calender years and an average load factor of $L = 0.26$.

operational lifetime	$T_{100} = 20 \cdot 0.26 = 5.2$	full-power years FPY
lifetime electricity production	$E = 45.55 \cdot 10^6$	kWh per MWe power capacity
assumed construction mass	$m = 750$	Mg per wind turbine
specific construction mass	$m_p = 150$	Mg/MWe
specific construction material input	$m_e = 3.29$	g/kWh

* $E = 1000 \cdot 20 \cdot 0.26 \cdot 8760 = 45.55 \cdot 10^6$ kWh

4 Nuclear power compared with wind power

The nuclear industry likes to characterise nuclear power as a sustainable energy source. Sustainability can be approached from different viewpoints. In this report the material consumption, normalised to grams per delivered kilowatt-hour, is at issue. How does the specific material consumption of the nuclear energy system compare to that of a renewable energy system, in this case wind turbines?
Comparison of the sustainability of different energy systems is scientifically correct only if the lifetime net energy production and material consumption of the systems under consideration are compared, measured from cradle to grave. Evidently a wrong picture is created if the energy debt of the nuclear system is not taken into account, by ignoring energy and material inputs necessary in the future, and the wind power system is taken with all inputs from cradle to grave. For that reason only the complete nuclear system of Table 1 is appropiate to be compared with a reference wind power system.
Both reference systems are of the same power capacity and are based on the most advanced currently proven and operational technology.

Not included in the material balance of the reference wind power system, in common with the reference nuclear power system, are:

- materials required for mining and processing of the construction materials
- materials for the distribution grid
- materials for maintenance and refurbishments of the system.

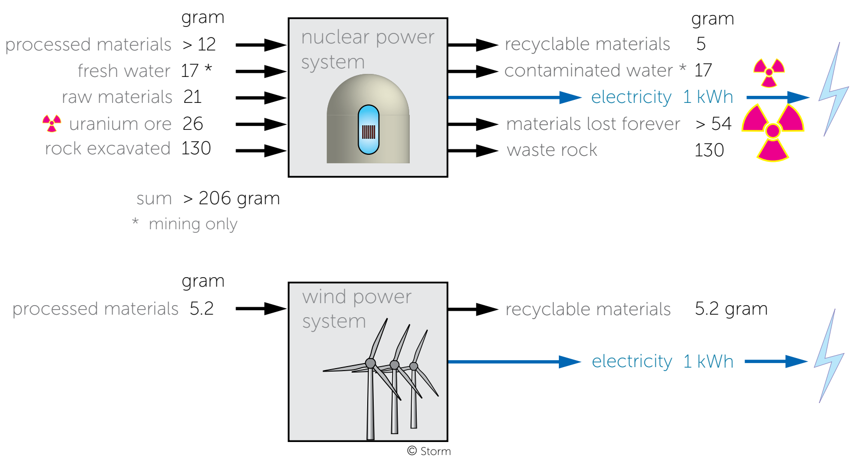

Figure 3

Material balances of a generic nuclear energy system and an offshore wind farm of current operational technology. Both systems are assessed from cradle to grave. The uranium ore feeding the nuclear system has a grade of 0.1% U.

Apart from the energy source (uranium ore) and excavated rock, the nuclear system consumes some 40 grams material per kilowatt-hour. Not all material inputs are known from the open literature, so the actual input is higher. The main part of the materials leaving the nuclear system are contaminated with human-made radionuclides and are lost forever. A significant part of those radioactive materials are discharged into the environment, for various reasons. The other part is packed and stored definitively in geologic repositories, as assumed in this study. In practice that part of the nuclear chain is still absent. Therefore above Figure 3 represents an idealised situation.
The complete water input, including cooling water of the reactor (primary and secondary cooling circuits), is discharged into the environment, contaminated with tritium and other radionuclides. As pointed out above, cooling water is not quantified in this study and is excluded from above material balances.

5 Materials consumed in the front end of the nuclear system

Uranium mining

Data on the specific material consumption are from assessment of Ranger mine, see L21p23 *Process analysis of the Ranger mine*. Assumed these figures are valid for other uranium mines as well. Probably this leads in most cases to an underestimation of the specific consumption of materials and energy, because Ranger has a relatively rich ore that is easily mineable.

diesel fuel		
density	*d* = 0.839 Mg/m3	
thermal energy content	*e*(th) = 36.0 GJ(th)/m^3 = 42.9 GJ(th)/Mg	
assume engine thermal efficiency	η = 35%	
=> mechanical energy content	*e*(mech) = 15.0 GJ(mech)/Mg	
energy consumption excavation of rock and ore	*E* = 5.84	MJ(mech)/Mg rock
energy consumption hauling of rock and ore	*E* = 1	MJ(mech)/km.Mg rock
diesel fuel for excavation of rock and ore	*m* = 0.389	kg/Mg rock
diesel fuel for hauling of rock and ore	*m* = 0.0667	kg/km.Mg rock
hauling over distance of 5 km	*m* = 0.333	kg/Mg rock
sum diesel fuel for excavating + hauling	*m* = 0.389 + 0.333 = 0.72	kg/Mg rock

diesel fuel for electricity generation for ore processing	*m* = 9.2	kg/Mg ore
explosives for blasting rock and ore	*m* = 0.25	kg/Mg rock
fresh water	*m* = 0.654	Mg/Mg ore
chemicals	*m* = 67	kg/Mg ore

