

Uranium mine rehabilitation

Jan Willem Storm van Leeuwen
Independent consultant

member of the Nuclear Consulting Group

August 2019
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.

Contents

- 1 Uranium mill tailings and health hazards
 - Mining dust and groundwater contamination
 - Radioactive elements in the mining waste
 - Thorium
 - Hazards of radioactive mill tailings
 - Need for rehabilitation
- 2 Concept of mine rehabilitation
 - Immobilisation and isolation
- 3 Auxiliary materials for mine rehabilitation: process analysis
 - Process outline
 - Limestone
 - Sodium phosphate Na_3PO_4
 - Bentonite
- 4 Energy consumption of mine rehabilitation: process analysis
 - Mining and milling of uranium
 - General data
 - Sodium phosphate
 - Limestone
 - Bentonite
- 5 Summary of specific energy input and CO_2 emission

References

TABLES

- | | |
|---------|--|
| Table 1 | Summary embodied energy of auxiliary materials |
| Table 2 | Summary specific energy consumption and CO_2 emission |

FIGURES

- | | |
|----------|---|
| Figure 1 | Satellite photo Rössing mine in Namibia |
| Figure 2 | Satellite photo sandstorm from Sahara over Atlantic |
| Figure 3 | Uranium content and radioactivity |
| Figure 4 | Radioactivity of tailings vs time |
| Figure 5 | Outline of uranium mining and rehabilitation |
| Figure 6 | Mass flows of mining and milling process |
| Figure 7 | Model of mine rehabilitation |
| Figure 8 | Size distribution of known uranium resources |

1 Uranium mill tailings and health hazards

Mining dust and groundwater contamination

Mining and milling operations disturb the geological formations that retain naturally occurring radioisotopes, and allow public exposure. In no way uranium ore itself can be considered to be a harmless substance. Uranium mining is rendering vast areas inhabitable, due to wind blown radioactive dust and pollution of groundwater by radioactive elements and other toxic non-radioactive chemical species.



Figure 1

Satellite photograph of the Rossing uranium mine in Namibia. The mining pit and the waste rock piles are visible in the center. The mill tailings ponds covering an area of some 4 km², are visible on top left. This photograph covers an area of more than 60 km². Source Google Maps.

In addition to the direct disruption of the landscape and ecosystems, the uranium mining poses health risks by the large heaps of often weakly radioactive waste rock in the open air and particularly by the mill tailings. The mill tailings are stored in large basins in which the slurry of the processed ore and the used chemicals are being dumped. The liquids are allowed to evaporate from the slurry and to seep into the ground. Sometimes the dam of a tailings pond fails and millions of cubic meters contaminated water and slurry escapes into the environment.

At the uranium mine the metal is extracted from its ore by physical and chemical separation processes. The decay products of uranium in the ore, most of which are dangerous alpha and gamma emitters, remain in the tailings (waste stream) of the extraction process. The mill tailings have the appearance of a watery mud and consist of the ore powder, chemicals and large volumes of water. The radioactive mud, often tens of millions of tonnes at a single mine, is stored in large ponds.

A part of the water from the mud evaporates during storage and the other part, including the dissolved radionuclides, drains into the ground. When the mill tailings go dry, the remaining fine powder can be easily spread by the wind. This situation occurs when one pond is filled up and a new one is taken into operation

and after the mine has been mined out and is abandoned.

Satellite photo's show dust from the Sahara desert crossing the Atlantic Ocean under certain conditions. An indication how far dust, and so radioactive dust, can be transported by the wind.

