Uranium mining + milling

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

TABLES

FIGURES

Flowsheet of a uranium mine

Recovery of uranium from the earth's crust, usually called mining + milling of uranium ore, occurs in a sequence of physical and chemical processes. Figure 1 represents the flowsheet of the Ranger mine in Australia, one of the cheapest operating mines in the world, due to its favourable conditions; this flowsheet is used as reference uranium mine in this study. Many open-pit and underground uranium mines in the world operate according a similar flowsheet.

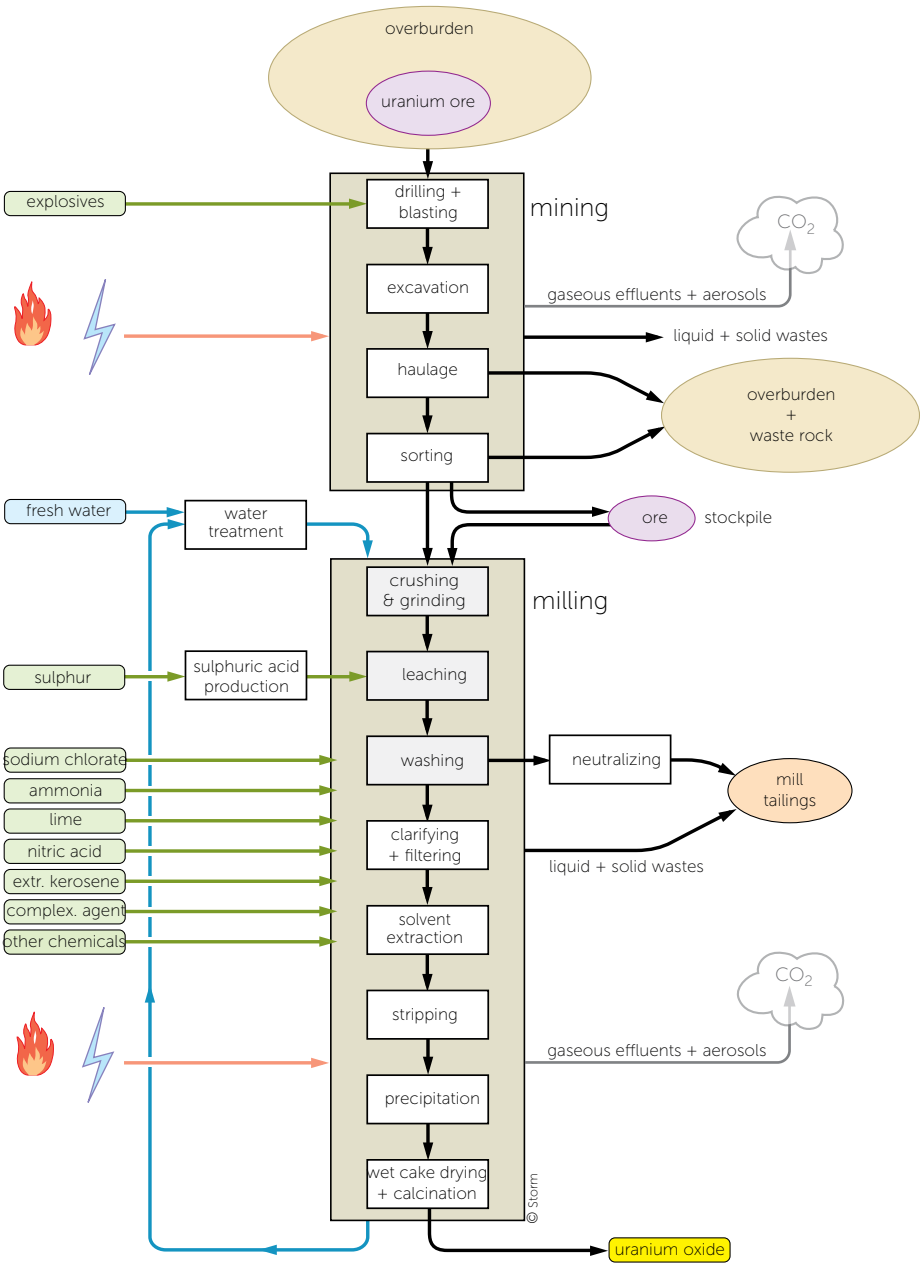

Figure 1

Flowsheet of the Ranger uranium mine, based on data from [ERA 2006]. Most uranium mines in the world are operating according to a similar flowsheet. This study uses this flowsheet as reference uranium mine.

Mines applying the In Situ Leaching (ISL) method have a different flowsheet in some respects. The specific energy consumption and accompanying CO_2 emission of ISL mines are similar to those of open-pit mines. Large numbers of injection and production wells are to be drilled due to clogging and large volumes of

leaching liquids are consumed; see also [CSIRO 2004], [Mudd 1998], [Mudd 2000], [Mortimer 1977], [Mudd & Diesendorf 2007]. The harmful impact of ISL on the environment is high [WISE-U 2015] and irreversible.

The reference uranium mine in this study is an open pit mine that may be taken as a world-averaged mine. Underground mining is generallly more energy intensive than open pit mining, ISL may be less energy intensive in some cases. Differences in specific energy consumption and CO_2 emission between individual uranium mines are substantial, due to widely varying conditions, as will be explained in the following sections, and for that reason it seems not useful to discern different types of mines in this assessment: the figures exhibit a significant scatter anyhow.