Reference uranium mine: ore grade	*G* = 0.1 % U	= 1 kg U per Mg ore
recovery factor (extraction yield)	*Y* = 0.93	(high estimate)
stripping ratio (overburden ratio)	*L* = 3	
Reference reactor lifetime consumption of natural uranium	*m* = 5212 Mg	
ore to be mined and processed	*m* = 5 610 000 Mg	
waste rock (overburden)	*m* = 3•5 610 000 = 16 830 000 Mg	
total mass of rock to be blasted, excavated and hauled	*m* = 22 440 000 Mg	

Materials consumed during lifetime

explosives	*m* = 0.25 kg/Mg•22 440 000 Mg = 5610 Mg
chemicals for ore processing	*m* = 0.067•5 610 000 = 376 000 Mg
fresh water for ore processing	*m* = 0.654•5 610 000 = 3 670 000 Mg
diesel fuel for excavating and hauling	*m* = 0.72 kg/Mg•22 440 000 Mg = 16 157 Mg
diesel fuel for ore processing	*m* = 9.2 kg/Mg•5 610 000 = 51 612 Mg
diesel fuel total	*m* = 67 770 Mg = 68.8 Gg (rounded)

ND (no data)• No data are found in the open literature on the consumption of other chemicals in the extraction process, such as organic solvents, complexing agents, ion exchange charges. Figures on the consumption of auxiliary materials consumed in the mining activities, such as lubricants, tyres and spare parts, are not included either.

Conversion

Yellow cake from the uranium mill, containing $Na_2U_2O_7$ and/or $(NH_4)_2U_2O_7$, is converted into UF_6, using fluorine and/or its compounds, for instance hydrogen fluoride HF and elemental fluorine (F_2).
The stoichiometric mass ratio fluorine/uranium in the compound UF_6 is:

m(F): m(U) = 6•M(F): M(U) = 114 : 238 = 0.48 M = molar mass (g/mol)

The stoichiometric ratio implies that for conversion of each gram uranium, a minimum of 0.48 gram fluorine is needed. In practice the ratio will be significantly higher than the stoichiometric ratio, due to unavoidable losses and secondary reactions. Because the uranium hexafluoride UF_6 has to be extremely pure, the fluorine and its compounds used in the process have to be extremely pure too.

fluorine consumption

stoichiometric minimum	m = 0.48 Mg F/Mg U_{nat}
practice (assumed)	m = 0.90 Mg F/Mg U_{nat}.
lifetime F consumption	m = 5212•0.90 = 4691 Mg F

fluorine fixation

Assumed chemical reaction:	2 F + $CaCO_3$ + x —> CaF_2 + CO_2 + xx	
stoichiometric ratio	m(F) : m($CaCO_3$) = 2•M(F) : M($CaCO_3$) = 38 : 100 = 19 : 50	
in practice assume	m(F) : m($CaCO_3$) = 1 : 5	
excess fluorine consumption	m(F) = 0.42•5212 = 2189 Mg = 2200 Mg	
=> lifetime consumption	m($CaCO_3$) = 5•2189 = 10 945 Mg = 11 000 Mg rounded	
excess limestone	m($CaCO_3$) = 5473 Mg	
	V($CaCO_3$) = 2027 m^3	
stoichiometric ratio	m(CaF_2) : m(F) = M(CaF_2) : 2•M(F) = 78 : 38 = 2.053	
calcium fluoride formed	m(CaF_2) = 2.053• 2189 = 4493 Mg = 4500 Mg	
	V(CaF_2) = 1413 m^3	
densities	d(CaF_2) = 3.18 Mg/m^3	d($CaCO_3$) = 2.7 Mg/m^3

ND• No data are found in the open literature on the actual consumption of fluorine and other chemicals in the conversion process.

Enrichment

No data are available in the open literature on the consumption of chemicals and other materials in the enrichment process, either by diffusion or by ultracentrifuges. Ultracentrifuges have a relatively short lifetime, so the material input of the enrichment process per separative work unit (SWU) may be be substantial .

ND• No data are found in the open literature on the actual consumption of materials by the enrichment process.

Fuel fabrication

After enrichment the amount of UF_6 enriched in U-235, has to be reconverted into uranium oxide UO_2 suitable for use as nuclear fuel. From the uranium oxide pellets are produced, which are clad in tubes of Zircalloy, an alloy of exceedingly pure zirconium with a few percents of another metal (e.g. tin or nickel). The tubes are assembled into fuel elements also made of Zircalloy.

Reconversion of uranium hexafluoride

It is unknown in which form the fluorine released in the reconversion disposed of, likely as caliumfluoride CaF_2. This study assumes reaction with limestone $CaCO_3$:

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

$2\ UO_3 \longrightarrow 2\ UO_2 + O_2$

stoichiometric ratio	$m(UF_6) : m(CaCO_3) = M(UF_6) : 3•M(CaCO_3) = 352 : 300 = 1.173$
in practice assume	$m(UF_6) : m(CaCO_3) = 3.5 : 7 = 1 : 2$
lifetime enriched uranium	m = 670 Mg U
stoichiometric ratio	$m(UF_6) : m(U) = M(UF_6) : M(U) = 352 : 238 = 1.479$
enriched UF_6	m = 1.479•670 = 991 Mg UF_6
limestone consumption	m = 1982 Mg = 2000 Mg $CaCO_3$
excess limestone	$m(CaCO_3)$ = 1982 – (0.8523• 991) = 1982 – 845 = 1150 Mg (rounded)
	$V(CaCO_3) = 421\ m^3$
stoichiometric ratio	$m(CaF_2) : m(UF_6) = 3•M(CaF_2) : M(UF_6) = 234 : 352 = 0.6648$
calcium fluoride formed	$m(CaF_2)$ = 0.6648•991 = 659 = 660 Mg
	$V(CaF_2) = 207 = 210\ m^3$
densities	$d(CaF_2) = 3.18\ Mg/m^3$ $d(CaCO_3) = 2.7\ Mg/m^3$

ND• No data are found in the open literature on the actual consumption of chemicals by the reconversion process.