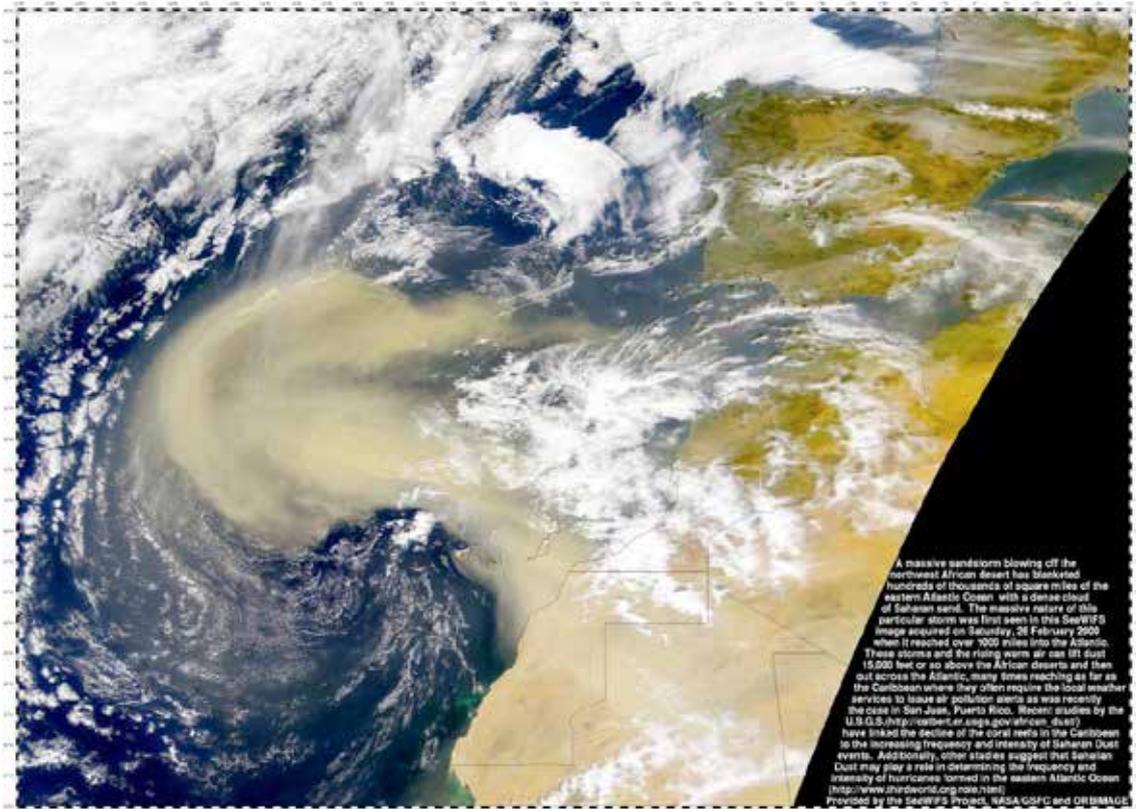


Figure 2

Dust storm from the Sahara into the Atlantic. A massive sandstorm blowing off the Northwest African desert has blanketed hundreds of thousands square kilometers of the Eastern Atlantic Ocean with a dense cloud of Saharan sand. This photo shows how far dust from arid areas, including radioactive dust from uranium mines, can be transported by the wind. Photo SeaWiFS/NASA.

Radioactive elements in the mining waste

Uranium is a radioactive element. Firstly that means that uranium and its chemical compounds emit nuclear radiation.

Secondly it means that uranium atoms spontaneously decay into other atoms; this decay is coupled to the emission of alpha and gamma radiation. The atoms resulting from the radioactive decay, called decay daughters or decay products, are also radioactive and decay into yet other elements. The decay chain of uranium-238 ends with the formation of the stable lead-206 isotope. So a series of radioactive isotopes of a number of elements comes into being.

As a result of this phenomenon uranium minerals contain, apart from U-238 and U-235, also a number of other radionuclides, for example, radium, radon, radioactive lead and polonium. All these radionuclides are highly dangerous when inhaled or ingested: the lethal dose of polonium-210 is just 50 nanograms.

The mixture emits all kinds of nuclear radiation: alpha, beta and gamma radiation. Due to the secular equilibrium of the radioactive decay in the mineral the activity of each of the components of the decay

series is the same. Because the half-lives of the radionuclides are different, the masses of nuclides present are different: the shorter half-life the lower mass.

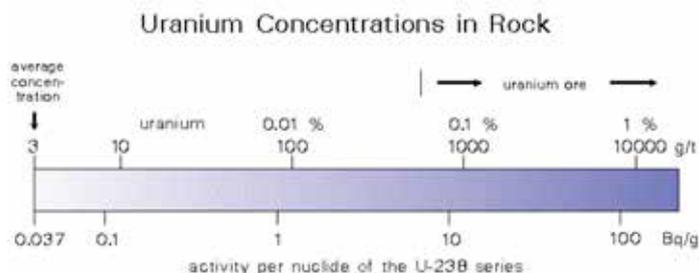


Figure 3

Relationship between the uranium content in rock and the radioactivity of the rock. Each radionuclide of the decay series contributes the same amount of the radioactivity to the total activity of the mineral. Source: Diehl 2011 [Q618].

During processing of the ore to extract uranium, all decay its products are discarded into the waste stream: the mill tailings. Unavoidably a part of the uranium remains also in the waste stream, because separation processes never go to completion. As a consequence the tailings are nearly as radioactive as the original ore minerals. This implies that the radioactivity of mill tailings may be ten to hundred times as high as the host rock from which the uranium minerals were separated.

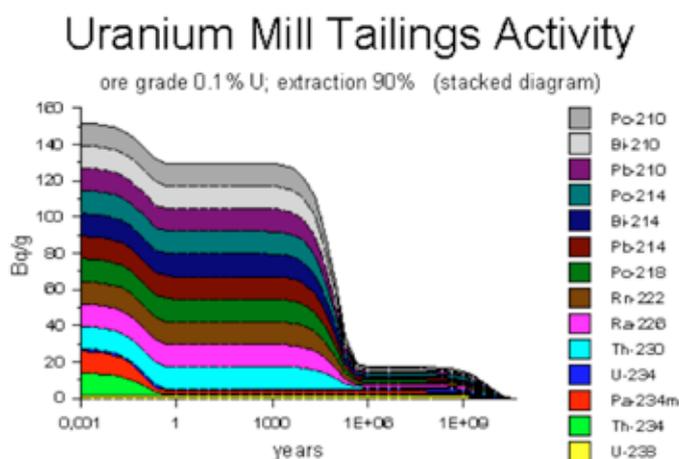


Figure 4

Radioactivity of mill tailings, with the contributions of the whole decay series. Source: Diehl 2011 [Q618].

Thorium

Many types of uranium ore contain also thorium, a radioactive element like uranium. In addition to the decay daughters of uranium, such an ore contains the decay series of thorium. During processing of the ore to extract uranium, all decay its products and thorium plus its decay products are discarded into the waste stream: the mill tailings. As a consequence the tailings are nearly as radioactive as the original ore minerals.

Human health effects from breaching thorium, short-term exposure as well as long-term exposure are not known, according to EPA 1990 [Q616]:

“... we know very little about specific exposure levels of thorium that result in harmful effects in people or animals. High levels of exposure have been shown to cause death in animals, but no direct cause of

death could be determined and no other health effects have been reported.”

According to PSR-IEER 2009 [Q617] the radiotoxicity of thorium and its decay products is far higher than of uranium and its decay products with the same radioactivity. The bone surface dose from breathing a given mass of insoluble thorium is about 200 times that of breathing the same mass of uranium.

Hazards of radioactive mill tailings

Apart from the remaining uranium (U-238, U-235, U-234) the mill tailings contain the uranium decay daughters, such as: Th-230, Ra-226, Rn-222, Pb-210, Po-210 and Pa-231. Some uranium ores contain a significant fraction of Th-232 and its decay products.