Apart from the specific variables discussed in the following sections the energy input and CO_2 emission of an operating uranium mine depends on some general parameters, such as:

- Size of the ore body and construction of the mine. Smaller mines have larger fixed energy input, due to its construction, including the processing plant and equipment.
- Availability of fresh water; a uranium mine consumes large volumes of fresh water.
- Location: the transport distances of the supplies to the mine vary over a wide range and may be thousands of kilometers in some cases. Remote uranium mines have longer supply routes and consequently have a higher specific energy consumption.
- Local climate and other conditions.

This study assumes that the electrical inputs at the mining site are provided by stationary oil-fuelled generators at a thermal efficiency of e = 40%, and that the thermal efficiency of diesel engines of mining equipment, dump trucks and excavators is e = 30%.
Specific combustion CO_2 emission of of fuel oil and diesel is assumed to be γ = 75 gCO_2/MJ_{th}.

Dilution factor and coal equivalence

The ore grade is defined as the uranium content of the uranium-bearing rock, usually given as mass-% U_3O_8, or in grams uranium oxide per kg rock. The minimum amount of rock to be mined and milled to obtain 1 kg uranium is inversely proportional to the ore grade. The *dilution factor* is a simple mathematical relationship between ore grade and mass of rock to be processed per mass unit of uranium, and does not depend on recovery technology nor on ore type.
Actually, more ore has to be processed than the mathematical minimum, due to the unavoidable losses in the extraction process (see section below). The blue curve in Figure 2 illustrates the relationship between the ore grade and the mass of ore to be mined and processed per kg recovered uranium.

At a grade of 0.1% uranium, one megagram (1 Mg = 1 metric tonne) of rock has to be mined and processed to obtain 1 kg uranium in the mill. This is ten times as much as from rock at a grade of 1%, containing 10 kg uranium per Mg rock. Consequently, the mining energy input per kilogram uranium is at least ten times as large. At a grade of 0.01% the energy input is at least 100 times as large.
The horizontal red line represents the mass of coal (2.0 Tg) consumed by a coal-fired power plant to generate the same amount of electricity as the reference reactor during one year (26 PJ). Below an ore grade of 0.02% U_3O_8 the annual mass of uranium ore to be processed to fuel one nuclear power plant equals the mass of coal: the *coal equivalence*.
Figure 2 shows that below the critical ore grade, at which the nuclear system will pass through the coal equivalence, virtually no recoverable uranium resources are been reported.

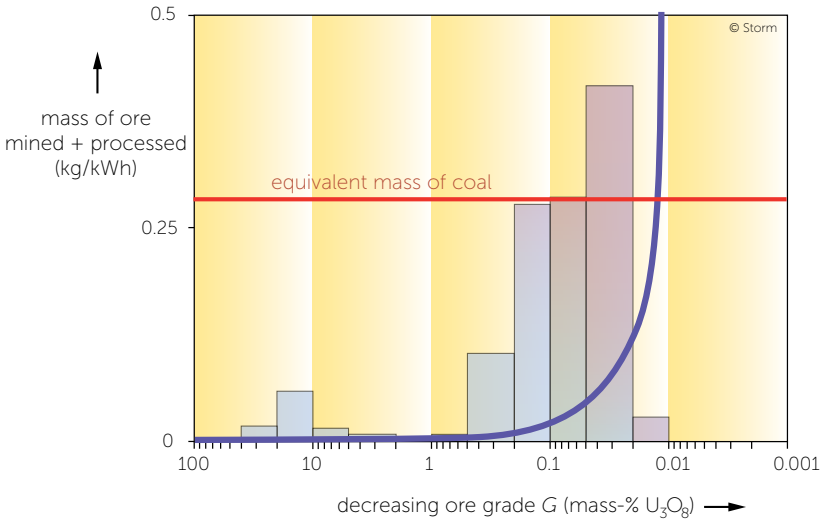

Figure 2

The dilution factor and the coal equivalence. The mass of rock to be processed to fuel one reactor for one year with uranium rises exponentially with falling ore grade. At a grade below 0.02% U_3O_8, 200 ppm, or 200 grams per Mg (metric ton) the mass of ore equals the mass of coal consumed by a coal-fired station to generate the same amount of electricity: this is the coal equivalence. The bar diagram of the known uranium resources as function of the ore grade is added for comparison; its relative scale has no numerical values in this diagram.

Ore types

Uranium occurs in many kinds of minerals in the earth's crust. The nuclear industry distinguishes sometimes two categories of uranium resources, based on economic considerations: conventional and unconventional resources. The term 'ore' is an economic notion: only rock from which uranium can be extracted in a economic way is called 'ore'.
Conventional resources are deposits of the kind now being mined. Examples of unconventional resources are shales, phosphates, granites. Unconventional resources are generally not exploited.

In this study the conventional ores are divided into two groups, based on information from many sources, among other [Orita 1995], [WNA-*Ugeol* 2015], [WNA-mining 2016]:

- soft ores, easily mineable and millable, e.g. sandstones and calcretes, with typical grades ranging from more than 10% down to about 0.02% U_3O_8,
- hard ores, hard to mine and mill, e.g. quartz pebble conglomerates, with grades varying typically from about 0.1% down to the mineralisation limit. Some high-grade vein-type ores are also hard to mill.

Below the mineralisation limit, at grades below 0.01% U_3O_8, the uranium is not present in the form of separate grains of uranium minerals, but dispersed at atomic scale among the other constituents of the rock. To extract uranium from rock types below the mineralisation limit the whole rock has to be brought into solution. If uranium is present as separate minerals the processing starts with selectively dissolving the uranium minerals and subsequently discarding the other minerals from the processed rock.