Zirconium for fuel element fabrication

lifetime zirconium consumption m = 1340 Mg

Zirconium is an integral part of the nuclear fuel elements and cannot be recycled. For that reason the chemicals and other materials needed for recovery of the zirconium from the earth's crust should be attributed to the energy source feeding the nuclear system and consequently included in the mass balance of the nuclear energy system.

About 80% of the world zirconium production is consumed by the nuclear industry. This is a one-way production flow, because Zircalloy cannot be recycled, due to the high radioactivity of the material after use in a nuclear reactor.

ND• No data are found in the open literature on the actual consumption of materials for the recovery process of zirconium from ore.

ND• No data are found in the open literature on the actual consumption of materials for fixation of excess chlorine for conversion of $ZrCl_4$ to Zr metal.

Chlorine consumption for zirconium purification

Technical-grade zirconium always contains hafnium, which has adverse effects in the core of a nuclear reactor and therefore has to be removed. Zirconium can be purified by chlorination of the metal and destillation of the resulting chlorides, to remove all traces of hafnium. The stoichiometric mass ratio chlorine/zirconium in the compound zirconium tetrachloride ZrCl4 is:

$m(Cl) : m(Zr) = 4•M(Cl) : M(Zr) = 142 : 91.2 = 1.56$

So a minimum of 1.56 grams of chlorine is consumed per gram of Zr to make ZrCl4.

To produce zirconium exceedingly pure chlorine (in any chemical form) is needed. In practice the amount of chlorine will be much larger than the stoichiometric minimum: to obtain an extremely pure product, large waste streams are unavoidable.

stoichiometric minimum	*m* = 1.56 Mg Cl/Mg Zr
practice assume	*m* = 3.0 Mg Cl/Mg Zr
lifetime Cl consumption	*m* = 1340•3 = 4020 Mg Cl

ND• No data are found in the open literature on the actual consumption of chemicals and materials by the purification of zirconium, by the production process of Zircalloy and by the other processes needed to fabricate nuclear fuel elements.

6 Construction + OMR of the nuclear power plant

During its operational lifetime a nuclear power plant consumes ordered materials for operation, maintenance and refurbishments (OMR). Many components are replaced by new ones. Most components of an NPP are replaced at the end of its operational lifetime.
Figures found in the open literature are scarce and different, see also report m39 *Construction and OMR of nuclear power plants*.

Construction
Materials excluding piping and wiring

structural steel	*m* = 55 000	Mg
reinforcing steel	*m* = 95 000	Mg
non-ferrous metals	*m* = 5000	Mg
other materials	*m* = 30 000	Mg
concrete	*m* = 850 000	Mg
sum	*m* = 1 035 000	Mg

OMR
Consumables for operating the reactor (filters, etc) amount to 4000 Mg/yr, so:
m = 30•4000 = 120 000 Mg

Fresh water
During the exchange of spent fuel for fresh fuel after each reload period large volumes of purified water, with added chemicals, are used. This study assumes a consumption of 1000 Mg per reload, so the lifetime mass of fresh water consumed is:
m = 30•1000 = 30 000 Mg

ND• No data are found in the open literature on the actual consumption of chemicals and materials needed for operation, maintenance during its operational lifetime, other than above figure.
ND• No data are found in the open literature on the actual consumption of materials for refurbishments of the nuclear power plant. At the end of its operational lifetime most components of an NPP are replaced, except the reactor vessel.
ND• No data are found in the open literature on the actual consumption of cooling water in the primary and secondary circuits of an NPP.

7 Downstream processes of the nuclear chain

Mine rehabilitation

Estimates below are based on the rehabilitation concept described in this study, see also report L21p22 *Uranium mine rehabilitation*. in practice no uranium mine in the world has ever been rehabilitated, so no empirical figures are available.

ore: assume grade G = 0.1% U and extraction yield Y = 0.93, see also under 'Mining'

ore mined and processed	$m = 5.61 \bullet 10^6$ Mg
waste rock (overburden)	$m = 16.83 \bullet 10^6$ Mg
total mass of rock displaced	$m = 22.44 \bullet 10^6$ Mg
tailings	$m = m(\text{ore}) + m(\text{chem}) = 5.610 \bullet 10^6 + 0.376 \bullet 10^6 = 6.0 \bullet 10^6$ Mg

specific consumption of immobilising chemicals

Na_3PO_4	m = 10 kg/Mg tailings
limestone $CaCO_3$	m = 20 kg/Mg tailings
bentonite	m = 50 kg/Mg tailings
diesel fuel for excavation of rock	m = 0.389 kg/Mg
diesel fuel for hauling of rock	m = 0.0667 kg/km.Mg

assume hauling distance of waste rock and tailings s = 5 km
assume transport distances from origin

bentonite	s = 1000 km
sodium phosphate	s = 1000 km
limestone	s = 100 km

lifetime consumption

Na_3PO_4	$m = 10$ kg/Mg$\bullet$ $6.0 \bullet 10^6$ Mg = $60 \bullet 10^6$ kg = 60 000 Mg
$CaCO_3$	$m = 20$ kg/Mg $\bullet 6.0 \bullet 10^6$ Mg = $120 \bullet 10^6$ kg = 120 000 Mg
bentonite	$m = 50$ kg/Mg$\bullet 6.0 \bullet 10^6$ Mg = $300 \bullet 10^6$ kg = 300 000 Mg
sum	m = 480 000 Mg

diesel fuel
hauling tailings + waste rock back into mining pit or mining galleries