Blanchard et al. 1982 [Q252] summarize the results of an EPA study that addresses radioactive effluents (gaseous, wind blown dust, rain water seeping into the ground water table) associated with active uranium mines in the USA. Principal exposure routes considered are inhalation of contaminants released into the air, external exposure from air submersion and radionuclides deposited on the ground, use of contaminated water and ingestion of food contaminated via either air or water.

All radionuclides present in the tailings pose a serious long term environmental risk (NRC 1996 [Q16], Andriess 1994 [Q77], Lipschutz 1980 [Q54], INFCE-7 1980 [Q277]) all the more so because the elements are chemically mobile after the milling process. The publications by Blanchard et al. 1982 [Q252], WISE-U 2006 [Q324] and Diehl 2006 [Q343] deepen that worries.

Need for rehabilitation

Although the concentration of radionuclides (the radioactive decay daughters of uranium and possibly also of thorium) in the tailing decreases with the grade, more ore has to be processed per kg uranium. Per kg recovered uranium the amounts of radioactive elements remaining in the tailings increases when using lower grade ores, due to a declining extraction yield with decreasing grades (see section 4.2). The amounts of mill tailings grow with falling ore grades, so the amounts of radioactive dust blown away by the wind and dissolved radionuclides draining into the ground water grow faster than inversely proportionally with falling ore grades. This study assumes an inversely proportional relationship between ore grade and the quantities of materials and useful energy required to achieve immobilisation and isolation of the mining wastes.

In one respect the above mining waste immobilisation concept does not comply with any sustainability criterium: an adequate treatment of the waste water flows of the uranium mine is missing. As illustrated by Figure 5, the ground water table will remain contaminated with radionuclides and other toxic elements forever, to an ever increasing extent. Avoiding this consequence of the current uranium mining operations would require the introduction of greatly revised mining techniques.

Mine rehabilitation should be included in the nuclear process chain, if the nuclear industry were to claim nuclear power is ‘clean’. This study is the first to include mine rehabilitation in the energy analysis of the nuclear system.

Striking is the following statement of the nuclear industry (WNA-04 2011 [Q271]):

‘Strictly speaking these (mining and milling wastes, JWSvL) are not classified as radioactive wastes’.

2 Concept of mine rehabilitation

Immobilisation and isolation

Until the present day, mill tailings and other waste of the uranium mining industry are being discharged into the environment. Obviously this practice cannot be reconciled with any sustainability definition. To make sure that this part of the nuclear cycle will become less harmful to the environment and to future generations, the mining and milling waste should be isolated from the biosphere. Broadly this would imply two basic processes:

- chemical fixation of the radionuclides (if possible) and of other toxic, non-radioactive species into a non-water-soluble chemical compound
- physical isolation of the waste from the biosphere, minimizing the chance that the radioactive and toxic substances reenter the human environment.

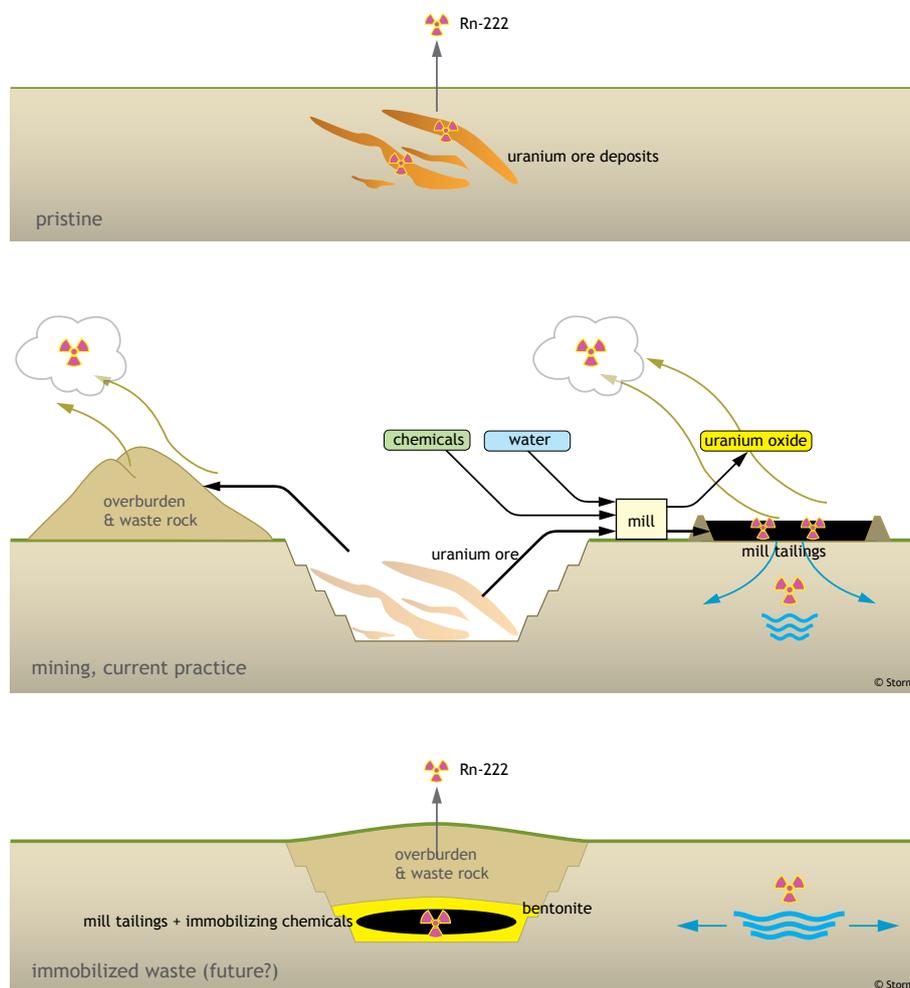


Figure 5

Outline 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.