Mining

Energy consumption and CO_2 emission per Mg mined ore of the mining of uranium ore from the earth's crust (mining), depends on a number of variable conditions, such as:

- Overburden ratio (= stripping ratio), determines the mass of waste rock to be removed per Mg ore. The overburden ratios of open pit mines vary roughly from 3-50. The overburden ratio in the USA averaged

50, according to [Blanchard *et al*. 1982]. An overburden ratio (or stripping ratio) of 3 means that for every Mg ore 3 Mg of waste rock has to be removed. Variations in overburden ratios may introduce a spread in the energy requirements with a factor of 5 [Chapman 1976b], with the same type of ore.
According to [Mortimer 1977] the waste rock ratios of underground mines vary from 1-5.

- Haulage distance: the distance the waste rock and ore has to be transported to the waste rock dumping site respectively to the ore processing plant. The hauling distance for ore may vary from a few kilometers to more than 200 km.
- Specific consumption of explosives (kg explosives per Mg rock).
- Thermal conversion efficiency of the diesel engines powering the mining equipment and the electricity generators.

A fifth important parameter is the hardness of the rock to be mined. This factor is difficult to quantify, and for that reason this study discerns two main types of ore: soft ores and hard ores. Variable rock properties may introduce considerable variations in the specific energy requirements and CO_2 emissions of mining from mine to mine. Some consequences of the mining of harder rock are, among other:

- Higher energy consumption per Mg rock removed by excavators.
- Higher wear of equipment, such as drill rigs and excavators, causing more time in the shop and a higher rate of replacement of components and higher use of consumables. These increased rates mean an higher direct and indirect energy consumption per Mg rock mined.
- Higher specific consumption of explosives: harder rock needs more explosives per Mg rock. The Ranger mine uses about 0.25 kg explosives per Mg rock. Likely many mines have significant higher explosives consumptions. This study assumes an explosives consumption rate of 1 kg/Mg rock in mines with hard ores and in underground mines .

The specific thermal energy consumption of mining per Mg of soft ore can be calculated by the following equation 1. The figures are derived from a process analysis of the Ranger mine, that is based on the publications [ERA 2006], [ERA-AR 2005], [Rotty et al.1975] and [Mortimer 1977]. These figures may be considered a low estimate of the world average uranium mine with soft ores, in view of the favourable geologic conditions at Ranger.
For conversion of mechanical energy input into thermal energy input, mechanical energy is equated with electrical energy: one unit of mechanical energy equals one unit electric energy, $J_{mech} = J_e$.

$$\begin{aligned} J_{mining} &= (S+1)\bullet\{(J_{d+b} + J_{excav} + d\bullet J_{haul})/e + J_{d+b}(\text{indir}) + J_{excav}(\text{indir}) + J_{explos} + d\bullet J_{haul}(\text{indir})\} = \\ &= (S+1)\bullet\{(0.60 + 4.49 + d\bullet 2.40)/e + 11.00 + 3.18 + x\bullet 69.40 + d\bullet 1.888\} = \\ &= (S+1)\bullet\{(5.09 + d\bullet 2.40)/e + 14.18 + x\bullet 69.40 + d\bullet 1.888\} \end{aligned} \qquad \text{eq 1}$$

Here is:	J_{mining}	= total (thermal) energy input of uranium mining	(MJ_{th}/Mg ore)
	J_{d+b}	= direct mechanical energy input of drilling and blasting	(MJ_e/Mg ore)
	J_{excav}	= direct mechanical energy input of excavation	(MJ_e/Mg ore)
	J_{haul}	= direct mechanical energy input of haulage	(MJ_e/Mg ore)
	J_{explos}	= indirect thermal energy input of explosives fabrication	(MJ_{th}/Mg ore)
	S	= overburden ratio (= stripping ratio)	
	d	= haulage distance	km
	e	= thermal conversion efficiency diesel engines $J_{th} \rightarrow J_e$ and $J_{th} \rightarrow J_{mech}$	
	x	= mass ratio explosives over mined rock	kg/Mg rock

The specific CO_2 emission of mining becomes:

$\gamma_{mining} = 75^* J_{mining}$ g CO_2/Mg ore

Figure 3 shows the depence of the specific CO_2 emission of mining in open pit mines on two parameters: the overburden ratio S and the haulage distance d. The diagrams are based on data from the process analysis

of the Ranger mine in Australia.