	$m = 0.389$ kg/Mg $\bullet 22.44 \bullet 10^6$ Mg = $16.159 \bullet 10^6$ kg = 16 160 Mg
transport sodium phosphate	m = 0.0667 kg/km.Mg •1000 km•60 000 Mg = 4002 Mg
transport limestone	m = 0.0667 kg/km.Mg •100 km•120 000 Mg = 800 Mg
transport sodium phosphate	m = 0.0667 kg/km.Mg •1000 km•300 000 Mg = 20 010 Mg
sum	m = 41 000 Mg (rounded)

Decommissioning + dismantling of the nuclear power plant

See report m04 *Decommissioning and dismantling*.

decontamination waste	$V = 5000$ m^3, $d = 1.5$ Mg/m^3 =>
	m = 7500 Mg
steel	m = 800
stainless steel	m = 800
reinforcing steel	m = 10 000

non-ferrous metals	*m* = 500
other materials	*m* = 3000
concrete	*m* = 30 000
sum	*m* = 52 600 Mg lost forever

These materials are radioactive by neutron radiation and or by contamination with radioactive materials. The debris and scrap contain an assortment of long-lived radionuclides and are to be packed in appropiate containers and isolated from the biosphere forever.

ND• No data are found in the open literature on the actual consumption of chemicals and materials needed during the Safestore period of a nuclear power plant, that is the cooling period between the final shutdown of the NPP and the start of the decommissioning and dismantling activities. This period is estimated to take minimal 30 years, but likely 60 years or longer.

ND• No data are found in the open literature on the actual consumption of chemicals and materials needed for decommissioning and dismantling and for cleaunup of the site.

Interim storage of spent fuel

After removal from the reactor spent fuel elements are cooled in cooling pools during many years, to prevent melting as a result of the residual heat these elements generate. A minor part of spent fuel elements are stored in dry casks after about ten years in cooling pools. Interim storage of spent fuel may cover a period of many decades. Even if spent fuel is reprocessed, a cooling period of 10-30 years (depending on the burnup of the fuel) is needed before reprocressing is possible.

Both options, cooling pools and dry casks, are not included in this assessment, due to lack of data.

ND• No data are found in the open literature on the actual consumption of construction materials, chemicals and materials needed (water, chemicals, filters, etcetera) needed to construct, maintain and safely operate cooling pools during decades of storage.

ND• No data are found in the open literature on the actual consumption of construction materials, chemicals and materials needed to construct, maintain and safely operate dry casks during decades of storage.

Interim storage of other radioactive wastes

In addition to spent fuel the nuclear energy system generates massive amounts of radioactive waste that does not generate heat, due to a lower content of radionuclides than spent fuel, see for example report m12 *Human-made radioactivity*. In the current practice these wastes are packed in containers and stored in temporary storage facilities, although a significant part of the radioactive waste is discharged into the environment, intentionally or unintentionally; see report m17 *Pathways of radioactive contamination*.

The assessment in this study is based on the view that all radioactive waste should be packed in appropiate containers and permanently stored in geologic repositories, see reports m40 *Radioactive waste management - future CO2 emissions* and m32 *Geologic repositories and wasteconditioning*. Mining waste has to be treated in a separate way, see report m41 *Uranium mine rehabilitation*.

ND• No data are found in the open literature on the actual consumption of materials needed to construct and maintain the currently used temporary storage facilites of non-heat-generating radioactive waste.

Reconversion depleted UF_6

in the enrichment process natural uranium, in the form of the volatile compound UF_6, is separated into a fraction enriched in the fissile U-235 isotope and a much larger fraction depleted of U-235.
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 reports 15 *Plutonium recycling in LWRs* and m01 *Uranium-plutonium breeder systems*. Based on 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.

Conversion assumed by reaction with limestone $CaCO_3$

$$UF_6 + 3\,CaCO_3 \longrightarrow UO_3 + 3\,CaF_2 + 3\,CO_2$$

$$3\,UO_3 \longrightarrow U_3O_8 + 1/2\,O_2$$

stoichiometric mass ratio: $m(UF_6) : m(CaCO_3) = M(UF_6) : 3\bullet M(CaCO_3) = 352 : 300 = 1.173$
in practice assume $m(UF_6) : m(CaCO_3) = 3.5 : 7 = 1 : 2$

depleted uranium $m = 4467$ Mg U
depleted UF_6 $m = 352/238\bullet 4467 = 6607 = 6600$ Mg UF_6
lime consumption $m = 2\bullet 6607 = 13414 = 13\,500$ Mg $CaCO_3$

excess limestone $m(CaCO_3) = 13414 - (6607/1.173) = 13414 - 5633 = 7781$ Mg
$V(CaCO_3) = 2882\ m^3$
stoichiometric ratio $m(CaF_2) : m(UF_6) = 3\bullet M(CaF_2) : M(UF_6) = 234 : 352 = 0.6648$
calcium fluoride formed $m(CaF_2) = 0.6648\bullet 6607 = 4392$ Mg
$V(CaF_2) = 1381\ m^3$
densities $d(CaF_2) = 3.18\ Mg/m^3$
$d(CaCO_3) = 2.7\ Mg/m^3$

ND• 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.