The problem of the mill tailings and the rehabilitation of the mine area are not addressed in any other study. Although the study of Prasser et al. 2008 [Q374] mentions mine remediation (reclamation) as a part of a full energy analysis, the authors did not account for mine reclamation in their analysis. Prasser et al. argue that the energy consumed in the direct mining and milling process is dominating, so a simplified assessment is sufficient. Apparently this simplification implies neglect of the mine reclamation.

The Australian study ISA 2006 [Q325], which largely endorses this study, omits mine reclamation from its analysis. As ISA put it:

“This study does not comment on the adequacy of existing and planned mine clean-up, storage and disposal procedures, because these aspects fall outside this study’s scope.”

This study assumes that the uranium mining area is restored to green field conditions after depletion of the ore deposit, to comply with sustainability criteria as well as possible. There is no or very limited practical experience with mine reclamation, so no empirical data are available. To make possible a rough estimation of the energy input of mine reclamation, a fictive but plausible procedure is adopted in this study, based on the above mentioned two notions.

This study adopted the following concept for the immobilisation and isolation from the biosphere of the radioactive wastes of the mining activities (see also Figure 5).

- Neutralizing the acids (e.g. with limestone) in the tailings in case of acid leaching and with sulfuric acid in case of alkaline leaching of the ore;
- Rendering the radioactive and other toxic elements insoluble (except radon) by mixing the tailings with appropriate chemicals, for example sodium phosphate.
- Returning the mill tailing into the mine between thick layers (several meters) of bentonite. Bentonite is a clay mineral that swells by absorption of water and so forms a poorly permeable mass, closing gaps and fissures. Ion migration through bentonite is very slow and in this way the mineral effectively isolates the unwanted elements from the environment for long periods.
- Replacing the non-radioactive overburden and waste rock into the mining pit (open pit mining) or galleries (underground mining).
- Restoring the top soil and vegetation.

3 Auxiliary materials for mine rehabilitation: process analysis

Process outline

The total mass of the mill tailings is given by equation 1 (see also Figure 6):

$$m_{\text{tailings}} = m_{\text{ore}} + m_{\text{chem}} - m_{\text{U}} \quad \text{eq 1}$$

The amount of process chemicals, needed to leach out the uranium compounds from the ore, may be a significant part of the total tailings mass. As a consequence the mass and volume of the tailings are larger than those of the processed ore, the study INFCE-7 1980 [Q277] estimates an additional mass of 8.6%. The Ranger mine, for example, consumes 40 kg sulfuric acid per Mg ore (or 4%) plus an undisclosed amount of other chemicals, such as limestone, oxidizers and extraction chemicals.

Besides, a large mass and volume of overburden of rock and earth has to be removed and stored. A significant part of the overburden mass may contain also radionuclides and has to be isolated from the biosphere. Apart from the ore about an equal mass of sub-ore is mined, which is not processed. The average ratio sub-ore/ore for underground mines is slightly more than 0.1, according to Blanchard et al. 1982 [Q252].

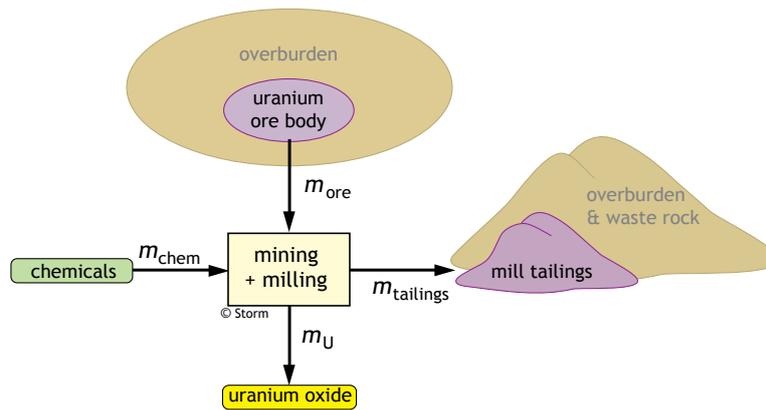


Figure 6
Mass flows of the mining and milling process

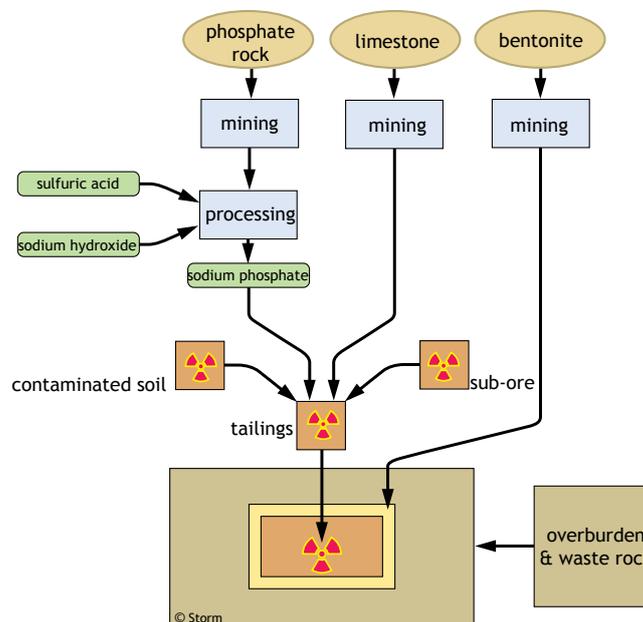


Figure 7
Outline of a hypothetical, but plausible model of mine reclamation

The mass of the mineral component of the tailings, excluding the added chemicals, related to the produced mass of uranium can be found by equation 2:

$$m_{\text{tail}} = m_U \cdot \left(\frac{100}{Y \cdot G} - 1 \right)$$

m_{tail}	= mass of tailings	Mg
m_U	= mass of produced uranium	Mg
Y	= extraction yield	fraction extracted U
G	= ore grade	mass-% U in ore

eq 2

In a rough approximation we assume the energy requirements of mine reclamation to be two times that of mining. The mass of the tailings, including the limestone and bentonite, is assumed to be about twice the mined ore mass. The limestone and bentonite have to be mined as well, the sodiumphosphate has to be produced from phosphate rock. The limestone, bentonite and sodiumphosphate generally would have to be transported over long distances, possibly 1000 – 10000 km or even more. The overburden and non-

radioactive waste rock has to be transported back to the mine and the reclaimed area has to be replanted. The total masses depend on the size and depth of the ore body.

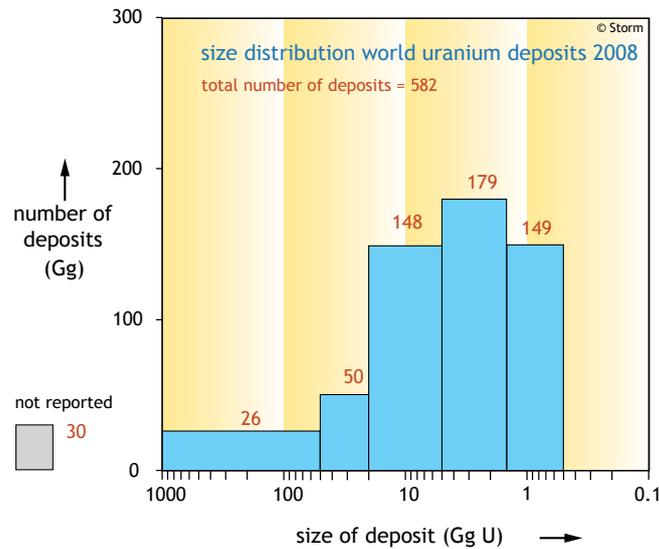


Figure 8

Size distribution of known uranium deposits according to IAEA 1996 [Q371]. Although the database this diagram is based on dates from 1996, the present distribution might not look much different, for a limited number of new deposits seems to be discovered since.

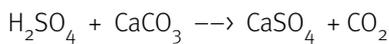
Limestone

Limestone assumed to be pure CaCO_3

Reference mine (Ranger model) consumes 40 kg H_2SO_4 per Mg ore

assume 1/2 is consumed by minerals in the ore

\Rightarrow 1/2 to be neutralized afterwards \Rightarrow 20 kg/Mg tailings



$$M(\text{H}_2\text{SO}_4) = 98 \text{ g/mol}, \quad M(\text{CaCO}_3) = 100.1 \text{ g/mol}$$

$$\Rightarrow m(\text{H}_2\text{SO}_4) : m(\text{CaCO}_3) = 1 \cdot M(\text{H}_2\text{SO}_4) : 1 \cdot M(\text{CaCO}_3) = 98 : 100.1 = 1 : 1$$

$$\Rightarrow 20 \text{ kg CaCO}_3/\text{Mg tailings}$$

Sodium phosphate Na_3PO_4

Heavy metal ions immobilized with sodium phosphate, pH neutral or weakly basic.

Assume 1 mass-% metal ions to be immobilized

10 kg Me^{n+} /Mg tailings

assumed mean molar mass $M = 200 \text{ g/mol}$

$$\Rightarrow 10000/200 = 50 \text{ mol per Mg tailings,}$$

$$\text{If MePO}_4 \Rightarrow 50 \text{ mol Na}_3\text{PO}_4 \text{ required} = 50 \cdot 164 = 8200 \text{ g}$$

$$\text{if oxidized to Me}^{4+} \Rightarrow \text{Me}_3(\text{PO}_4)_4 \Rightarrow 4/3 \cdot 50 \cdot 164 = 10993 \text{ g Na}_3\text{PO}_4 \text{ required}$$

$$\Rightarrow \text{assume roughly mass ratio Me} : \text{PO}_4 = 1:1$$

$$\Rightarrow 10 \text{ kg Na}_3\text{PO}_4 / \text{Mg tailings}$$

Bentonite

Assumed as a rough approximation tailings stored in mining pit as an ellipsoid with circular diameter r and short axis = 0.5 radius circle r

$$V(\text{ellipsoid}) = 4/3 \cdot \pi \cdot 0,5r^3$$

$$V(\text{tailings}) = 7 \cdot 10^6 \text{ m}^3 = 4/3 \cdot \pi \cdot 0,5r^3 \Rightarrow r = (\sqrt[3]{(3/2 \cdot 7)/\pi}) \cdot 100 = 150 \text{ m}$$

Assume bentonite layer thickness $l = 3 \text{ m}$

$$\Rightarrow r = 150 + 3 = 153 \text{ m}$$

$$V(\text{total}) = 2/3 \cdot \pi \cdot 153^3 = 7,50 \cdot 10^6 \text{ m}^3 \Rightarrow$$

$$V(\text{bentonite}) = 7,50 - 7,0 \cdot 10^6 \text{ m}^3 = 5 \cdot 10^5 \text{ m}^3 \Rightarrow$$

$$m(\text{bentonite}) = 5 \cdot 10^5 \text{ m}^3 \cdot 2,3 \text{ Mg/m}^3 = 1,15 \cdot 10^6 \text{ Mg}$$

$$\text{If bentonite layer } l = 2 \text{ m} \quad m(\text{bentonite}) = 2/3 \cdot 1,15 \cdot 10^6 \text{ Mg} = 0,77 \cdot 10^6 \text{ Mg}$$