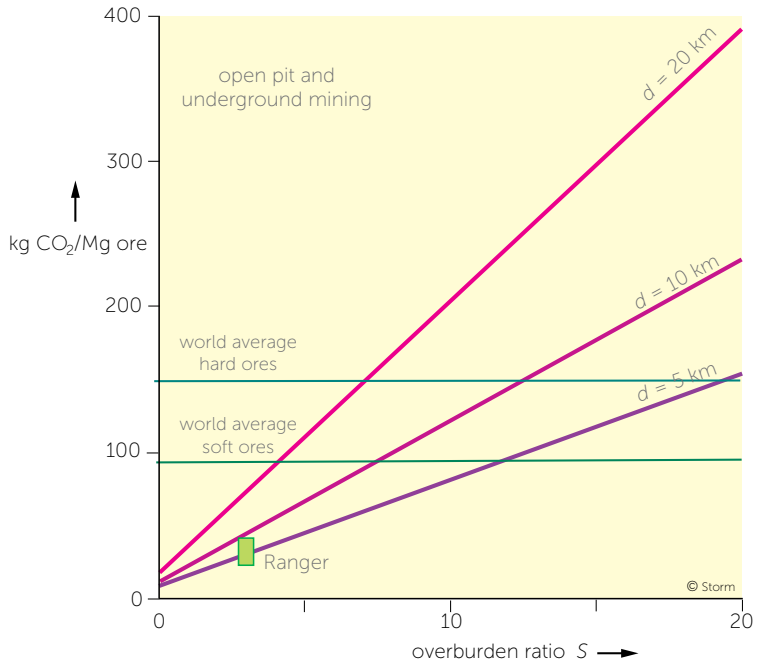

Figure 3

Specific CO_2 emission of mining uranium ore (kg CO_2/Mg ore) as function of the overburden ratio *S*, at three different hauling distances. In this diagram the explosives consumption is assumed *x* = 0.25 kg/Mg; underground mines and open-pit mines with hard ores may consume 1 kg explosives per Mg rock, or more. There are mines with overburden ratios as high as 50. Hauling distances of up to 200 km are reported. Consequently the specific CO_2 emission at many mines in the world might be considerably higher than the world average figure.

Figure 3 shows that the specific energy consumption and CO_2 emission of mining uranium ore can widely differ from mine to mine, due to different overburden ratios and haulage distances. In practice the scatter of the figures might be enhanced by various other factors. The values of the energy requirements given in other studies vary widely, from a low of 0.08 GJ/Mg ore [Franklin *et al.*1971] to a high of 77 GJ/Mg ore [Orita 1995]. The large scatter of values may be partly explained bij individual differences between mines but mainly by methodological differences.

In-situ leaching (ISL) uranium mining

In some places in-situ leaching (ISL) is applied to extract uranium from ore still in the ground. Chemicals are pumped down via injection wells into the ore body and the uranium-bearing liquor is pumped up from production wells, after a residence time of 3-25 years.

ISL has been applied to conventional low-grade ores containing 0.03-0.05% uranium. In common practice sulfuric acid leaching is used at a concentration of 2-5 g/l (0.02-0.05 M H_2SO_4). However, an initial concentration of 15-25 g/l (about 0.15-0.25 molar H_2SO_4) is generally used to reduce the ore preparation period. Often an oxidant is required to dissolve the uranium mineral. Oxidants in use include hydrogen peroxide, nitrate ions (nitric acid) and sodium chlorate. Acid consumption is typically 5-6 kg per Mg rock, but up to 10-15 kg/Mg rock. Overall recovery is typically 50-80% of the in-the ground resource [CSIRO 2004]. Large quantities of chemicals are needed: sulphuric acid, nitric acid, hydrofluoric acid, ammonia and other, together tens hundreds of tonnes (Mg) chemicals per Mg uranium [Mudd 2000].

The reported recovery yield of *Y* = 50-80% refers only to the extraction from the rock. Given the low uranium

content of the parent rock and of the pregnant solution pumped from the production wells, the extraction yield of uranium from the pregnant solution may be low. The overall yield, extraction from ore in the ground to yellow cake, may be in the range of 20-40%.

A major problem of ISL is the large-scale and irreversible contamination of aquifers, not only by the added chemicals, but also by radioactive and toxic elements, such as radium, heavy metals and arsenicum, which are chemically mobilized from the parent rock as well [Mudd 1998]. It might be difficult to reconcile the ISL technique with any sustainable development, for reason of its harmful and irreversible effects in the environment.

A rough impression of the energy requirements embodied in the chemicals for extraction can be figured out. Assuming 100 Mg sulfuric acid plus 3 Mg ammonia are needed to extract one Mg uranium from the ground – in some places two to three times as much is consumed – the embodied energy in these two chemicals alone is: J_{isl} = 0.547 TJ/Mg (U) J_{th}/J_e = 2.8

These figures are based on the specific energy intensities according to [Rotty et al. 1975]:
sulfuric acid H_2SO_4: J_{spec} = 2.87 GJ/Mg J_{th}/J_e = 100
ammonia NH_3: J_{spec} = 86.65 GJ/Mg J_{th}/J_e = 1.41

It should be emphasized that the above figure represents only a fraction of the total specific energy requirements of ISL per Mg extracted uranium. Not included are, for example, the energy requirements of:

- embodied energy in pipes and drilling equipment
- drilling the injection and production wells,
- pumping the fluids into the ground, via injection wells, and from the ground via production wells
- extraction of the uranium from the solution.

The energy requirements of in situ leaching will vary over a wide range, due to widely different geochemical conditions, depth of ore body, number of wells, operational life of each well and ore properties. In addition the energy requirements depend on the ore grade, as with conventional mining and milling. Data on actual ISL mines are scarce in the open literature, so the average values are unknown. Due to clogging the productive life of the wells is short, so during the production lifetime of the mine constantly new wells are to be drilled.

In this study the specific energy requirements of ISL are assumed to be the same as of open pit mining. This assumption may not lead to overestimation of the specific extraction energy of uranium from ore, the average of all mines and mills. [Mortimer 1977], one of the few studies which include ISL, gives figures in the same range as soft ore mining and milling.
The direct energy consumption of the Beverley ISL mine turns out to be as high as that of the Ranger open pit mine, both mines are located in Australia [Mudd & Diesendorf 2007]. Impacts of ISL on the environment are addressed in [WISE-U 2015].

Mining of soft ores

For reason of the wide dispersion in published figures this study uses the figures from [Rotty *et al.* 1975], that may be seen as a world average of uranium mines (open pit, underground, ISL), with average overburden ratio and haulage distance, and with soft ores.