8 Containers for radioactive waste

This study assumes that all radioactive waste originating from the nuclear process chain will be packed in appropiate containers. The four types of waste containers for permanet disposal are shown in Figure 4. The dimensions, materials, masses and specific applications of these containers are addressed in the following tables.

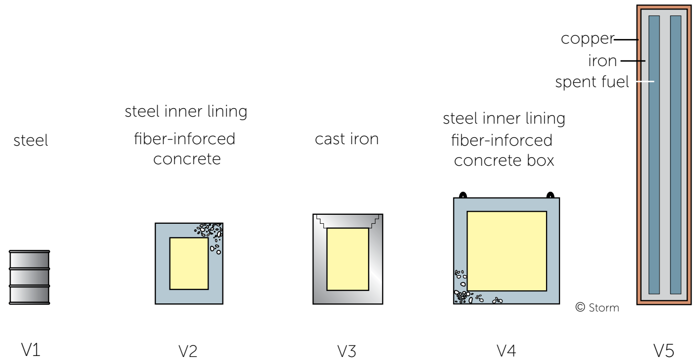

Figure 4
Containers for all categories of radioactive waste, used as reference in this study. Container V1, not much more than a common oil barrel, is not suitable for permamanent disposal and should be used only for temporary storage of very low-level radioactive waste. Container V5 is specificly designed for permanent storage of spent fuel elements.

Table 3
Dimensions and mass of the waste containers used as reference in this study for the packaging of the dismantling waste.

type	diameter m	height m	wall thickness m	external volume m^3	capacity m^3	mass concrete Mg	mass steel Mg	mass empty Mg
V2	1.02	1.22	0.20	1.00	0.25	1.80	0.035	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	0.82	5.50	0.12 *	2.90	-	-		19.35

Table 4
Characteristics of the waste containers used as reference in this study for the packaging of the dismantling waste.

container type	waste type	displacd volume m^3	capacity m^3	mass empty Mg	mass loaded* Mg	energy input GJ	remarks
V2	LLW + ILWα	1.00	0.25	1.84	2.4	146	
V3	HLW + α	1.18	0.29	6.46	8.0	517	German Type II
V4	LLW + ILW	4.10	1.73	5.82	14.7	465	not for alpha waste
V5	spent fuel	2.90	-	19.35	25.35	4000	SKB-3

* 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.

Wall thickness 10 cm Cu ultrapue, 2 cm steel, stainless steel or Ti, filled with Pb

copper	m = 11.65 Mg	V(Cu) = 1.30 m^3
steel	m = 1.68 Mg	V(steel) = 0.21 m^3
lead	m = 6.02 Mg	V(Pb) = 1.39 – V(fuel) = 0.96 m^3
nuclear fuel	m = 2.0 Mg HM + 4.0 Mg Zr	V(fuel) = 0.43 m^3

waste container V2

concrete	m = 1.80 Mg
steel	m = 0.04 Mg
total mass empty	m = 1.84 Mg
mass loaded	m = 2.4 Mg
capacity	V = 0.25 m^3
displaced volume	V = 1.00 m^3

9 Packing the wastes of the nuclear chain

Radioactive wastes from the front end processes are relatively low-level, but contain long-lived alpha-emitters. Assumed these wastes are packed in V2 containers.
Volumes and masses of the operational wastes of the front end and of the reconversion of depleted uranium hexafluoride are summarised in Table 5.

Conversion

Official figure of operational waste generation of the conversion process:

$V = 54$ m^3/GWe.a

=› lifetime waste $V = 30 \bullet 0.82 \bullet 54 = 1329$ m^3

Unknown is if this amount includes the volume of the calcium fluoride waste product of the fixation of excess fluorine used in the conversion process, in chapter 2 estimated at: $V = 1342$ m^3. As no data are available on the actual amounts of radioactive waste generated in the conversion process, this study estimates the lifetime waste volume at $V = 1413$ m^3, to be packed in waste containers type V2

number	$N = 1413/0.25 = 5652$	
displaced volume	$V = 5652 \bullet 1.00 = 5652$ m^3	
total mass	$m = 5652 \bullet 2.4 = 13\,565$ Mg	
construction mass	$m = 5652 \bullet 1.84 = 10\,400$ Mg	(steel+concrete)

Enrichment

Official figures of the waste generation of the enrichment process are:

diffusion	$V = 59$ m^3/MSWU	(million SWU)
ultracentrifuge (UC)	$V = 230$ m^3/MSWU	

This study assumes a ratio diffusion : ultracentrifuge = 3 : 7

=› specific waste	$V = 0.3 \bullet 59 + 0.7 \bullet 230 = 17.7 + 161 = 179$ m^3/MSWU	
lifetime separative work	$S = 4.671 \bullet 10^6$ SWU = 4.671 MSWU	
=› waste	$V = 4.671 \bullet 179 = 836$ m^3	
waste containers V2		
number	$N = 836/0.25 = 3344$	
displaced volume	$V = 3344 \bullet 1.00 = 3344$ m^3	
total mass	$m = 3344 \bullet 2.4 = 8026$ Mg	
construction mass	$m = 3344 \bullet 1.84 = 6253$ Mg	(steel+concrete)
waste mass	$\Delta m = 8026 - 6253 = 1773$ Mg	

As pointed out above, no data are found in the open literature on the actual consumption and composition of the materials by the enrichment process.