Amount of bentonite depends on size of deposit and on ore grade: larger size corresponds with lower specific bentonite requirement. Lower grade \Rightarrow more tailings per kg U \Rightarrow higher specific bentonite requirement. Larger sized deposits generally at lower ore grade. Assume both trends cancel each other out.

$$\text{Specific bentonite consumption} \quad m = 1,15 \cdot 10^6 \text{ Mg} / 19,125 \cdot 10^6 \text{ Mg} = 60 \text{ kg/Mg tailings}$$

$$\text{low estimate} \quad m = 2/3 \cdot 60 = 40 \text{ kg/Mg tailings}$$

4 Energy consumption of mine rehabilitation: process analysis

The energy input of the mining and processing of the materials required for mine rehabilitation are based on the figures of uranium mining and milling. These figures are summarized below.

Mining and milling of uranium

direct energy input

drilling + blasting	$J_e = 5$	MJ/Mg rock	
excavation	$J_{th} = 14,6$	MJ/m ³ earth	
	$J_{th} = 5,84$	MJ/Mg rock , assumed $d = 2,5 \text{ Mg/m}^3$	
haulage	$J_{th} = 1$	MJ/Mg.km	
crushing & grinding	$J_e = 74$	MJ/Mg rock	hard ore
leaching, excl chemicals	$J_e = 42$	MJ/Mg rock	
	$J_{th} = 230$	MJ/Mg rock	[Q98] p.252

indirect energy

drilling + blasting	$J_{th} = 12$	MJ/Mg rock	
excavation + haulage	$J_{th} = 38$	MJ/m ³ earth	
	$J_{th} = 15,2$	MJ/Mg rock	assumed $d = 2,5 \text{ Mg/m}^3$
explosives	$m = 0,25$	kg/Mg rock	(assumed similar to Ranger)
crushing & grinding	$J_e = 3$	MJ/Mg rock	hard ore
	$J_{th} = 76$	MJ/Mg rock	

ore processing	$J_e = 6.0$	MJ/Mg ore	excluding chemicals
	$J_{th} = 44$	MJ/Mg ore	excluding chemicals
leaching (capital)	$J_e = 1.5$	MJ/Mg ore	
	$J_{th} = 10.6$	MJ/Mg ore	

General data

embodied energy

H ₂ SO ₄	$J_{th} = 2.87$	MJ/Mg	[Q98]
NaOH	$J_e = 5.8$	MJ/Mg	
	$J_{th} = 19$	MJ/Mg	[Q98]
explosives	$J_{th} = 71$	MJ/Mg	[Q98] + [Q95]

densities d Mg/m³ (Handbook of Chem & Physics)

limestone	2.68 - 2.76	=> 2.7
sandstone	2.14 - 2.36	2.3
granite	2.64 - 2.76	2.7
clay	1.8 - 2.6	2.3
assume average rock	$d = 2.5$	Mg/m ³

Sodium phosphate

Energy requirements of the production of sodium phosphate Na₃PO₄

energy input mining

		J_e	J_{th} (MJ/Mg rock)	
drilling + blasting	direct	5	-	
	indirect	-	12	
excavation	dir	-	5.84	
haulage	dir	-	10	assume haulage distance = 10 km
excavation + haulage	indirect	-	15.2	assume mean density $d = 2.5$ Mg/m ³
explosives	indirect	-	17,8	assume 0.25 kg expl/Mg rock
	sum	5	60.8	

energy input milling

fluorapatite is a hard ore

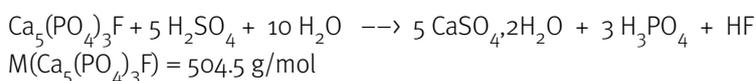
		J_e	J_{th} MJ/Mg rock
crushing + grinding	direct	74	-
	indirect	3	76
leaching, excl chem	direct	42	230
	indirect	1.5	10.6
	sum	121	317

mining + milling

		126	378	MJ/Mg rock excluding chemicals
	3x	378	1134	MJ/Mg phosphate excluding chemicals

assume mined rock contains 33% phosphate PO₄, no overburden: $S = 0$

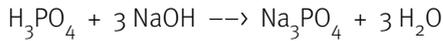
=> the thermal and electric energy inputs of mining + milling per Mg phosphate are 3x energy inputs per Mg rock



$M(\text{H}_2\text{SO}_4) = 98.1 \text{ g/mol}$
 \Rightarrow stoichiometric mass ratio fluorapatite : sulfuric acid =
 $= 504.5 : 5 \cdot 98.1 = 504.5 : 490.5 = 1:1$

energy intensities chemicals

	J_e	J_{th}	MJ/Mg	
H_2SO_4	28	2495		[Q95] p.54
NaOH	5800	19000		[Q98] p.34



$M(\text{H}_3\text{PO}_4) = 98.0 \text{ g/mol}$
 $M(\text{NaOH}) = 40.0 \text{ g/mol}$
 stoichiometric mass ratio $m(\text{H}_3\text{PO}_4) : m(\text{NaOH}) = 98 : 3 \cdot 40 = 1 : 1.22$

energy requirements per Mg sodium phosphate Na_3PO_4

	J_e	J_{th}	MJ/Mg Na_3PO_4
mining + milling	378	1134	
H_2SO_4	28	2495	
NaOH 1.22x	7076	23180	
sum	7482	26809	

transport

assume average distance 10000 km by truck, train and ship, including several times transshipment

direct + indirect E input $J_{th} = 10000 \text{ km} \cdot 2.0 \text{ MJ/Mg.km} = 20000 \text{ MJ/Mg Na}_3\text{PO}_4$