$J_{mining} = J_e + J_{th}$ = 1.06 GJ/Mg ore J_{th}/J_e = 8.0

The figures from Rotty *et al.* are based on an unpublished survey of energy consumption in the USA mining and milling operations, conducted by the US Bureau of Mines in 1973. At that moment virtually all uranium

in the USA was recovered from high-grade sandstone deposits. The figures represent the average of 60% open-pit and 40% underground mining and include, according to the authors, indirect energy consumption: the energy embodied in chemicals and equipment. The figures from Rotty *et al.* are used in [ERDA-76-1], a study also referred to by [WNA-*eroi* 2016]. Rotty nor ERDA made distinction between hard ores and soft ores, e.g. between sandstone and granite, probably because their data base concerned soft ores only, mainly sandstones.

Assumed that the electric input, including that for production of the explosives, is generated by fossil-fuelled power plants with an average thermal efficiency of e = 40%, the total thermal input becomes:

J_{m+m} (Σth, ore) = 1.237 GJ/Mg ore

Assumed an average specific CO_2 emission of γ= 75 g/MJ_{th}, the specific emission of mining soft uranium ore at a world average mine would become:

γ_{mining} = 93 kg CO_2/Mg ore

The specific CO_2 emission of ISL mines (In Situ Leaching) is assumed to be of the same magnitude, based on the studies [Mudd 1998], [Mudd 2000], [Mudd & Diesendorf 2007].

Mining of hard ores

The mining of hard ores consumes more energy and materials than soft ores. The equipment, such as drills, excavators and dump trucks, suffer by heavier wear and more explosives are consumed per Mg rock. For that reason this study assumes the specific mining energy consumption of hard ores at 1.5 times that of soft ores:

$J_{mining} = J_e + J_{th}$ = 1.58 GJ/Mg ore $\qquad J_{th}/J_e$ = 8.0

Assuming the indirect energy consumption of the excavation en haulage equipment would double by heavy wear, an overburden ratio S = 3, a haulage distance d = 30 km and an explosives consumption of x = 1 kg/Mg rock, the specific energy consumption of mining hard ore calculated by equation 1 would become:

J_{mining} = 1.68 GJ/Mg ore.

So the figure of 1.58 GJ/Mg ore seems plausible and not overestimated, but unfortunately no practical data are found to ustain this figure, other than qualitive statements.

Assumed that the electric input, including for production of the explosives, is generated by fossil-fuelled generators at the mining sites, the average total thermal input of mining hard oresbecomes:

J_{th} = 1.843 GJ/Mg ore

and the specific CO_2 emission:

γ_{mining} = 138 kg CO_2/Mg ore

Ore processing (milling)

Energy consumption and CO_2 emission of the extraction of uranium from the ore, per Mg recovered uranium, depends on a number of variable conditions, such as:

- Ore grade, determines the dilution factor: the mass of ore to be processed per Mg uranium; the ore grade of the currenty operating mines varies from roughly 10% to 0.01% U, a factor of 1000. The world average ore grade of currently operating uranium mines is about 0.1-0.05% U_3O_8. The ore grade determines the energy consumption of crushing and grinding and the amount of chemicals consumed per kg U for leaching and extraction. Lower grade means the need to grind the ore to a finer mesh and to use more chemicals per Mg uranium, and consequently the specific energy consumption per Mg ore increases.
- Extraction yield (= recovery factor): fraction of uranium that is actually extracted from the ore.

- Mineralogy of the ore, determines the hardness of the minerals to be crushed and grinded and the chemical refractoriness of the uranium minerals to be dissolved.
- Chemical composition of the ore, determines the type of chemicals used, for example acid leaching or alkaline leaching, and reaction conditions, such as high or ambient temperature. The world average includes alkaline ores. The leaching of alkaline ores takes much more energy than acidic ores (as at Ranger), due to the elevated temperatures (60-80 °C) and the consumption of chemicals with high embodied energy, such as sodium hydroxide and sodium carbonate.

Ore grade and extraction yield are two quantifyable variables in the assessment of the energy consumption and CO_2 emission of the exraction of uranium from its ore. The different ore types are simplified to two classes: soft ores and hard ores. World average figures of other variables and parameters are used.

Milling of soft ores

For ore processing (milling) at Ranger (based on [ERA 2006] and [ERA-AR 2005]) this study found the following figures:

$J_{milling} = J_e + J_{th}$ = 1.133 GJ/Mg ore $\quad J_{th}/J_e$ = 4.56

This figure is a low estimate, for several energy inputs of the ore processing are not included:

- fresh water supply
- treatment of process water and pond water
- embodied energy of the extraction chemicals, kerosene and complexing agent
- direct and indirect energy of several partial processes of the ore processing chain, e.g. thickeners and centrifuge
- waste management
- construction of the ore processing facilities.

The energy input of each of these items may be of minor importance, but jointly the inputs may be a significant contribution to the overall specific energy consumption.

For that reason this study applies the somewhat higher figure of [ERDA-76-1] for soft ores:

$J_{milling} = J_e + J_{th}$ = 1.27 GJ/Mg ore $\quad J_{th}/J_e$ = 7.0

Usually the electric inputs of uranium mines are generated on site by oil-fuelled generators. Consequently the total thermal energy input is:

J_{th} = 1.508 GJ/Mg soft ore

and the specific CO_2 emission:

$\gamma_{milling}$ = 75•1.508 = 113 kg CO_2/Mg soft ore

Milling of hard ores

For hard ores this study applies the figures based on [Kistemaker 1976] and [Kistemaker 1975]. Kistemaker published figures for the milling of poor hard ores, based on the data of 1974 supplied by NUFCOR (Nuclear Fuels Corporation), responsible at that time for the mining and milling activities at the South African uranium mines. The Kistemaker figures include the embodied energy of a number of chemicals, not all, but do not include the energy input of equipment and capital goods. The electric inputs are generated on site by oil-fuelled generators. Consequently the total thermal energy input is:

$J_{milling}$ (Σth, ore) = 8.67 GJ/Mg hard ore

and the specific CO_2 emission is:

$\gamma_{milling}$ = 75•8.67 = 650 kg CO_2/Mg hard ore

Extraction yield

The *extraction yield*, also called the *recovery factor* or *recovery yield Y*, is the ratio of the mass of uranium actually extracted and the mass of the uranium present in the treated amount of rock.