Reconversion and fuel fabrication

Official figure of operational waste generation of the reconversion and fuel fabrication process:

$V = 75$ m^3/GWe.a

=› lifetime waste $V = 30 \bullet 0.82 \bullet 75 = 1845$ m^3

Probably this figure includes the amount of vontaminated calcium fluoride from the reconversion:

$V(CaF_2) = 207\ m^3$

Waste assumed to be packed in containers V2

number $N = 1845/0.25 = 7380$

displaced volume $V = 7380 \bullet 1.00 = 7380\ m^3$

total mass $m = 7380 \bullet 2.4 = 17\ 712$ Mg

mass (steel+concrete) $m = 7380 \bullet 1.84 = 13\ 580$ Mg

Reactor consumables

assume 1000 m^3/GWe.a radioactive waste, remainder of consumables non-radioactive

lifetime waste $V = 30 \bullet 0.82 \bullet 1000 = 24\ 600\ m^3$

waste container V2

number $N = 24\ 600/0.25 = 98\ 400$

displaced volume $V = 98\ 400 \bullet 1.00 = 98\ 400\ m^3$

total mass $m = 98\ 400 \bullet 2.4 = 236160$ Mg

mass (steel+concrete) $m = 98\ 400 \bullet 1.84 = 181056 = 181\ 000$ Mg

Depleted uranium

U_{depl} —> UF_6 —> U_3O_8 $M(U_3O_8) = 842$ g/mol

$m(U) : m(U_3O_8) = M(U) : 1/3 \bullet M(U_3O_8) = 238 : 281$

lifetime depleted uranium $m = 4467$ Mg U =>

uranium oxide $m = 281/238 \bullet 4467 = 5274$ Mg U_3O_8 $d = 11\ Mg/m^3$

$V = 5274/11 = 480\ m^3$

waste containers V2 for packing depleted uranium oxide

number $N = 480/0.25 = 1920$

displaced volume $V = 1920 \bullet 1.00 = 1920\ m^3$

total mass $m = 1920 \bullet 2.4 = 4608$ Mg

construction materials $m = 1920 \bullet 1.84 = 3533$ Mg (steel+concrete)

chemical waste contaminated with U compounds

remaining $CaCO_3$ $m = 1/2 \bullet 13414 = 6707$ Mg $d = 2.71\ Mg/m^3$

$V = 6707/2.71 = 2475\ m^3$

converted CaCO3 $m = 1/2 \bullet 13414 = 6707$ Mg =>

formed CaF_2 $m = M(CaF_2)/M(CaCO_3) \bullet 6707$ Mg =

$m = 78/100 \bullet 6707 = 5232$ Mg $d = 3.18\ Mg/m^3$

$V = 5232/3.18 = 1645\ m^3$

waste container V2 for packing contaninated chemical waste

number $N = (2475 + 1645)/0.25 = 16480$

displaced volume $V = 16480 \bullet 1.00 = 16480\ m^3$

total mass $m = 16480 \bullet 2.4 = 39552$ Mg

mass (steel+concrete) $m = 16480 \bullet 1.84 = 30323$ Mg

Summary, total waste container V2

number $N = 1920 + 16480 = 18\ 400$

displaced volume $V = 1920 + 16480 = 18\ 400\ m^3$
total mass $m = 18400 \cdot 2.4 = 44\ 160$ Mg
mass (steel+concrete) $m = 18400 \cdot 1.84 = 33\ 856$ Mg = 33.9 Gg

Table 5
Containers V2 for front end wastes and depleted uranium: numbers, displaced volume and masses

process	number of containers	displaced volume m^3	total loaded mass Mg	construction steel +concr. Mg
conversion	5652	5652	13 565	10 400
enrichment	3344	3344	8026	6253
reconversion + fuel fabrication	7380	7380	17 712	13 580
reactor omr	98 400	98 400	236 160	181 056
reconversion and packing depleted U	18 400	18 400	44 160	33 856
sum	133 176	133 176	319 623	245 145

Mass of contents $\Delta m = 319623 - 245145 = 74\ 478$ Mg

Dismantling waste

This assessment assumes that all radioactive dismantling waste is packed in containers which are permanently stored in a geologic repository. No large commercial nuclear power station has been completely dismantled and it is unclear how the nuclear industry will manage the dismantling waste. This assessment is based on the scarce data found in the open literature.

Table 6
Categories of dismantling waste, numbers and types of containers needed

material	mass waste Mg	volume waste m^3	waste class *	type contnr	capacity ** m^3	number contnrs	displaced volume m^3
decontamination	7500	5000	HLW	V3	0.29	17241	20335
steel	800	101	HLW	V3	0.29	348	411
stainless steel	800	101	HLW	V3	0.29	348	411
steel	10000	1266	LLW	V4	1.73	732	3001
non-ferrous metals	500	80	LLW	V4	1.73	46	189
concrete	30000	12500	LLW	V4	1.73	7226	29627
other	3000	3000	LLW	V4	1.73	1734	7110
sum	52600	22048				27675	61084

* Assumed
** Assumed fill fraction = 1

The totals of volume and mass of packaging the dismantling waste of the reference nuclear power plant are listed in Table 7.