See report L21p23 *Process analysis of the Ranger mine*, section 7.

excluding packaging: Na_3PO_4 has to be transported in containers

Total energy input per Mg Na_3PO_4 on site:(rounded)

$$J_e = 7482 = 7500 \quad \text{MJ/Mg Na}_3\text{PO}_4 \quad (\text{rounded})$$

$$J_{th} = 26809 + 20000 = 46800 \quad \text{MJ/Mg Na}_3\text{PO}_4 \quad (\text{rounded})$$

Specific CO_2 emission of sodium phosphate on site

$$\gamma = 46800 \text{ MJ/Mg} \cdot 75 \text{ gCO}_2/\text{MJ} = 3510 \text{ kg CO}_2/\text{Mg Na}_3\text{PO}_4$$

Limestone CaCO_3

energy input mining, assume no overburden: $S = 0$

		J_e	J_{th}	MJ/Mg rock
drilling + blasting	direct	5	-	
	indirect	-	12	
excavation	dir	-	5.84	
haulage	dir	-	10	assume haulage distance = 10 km
excavation + haulage	indirect	-	15.2	assume mean density $d = 2.5 \text{ Mg/m}^3$
explosives	indirect	-	17,8	assume 0.25 kg expl/Mg rock
	sum	5	60.8	

energy input milling

limestone is a soft ore

	J_e	J_{th}	MJ/Mg rock
--	-------	----------	------------

crushing + grinding	direct	2	15	[Q98] p.253
	indirect	7	-	
	sum	9	15	

mining + grinding 14 76 MJ/Mg rock (assume pure CaCO₃)

transport

Based on the same assumption as in case of sodium phosphate (see above)

sum transport $J_{th} = 20000$ MJ/Mg CaCO₃

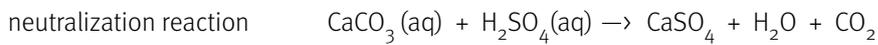
Total energy input per Mg CaCO₃ on the site:

$$J_e = 14 \text{ MJ/Mg CaCO}_3$$

$$J_{th} = 20076 \text{ MJ/Mg CaCO}_3$$

Specific CO₂ emission of limestone on site

Limestone is used to neutralize the acids in the mill tailing and to enhance the insolubility of the heavy metals.



stoichiometric mass ratio $m(\text{CO}_2) : m(\text{CaCO}_3) = 44 : 100$

=> $m(\text{CO}_2)$ generated by neutralizing sulfuric acid:

$$m(\text{CO}_2) = 0.44 \text{ Mg per Mg CaCO}_3$$

emodied $\gamma = 20076 \text{ MJ/Mg} \cdot 75 \text{ gCO}_2/\text{MJ} = 1506 \text{ kg CO}_2/\text{Mg CaCO}_3$

neutralization $\gamma = 440 \text{ kg CO}_2/\text{Mg CaCO}_3$

Total specific emission $\gamma = 1946 \text{ kg CO}_2/\text{Mg CaCO}_3$

Bentonite

Mining energy input

		J_{th} MJ/Mg	
excavation	dir	5.84	
haulage	dir	10	assume haulage distance = 10 km
excavation + haulage	indirect	15.2	assume mean density $d = 2.5 \text{ Mg/m}^3$
	sum	$J_{th} = 31.0$	MJ/Mg

transport

Based on the same assumption as in case of sodium phosphate (see above)

sum transport $J_{th} = 20000$ MJ/Mg bentonite

Total energy input per Mg bentonite on the site:

$$J_{th} = 20031 \text{ MJ/Mg bentonite}$$

Specific CO₂ emission

bentonite on site $\gamma = 20031 \text{ MJ/Mg} \cdot 75 \text{ gCO}_2/\text{MJ} = 1502 \text{ kg CO}_2/\text{Mg bentonite}$

5 Summary of specific energy input and CO₂ emission

Auxiliary materials for rehabilitation

Based on the process analyses of mine rehabilitation the specific energy input and CO₂ emission of mine rehabilitation can be estimated. Tables 2 and 3 summarize the results of the process analysis in the previous sections.

Table 1

Summary of embodied energy, including transport to the mining site, and specific CO₂ emission per Mg product used in rehabilitation of a uranium mine

material	thermal J_{th} MJ/Mg product	electric J_e MJ/Mg product	$m(\text{CO}_2)$ * kg/Mg product
limestone	20076	14	1946 **
sodium phosphate	46800	7500	3510
bentonite	20031	–	1502

* Assumed 75 g CO₂/MJ(th), about average fossil fuel

** Including CO₂ emitted during neutralization of acid leach liquids

Table 2

Summary of specific consumption of materials, energy, including transport to the mining site, and specific CO₂ emission per Mg tailings

material	specific consumption kg/ Mg tailings	thermal J_{th} MJ/Mg tailings	electric J_e MJ/Mg tailings	$m(\text{CO}_2)$ kg/Mg tailings
limestone	20	402	0.28	38.9
sodium phosphate	10	468	75	35.1
bentonite	40	801	–	60.1
sum	70	1671	75.3	131.1

Haulage of tailings and waste back into the mine

Estimate of the energy input of replacing tailings and waste rock back into the mine and restoring the top soil is based on the figures of uranium mining.