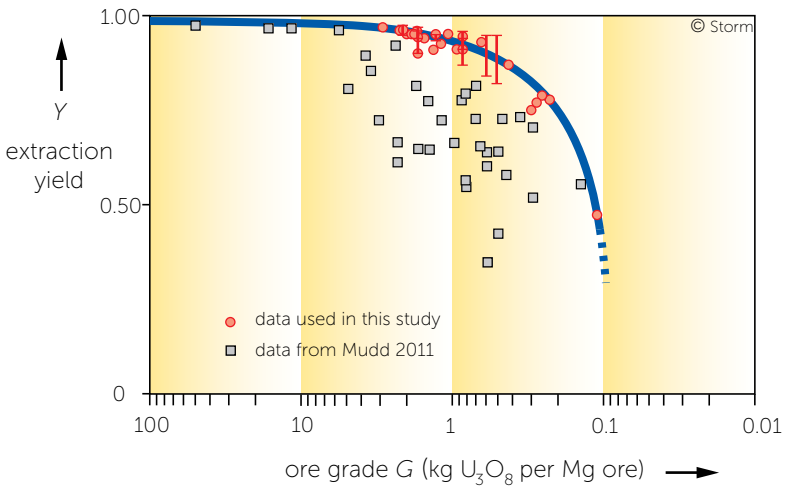

Figure 4

The extraction yield of uranium from ore as function of the ore grade. The red dots are the highest reported figures from the literature, based on actual mining operations. This curve may be seen as the upper limit of the attainable extraction yields using the current extraction technology. The grey squares are empirical data from [Mudd 2011].

The data used in this study (red dots and bars) have been taken from: [Burnham *et al.* 1974], [Franklin *et al.* 1971], [GJO-100 1980], [Huwyler *et al.* 1975], [James & Simonson 1978], [James *et al.* 1978], [Kistemaker 1976], [Kistemaker 1975], [Mutschler *et al.* 1976], [Rombough & Koen 1975], [Ross & Guglielmin 1968], [Rotty *et al.* 1975], [Simonson *et al.* 1980], [SRI 1975].

Reported yield data are not always unambiguous. In many cases it is not clear on which quantity of uranium the reported yields are based:

- the *in-situ* uranium (as present in the undisturbed ore body),
- in the actually mined ore
- in the ore entering the mill (the mined ore minus the waste)
- in the ore entering the chemical separation processes.

Some mining companies published data which would result in yields of 100% or higher.

The data used in Figure 4 may seem perhaps outdated, but during the past 4-5 decades the extraction techniques applied in the uranium industry have not changed significantly. The study of [Mudd 2011] proves the curve of Figure 4 to be at the upper limit of the current practice. In practice nearly all uranium mines achieve substantially lower extraction yields at a given ore grade than suggested by the curve of Figure 4.

The extraction is governed by basic physical and chemical laws, which cannot be circumvented by technology. A low yield at low grades may be improved by application of more selective separation processes, at the expense of much higher specific energy requirements per mass unit recovered uranium.

The extraction of any metal from its ore involves a number of physical and chemical equilibria. From the Second Law of thermodynamics follows that these equilibria never go to completion. That means that a complete separation is not possible, there always will be losses. The decline of the extraction yield at lower grades is a direct consequence of this observation. The lower the concentration of uranium in the pregnant liquor, the higher its entropy and the more energy is required to extract a certain amount of uranium from that liquor. The higher the entropy of the uranium, the less complete its separation from the liquor and the greater the fraction lost in the waste streams.

Table 1

Summary of specific energy investment and CO_2 emission of uranium mining + milling at mines with average overburden ratio and hauling distance.

quantity	unit	soft ores	hard ores
total thermal energy investment mining	GJ/Mg ore	1.237	1.843
total thermal energy investment milling	GJ/Mg ore	1.508	8.67
total thermal energy investment mining + milling	GJ/Mg ore	2.745	10.51
CO_2 emission mining + milling	kg CO_2/Mg ore	206	788

Specific energy input of uranium mining + milling

The thermal energy requirements of the recovery of one kilogram of uranium leaving the mill, $J_{m+m}(U)$, as function of the ore grade G, counted in kg uranium per Mg ore, and the recovery yield Y, can be calculated via the following equation 2:

$$J_{m+m}(U) = \frac{J_{m+m}(ore)}{Y \bullet G}$$

$J_{m+m}(U)$ = specific energy consumption, GJ/kg uranium
$J_{m+m}(ore)$ = specific energy consumption, GJ/Mg ore
Y = extraction yield = fraction of recovered U
G = ore grade, kg U/Mg ore