Table 7

Containers for dismantling wastes: numbers, displaced volume and masses

container type	number of containers (rounded)	displaced volume m^3	total empty mass Mg	total loaded mass Mg
V3	18000	21240	116 280	125 380
V4	9800	40180	57 036	100 536
sum	27800	61420	173 316	225 916

Mass of contents Δm = 225 916 – 173 316 = 52 600 Mg

Spent fuel

lifetime mass spent fuel m = 670 Mg U
zirconium cladding m = 1340 Mg Zr
sum m = 2010 Mg
waste container V5, 2 Mg HM per V5 =>
number of V5 N = 670/2 = 335
total loaded mass m = 335•25.35 = 8492 Mg
total empty mass m = 335•19.35 = 6482 Mg (Cu + Fe + Pb)
displaced volume V = 335•2.90 = 972 m^3

Summary waste packaging

sum construction mass containers m = 245 145 + 173 316 + 6482 Mg = 424 943 Mg = 425 Gg
sum displaced volume containers V = 133 176 + 61420 + 972 m^3 = 195568 m^3
sum waste mass in containers m = 74 478 + 52 600 + 2010 = 129 088 Mg = 129 Gg

10 Geologic repositories

Details are addressed in report m32 *Geologic repositories and waste conditioning*.

densities (Handbook of Chem & Physics)

limestone	d = 2.7	Mg/m^3
sandstone	d = 2.3	
granite	d = 2.76	
clay	d = 2.3	
assume average rock	d = 2.5	
sand	d = 2.5	
bentonite	d = 2.3	

construction of repositories

diesel fuel for excavation of rock	m = 0.389	kg/Mg
diesel fuel for hauling of rock	m = 0.0667	kg/km.Mg
explosives for blasting rock	m = 0.25	kg/Mg rock

bentonite/sand mixture backfill, assume 50% bentonite + 50% sand by volume

assume hauling distance of waste rock from repositories	s = 20 km
assume transport distance of bentonite from its mine	s = 1000 km
assume transport distance of sand from its mine	s = 100 km

Spent fuel repository

Swedish SKB-3 concept. Details are addressed in report m32 *Geologic repositories and waste conditioning*.

rock to be removed $V = 830\ m^3$ rock/Mg spent fuel,
m = 830•2.76 = 2290 Mg rock/Mg spent fuel

total rock removed: $V = 830•670 = 556\ 100 = 556\ 000\ m^3$ rounded
m = 2290•670 = 1 534 300 Mg =1 534 000 rounded
backfill $V = 556\ 100 – 972 = 556\ 000\ m^3$
(ignore volume of V5 containers: figures are rough estimates)

sand	$V = 278000\ m^3$
	m = 278000•2.5 = 695 000 Mg
bentonite	$V = 268000\ m^3$
	m = 278000•2.3 = 640 000 Mg
sum	m = 1 335 000 Mg

explosives m = 1 534 000 Mg•0.25 kg/Mg = 384 Mg = 390 Mg rounded
diesel fuel (rounded figures)

excavating	m = 1 534 000 Mg•0.389 kg/Mg = 597 Mg = 600 Mg
hauling rock	m = 1 534 000 Mg•20 km•0.0667 kg/km.Mg = 2046 Mg = 2050 Mg
transport bentonite	m = 640 000 Mg•1000 km•0.0667 kg/km.Mg = 42 700 Mg
transport sand	m = 695 000 Mg•100 km•0.0667 kg/km.Mg =4640 Mg
total diesel	m =49 990 Mg = 50.0 Gg

Repository of other radioactive waste

Swedish SFR concept (see report L23p32 *Isolation of radioactive waste from the biosphere*)
bentonite/sand mixture backfill, assume 50% bentonite by volume.
rock to be removed

V = 7.17 m^3 rock/m^3 waste
m = 7.17•2.76 = 19.79 Mg rock/m^3 waste
rounded: V = 7.2 m^3 rock/m^3 waste
m = 20 Mg rock/m^3 waste

displaced volume V2 + V3 + V4 containers

V2 front end + depleted uranium	V = 133 176 m^3	(Table 5)
V3 + V4 dismantling	V = 61 420 m^3	(Table 7)
sum	V = 194 596 m^3	

total rock removed V = 194 596•7.2 = 1 401 091 m^3 = 1 401 000 m^3 rounded
m = 194 596•20 = 3 891 920 Mg = 3 892 Gg rounded

backfill V = 1 401 000 – 194 596 = 1 206 404 m^3
sand V = 603 202 m^3
m =603 202•2.5 = 1 508 005 Mg
bentonite V = 603 202 m^3
m = 603 202•2.3 = 1 387 365 Mg
sum m = 2 895 370 Mg

explosives m = 3 892 000 Mg•0.25 kg/Mg = 973 Mg
diesel fuel
excavating m = 3 892 000 Mg•0.389 kg/Mg =1514 Mg
hauling rock m = 3 892 000 Mg•20 km•0.0667 kg/km.Mg = 5192 Mg
transport bentonite m = 1 387 365 Mg•1000 km•0.0667 kg/km.Mg = 92 537 Mg
transport sand m = 1 508 005 Mg•100 km•0.0667 kg/km.Mg = 10 058 Mg
total diesel m = 109 301 Mg

Sum waste repositories

rock removed V = 556 000 + 1 401 000 = 1 957000 m^3
m = 1534 + 3892 Gg = 5 426 Gg
backfill V = 556 000 + 1 206 000 = 1 762 000 m^3
backfill sand V = 0.5• 1 760 000 = 881 000 m^3
m = 880 000•2.5 = 2 203 Gg
bentonite V = 881 000 m^3
m = 881 000•2.3 = 2 026 Gg
sum mass backfill m = 4 229 Gg