Direct energy input

excavation	$J_{th} = 14.6$	MJ/m ³ earth	assumed $d = 2.5$ Mg/m ³
	$J_{th} = 5.84$	MJ/Mg rock	
haulage	$J_{th} = 1$	MJ/Mg.km	
assumed haulage distance of	5 km		
total direct energy input	$J_{th} = 10.84$	MJ/Mg rock	

Indirect input

excavation + haulage $J_{th} = 38$ MJ/m³ earth
 $J_{th} = 15.2$ MJ/Mg rock assumed $d = 2.5$ Mg/m³

sum excavation + haulage $J_{th} = 10.84 + 15.2 = 26.04$ MJ/Mg rock

Specific CO₂ emission

excavation + haulage $\gamma = 26.04$ MJ/Mg • 75 gCO₂/MJ = 1.95 kg CO₂/Mg rock

Total specific energy input of rehabilitation per Mg recovered uranium ???###

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 $J_{th} = 26.04$ MJ/Mg rock or tailings
 $\gamma = 1.95$ kg CO₂/Mg rock or tailings

auxiliary materials $J_{th} = 1671$ MJ/Mg tailings
(see Table 2) $J_e = 75.3$ MJ/Mg tailings
 $\gamma = 131.1$ kg CO₂/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).

This study assumes an overburden ratio of $S = 3$ for an average uranium mine, so the mass of waste rock to be replaced into the depleted mine is 3x mass of the tailings. The haulage distance is assumed to be 5 km. Haulage distances may be more than 5 km for many uranium mines and overburden ratios are often considerably higher than 3.

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.

References

- Q6
Storm & Smith 2008
Storm van Leeuwen J W & Smith Ph B,
Nuclear power - the energy balance
Ceedata, Chaam (Netherlands), February 2008
www.stormsmith.nl
- Q16
NRC 1996
Rasmussen N C (chair) et al.,
Nuclear Wastes. Technologies for separations and
transmutation,
National Research Council, NRC
Washington DC: National Academy Press, 1996.
- Q54
Lipschutz 1980
Lipschutz RD,
Radioactive waste: politics, technology and risk,
A report of the Union of Concerned Scientists,
Ballinger Publishing Company, Cambridge, Mass, 1980
ISBN 0 8 8410 621 7.
- Q77
Andriess 1994
Andriess C D,
Comment on prospects for nuclear power, Energy technologies
to reduce CO₂ emissions,
OECD/IEA, Paris, 1994.
- Q95
Rotty et al. 1975
Rotty R M, Perry A M & Reister D B,
Net energy from nuclear power,
ORAU-IEA-75-3,
Institute for Energy Analysis, Oak Ridge Associated Universities,
November 1975.
- Q98
Mortimer 1977
Mortimer N D,
The Energy Analysis of Burner Reactor Power Systems,
PhD dissertation, Milton-Keynes Open University, UK, December
1977.
- Q252
Blanchard et al. 1982
Blanchard RL, Fowler TW, Horton TR & Smith JM,
Potential health effects of radioactive emissions from active
surface and underground uranium mines,
Nuclear Safety, Vol 23 no 4, July-August 1982.
- Q271
WNA-04 2011
Radioactive waste management,
World Nuclear Association.
<http://www.world-nuclear.org/info/info4.html>
updated July 2011, retrieved December 2011
- Q277
INFCE-7 1980
Waste management and disposal,
Report of the INFCE Working Group 7,
International Nuclear Fuel Cycle Evaluation,
IAEA, Vienna, 1980.
- Q324
WISE-U 2008
WISE Uranium Project,
www.wise-uranium.org
- Q325
ISA 2006
Life-Cycle Energy Balance and Greenhouse Gas Emissions of
Nuclear Energy in Australia,
A study undertaken for the Department of Prime Minister and
Cabinet of the Australian Government,
ISA, The University of Sydney, 3 November 2006,
www.isa.org.usyd.edu.au/publications/reports.shtml
- Q343
Diehl 2006
Diehl P,
Environmental consequences of uranium mining,
Seminar Kernenergie "ja mits" of "nee, tenzij",
Amsterdam, 9 november 2006,
www.tegenstroom.nl
- Q371
IAEA 1996
*Guidebook to accompany IAEA map: world distribution of
uranium deposits*,
STI/PUB/1021
IAEA, Vienna, 1996
- Q374
Prasser et al. 2008
Prasser H-M, Bayard A-S & Dones R,
'Sustainability of uranium sources',
International Conference on the Physics of Reactors "Nuclear
Power: A Sustainable Resource",
PHYSOR08, Interlaken, Switzerland, September 14-19, 2008
< Prasser-FP343.pdf >
www.physor2008.ch
16 Sept 2014: website physor2008 no longer existent;
publication may be not available on the web
[http://www.lke.mavt.ethz.ch/publications-and-awards/
conference-contributions.html#2008](http://www.lke.mavt.ethz.ch/publications-and-awards/conference-contributions.html#2008)
Paper copy or cdrom can be ordered via:
www.library.ethz.ch/search/action/
- Q616
EPA 1990
Toxicological profile for thorium,
Agency for Toxic Substances and Disease Registry U.S. Public
Health Service, in collaboration with: U.S. Environmental
Protection Agency, October 1990
<tp147.pdf>
www.atsdr.cdc.gov/toxprofiles/tp147.pdf
download September 2014
- Q617
PSR-IEER 2009
Makhijani A & Boyd M,
Thorium fuel: no panacea for nuclear power,
Factsheet by Physicians for Social Responsibility (PSR) and
Institute for Energy and Environmental Research (IEER).
January 2009, updated July 2009.
<thorium2009factsheet.pdf>
[http://ieer.org/wp/wp-content/uploads/2012/04/
thorium2009factsheet.pdf](http://ieer.org/wp/wp-content/uploads/2012/04/thorium2009factsheet.pdf)
- Q618
Diehl 2011
Diehl P,
Uranium mining and milling wastes: an introduction,
WISE Uranium Project, 18 May 2011.
< Uranium mining and milling wastes/ an introduction.pdf >
<http://www.wise-uranium.org/uwai.html>