eq 2

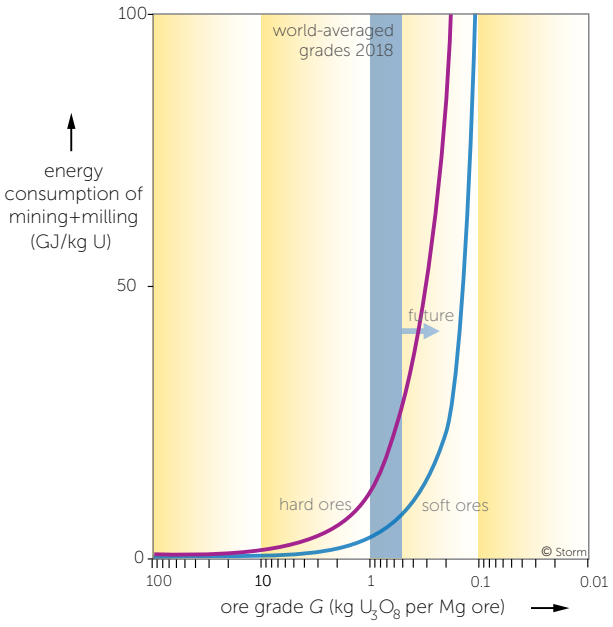

Figure 5

Energy consumption of the recovery of uranium from the earth's crust (mining + milling) as function of the ore grade, in gigajoule per kg recovered uranium. At present the world-averaged ore grade is in the range of G = 0.1-0,05% U_3O_8 and the trend is decreasing over time.

mining + milling soft ores:

J_{m+m} (Σth, ore) = 1.237 + 1.508 = 2.745 GJ/Mg ore

mining + milling hard ores:

$$J_{m+m}\ (\Sigma \text{th, ore}) = 1.84 + 8.67 = 10.51 \text{ GJ/Mg ore}$$

From the this the specific CO_2 emission of uranium mining + milling can be calculated:

$$\gamma_{m+m} = 75 \bullet J_{m+m}(U) \qquad \text{kg } CO_2\text{/kg U}$$

Energy cliff

The thermodynamic quality of a uranium resource is the determinant of being a net energy source or not. Here we define the thermodynamic quality of a uranium resource as the net quantity of useful energy that can be extracted from 1 kg natural uranium from that resource, that is the amount of electricity available to the consumer, minus the useful energy (work) required to extract 1 kg pure uranium from that resource. If the extraction of 1 kg uranium requires as much work as the amount that than can be generated from that quantity ofuranium, the uranium resource in question is not an energy source, but an energy sink. The minimum amount of extraction work is governed by basic physical laws. Advanced technology may come closer to the thermodynamic minimum, at the expense of more useful energy, but never can surpass the minimum.

The previous sections discussed the factors determining the work required to extract uranium from uranium deposits as found in nature. This study took into account: ore grade, extraction yield of milling, and mineralogy of the ore, the latter being simplified to a classification into soft ores and hard ores. Other mining conditions are averaged in the assessment.

Net energy content of a uranium resource

The quantity of potential energy in 1 kg natural uranium that can be released is not unambiguously defined, like the combustion heat of a fossil fuel, because this quantity depends on the applied reactor technology. As pointed out in the introduction, modern power reactors cannot fission more than about 0.5% (5 g/kg U) of the nuclei in natural uranium. This figure sets a practical limit to the energy content of natural uranium.

Assumed that fission of one uranium nucleus releases 200 MeV = $3.2 \bullet 10^{-11}$ J, then the complete fission of 1 g uranium-238 releases $J_{fission}$ = 81.1 GJ/g, and 1 g U-235 releases 82.1 GJ/g. In power reactors 60% of the fission energy comes from U-235 and 40% from plutonium nuclei formed from U-238 by neutron capture.

This study assumes an average fission energy of $J_{fission}$ = 82 GJ/g U.

At a fissioned fraction of 5 g/kg U_{nat} the practical energy content of natural uranium, released as heat and radiation, then becomes:

$$J_{fission} = 5 \bullet 82 = 410 \text{ GJ/kg } U_{nat}$$

The fission heat and radiation is not directly useable and has to be converted into electricity in order to become useful energy. At an average thermal efficiency of 33% the gross content of useful energy of natural uranium becomes:

$$J_U \text{ (gross)} = 0.33 * 410 = 137 \text{ GJ/kg } U_{nat}$$

The thermodynamic quality of uranium *in situ*, that is still present in the earth's crust in a given deposit, is the amount of useful energy extractable from 1 kg of uranium, minus the energy required to recover 1 kg of uranium from that resource:

$$J_U \text{ (net)} = 137 - J_{m+m}(U) \text{ GJ/kg } U_{nat}$$

Figure 5 shows that the recovery energy of uranium, J_{m+m} (U), exponentially increases with decreasing ore grade. Consequently the thermodynamic quality of uranium resources declines with decreasing ore grade and becomes zero at a certain ore grade; this phenomenon is called the energy cliff, see Figure 6. For soft ores the cliff falls to zero at a grade of about 0.01% U_3O_8, corresponding with 85 g U per Mg rock, and for hard ores the zero point lies at a slightly higher grade.

There are various types of uranium ores, so in practice the thermodynamic quality of a currently exploited uranium resource may lay between the two curves. Uranium deposits tend to be harder to mine and mill, consisting of more refractory minerals, the lower their grade, a geologic phenomenon.