explosives m = 390 + 973 = 1363 Mg
diesel fuel m = 50.0 + 109.3 = 159.3 Gg

11 Summary of material consumption of the nuclear chain

Processes of the nuclear chain

Figures in gigagram Gg

Mining			
diesel fuel	67.8 Gg		
fresh water	3670		
explosives	5.61		
chemicals	376	H_2SO_4, $CaCO_3$	
rock moved	22 440		
of which ore	5610		
uranium produced	5.212		
ND other chemicals, auxiliary materials			x1
Conversion			
fluorine	4.700		
limestone	11.0		
ND actual consumption, other chemicals			x2
fuel fabrication			
reconversion			
limestone	2.00		
ND actual cons , other chemicals			x3
fabrication			
zirconium	1.340		
chlorine	4.020		
ND chemicals recovery Zr from ore			x4
ND chem purification Zr, production Zircalloy, fabrication fuel elements			x5
ND chem for fixation chlorine			x6
Construction NPP + omr			
construct materials	1035 Gg		
omr	120		
ND materials maintenance + refurbishments			x7
Mine rehabilitation			
sodium phosphate	60		
limestone	120		
bentonite	300		
diesel fuel	41		
sum	521		
rock moved	22 440		
decommissioning + dismantling			
decontamination waste	7.50		
materials lost forever	52.6		
ND consumables, aux materials decom + dismantling			x8

ND idem, during safestore period	x9

Interim storage spent fuel
during decades of storage

ND construct mat, chem., aux mat. cooling pools	x10
ND idem dry casks	x11

Interim storage other radioactive waste

ND construct mat, chem., aux mat.	x12

reconversion depleted UF6

(depleted UF6	6.60)
limestone	13.5

construction waste containers

	construction materials (Mg)	displaced volume (m^3)	type
front end + depleted U	245 145	133 176	V2
dismantling	173 316	61420	V3 + V4
spent fuel	6.482	972	V5
sum	424 943 Mg = 425 Gg	195568 = $196 \cdot 10^3$ m^3	

sum waste mass in containers $m = 74\,478 + 52\,600 + 2010 = 129\,088$ Mg = 129 Gg

Geologic repositories

Summary of figures of the spent fuel repository (first number) and the repository for other radioavtive wastes (second number).

rock removed	$V = 556\,000 + 1\,401\,000 = 1\,957000$ m^3
	$m = 1534 + 3892$ Gg = 5 426 Gg
backfill	$V = 556\,000 + 1\,206\,000 = 1\,762\,000$ m^3
backfill sand	$V = 0.5 \cdot 1\,760\,000 = 881\,000$ m^3
	$m = 880\,000 \cdot 2.5 = 2\,203$ Gg
bentonite	$V = 881\,000$ m^3
	$m = 881\,000 \cdot 2.3 = 2\,026$ Gg
sum mass backfill	$m = 4\,229$ Gg
explosives	$m = 390 + 973 = 1363$ Mg
diesel fuel	$m = 50.0 + 109.3 = 159.3$ Gg

12 Material balances

Material balance of the nuclear system from cradle to grave

Input of materials (Gg)	
zirconium	1.340
explosives, mining + repositories	5.610 + 1.363 = 7.0
chemicals + auxiliary materials:	
mining	376
conversion	15.7
fuel fabrication	6.1
reactor consumables	120
mine rehabilitation	180
reconversion depleted UF6	13.5
sum chemicals + auxiliary materials	719.64 = 720 + unknowns Σx = x1 —> x12
diesel (only mining + mine rehab. + repositories)	68.8 + 41.0 + 159.3 = 269
sum ordered materials excl. construct. materials	988.64 = 989 + Σx
construction materials, NPP + waste containers	1035 + 425 = 1460
sum ordered materials incl. construct. materials	2449 + Σx
backfill bentonite, mine rehab + repositories	300 + 2026 = 2326
backfill sand	2203
sum raw materials	4529
uranium ore	5610
fresh water (mining only)	3670
sum input of materials	16 258 + Σx
rock excavated for mining + repositories	22 440 + 5426 = 27 866
rock moved back into place	22 440
Output of materials (Gg)	
recyclable materials, construction NPP	1035 – 53 = 982
construction materials, reactor + waste containers	53 + 425 = 478
chemicals + auxiliary materials	989 + Σx
ordered materials lost forever (contruct+ chem)	1467 + Σx
uranium mill tailings	5610
raw materials	4529
sum materials lost forever	12 588
fresh water (mining only), irreversibly contaminated	3670
sum output of materials	16 258 + Σx
waste rock excavated	27 866

recyclable materials + materials lost forever m = 982 + 1467 = 2449 Gg

Material balance of the incomplete nuclear system of the current practice

Input of materials (Gg)

zirconium	1.340
explosives, mining + repositories	5.610
chemicals + auxiliary materials:	
mining	376
conversion	15.7
fuel fabrication	6.1
reactor consumables	120
mine rehabilitation	–
reconversion depleted UF6	–
sum chemicals + auxiliary materials	524.75 + unknowns $\Sigma x = x1 \rightarrow x12$
diesel, mining only	68.8
sum ordered materials excl. construct. materials	593.55 + Σx
construction materials, NPP	1035
sum ordered materials incl. construct. materials	1629 + Σx
backfill bentonite, mine rehab + repositories	–
backfill sand	–
sum raw materials	–
uranium ore	5610
fresh water (mining only)	3670
sum input of materials	10 909 + Σx
rock excavated for mining + repositories	22 440
rock moved back into place	–

Output of materials (Gg)

recyclable materials, construction NPP	1035 – 53 = 982
construction materials, reactor + waste containers	53
chemicals + auxiliary materials	594 + Σx
ordered materials lost forever (contruct. + chem)	647
uranium mill tailings	5610
raw materials	–
sum materials lost forever	6257
fresh water (mining only), irreversibly contaminated	3670
sum output of materials	10 909 + Σx
waste rock	22 440

recyclable materials + materials lost forever m = 982 + 647 = 1629 Gg