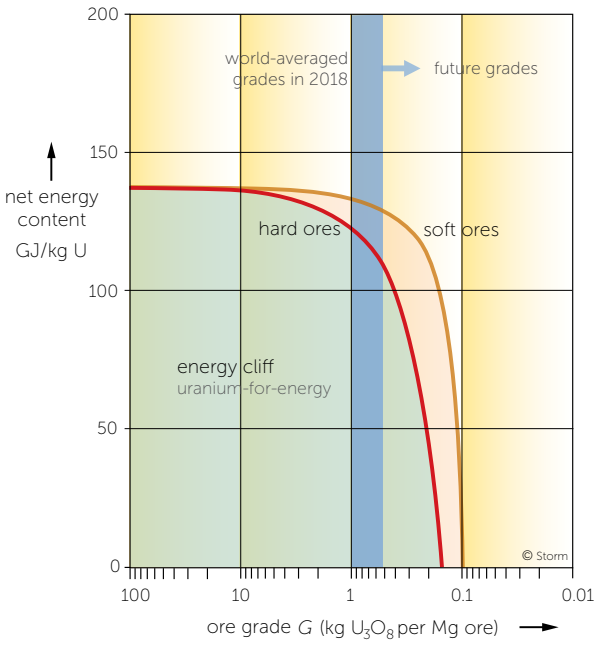

Figure 6

Energy cliff. Net energy content of natural uranium as function of the ore grade. The net energy content is defined as the amount of useful energy that can be generated per kg natural uranium minus the energy required for recovery of 1 kg uranium from the earth's crust, ignoring the remaining processes of the nuclear chain. Beyond a certain grade no net energy generation from a uranium deposit is possible.

The net useful energy content per kg U_{nat} that eventually becomes available to the consumer equals the above defined useful energy content minus the useful energy investments required for the remaining processes of the nuclear process chain.
Taking these energy investments also into account, the curves of Figure 6 would have to be moved to a lower net energy content. In this way the practical energy cliff would become observable.

$$\gamma_{m+m}(U) = 75 \bullet \frac{J_{m+m}(\Sigma th,ore)}{Y \bullet G}$$

$\gamma_{m+m}(U)$ = specific CO_2 emission, kg CO_2 /kg uranium
$J_{m+m}(\Sigma th,ore)$ = specific all-thermal energy consumption, GJ/Mg ore
Y = extraction yield = fraction of recovered U
G = ore grade, kg U/Mg ore

eq 3

mining + milling soft ores: J_{m+m} (Σth, ore) = 2.745 GJ/Mg ore
hard ores: J_{m+m} (Σth, ore) = 10.51 GJ/Mg ore

CO_2 trap

Generally the electricity consumed at uranium mines is generated by oil-fuelled generators, so all energy inputs of mining and miling may be considered to be provided by fossil fuels. This study assumes a thermal-to-electric conversion efficiency of 40% to calculate the all-thermal energy input of mining + milling,

indicated by the quantity J_{m+m} (Σth, U). From the specific thermal energy input of uranium mining and milling the specific CO_2 emission were calculated by equation B3, assumed the specific CO_2 emission of the used fossil fuels (diesel oil and fuel oil) is 75 g CO_2/MJ.

$$\gamma_{m+m}(U) = 75 \bullet J_{m+m}(\Sigma th, U) \qquad \text{kg } CO_2/\text{kg U}$$

The specific CO_2 emission of mining +milling, γ_{m+m}(e) g CO_2/kWh, can be calculated by equation B4.

$$\gamma_{m+m}(e) = \frac{\gamma_{m+m}(U) \bullet m(U_{nat})}{E_{gross}}$$

γ_{m+m}(e) = specific CO_2 emission, g CO_2 /kWh
γ_{m+m}(U) = specific CO_2 emission, kg CO_2 /kg uranium
$m(U_{nat})$ = lifetime consumption of natural uranium, Mg
E_{gross} = lifetime gross electricity production, kWh

eq 4

The specific CO_2 emissions of mining + milling of uranium from ore in the range of 0.1- 0.05% U_3O_8, the present world average, related to the advanced reference reactor and the hypothetical EPR are summarised in Table 2.

Figure 7 represents the curves derived from equation 4 for hard ores and soft ores, valid for reference advanced reactor. For many uranium mines the figures will be between the two curves, due to widely different conditions from mine to mine. The differences between the two reference reactors (advanced reactor and EPR design) lie within the range between the two curves.

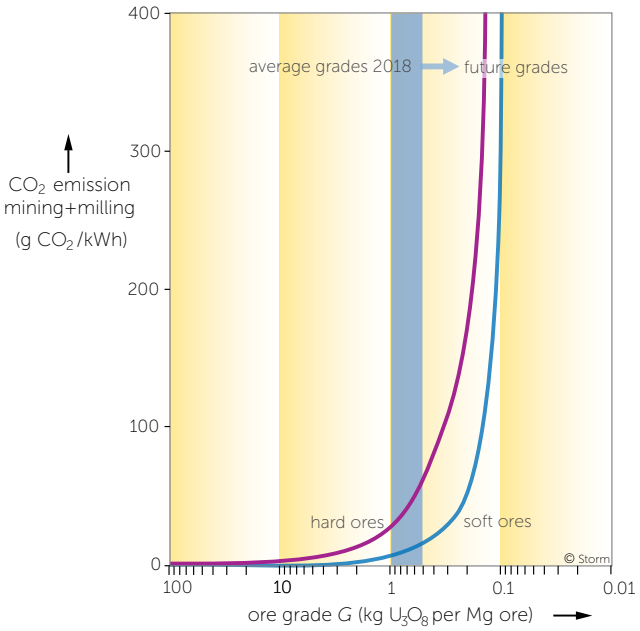

Figure 7

Specific CO_2 emission of the recovery of uranium from ore as function of the ore grade. Differences between the curves concerning the advancedcreactor and the EPR design are minor and remain within the range of the data the curves are based on.

As indicated in the diagram of Figure 7, the world average ore grade decreases with time. The most easily exploitable ore deposits with highest grades are mined first, because these offer the highest return on investment. During the past decades virtually no new rich ore deposits of significant size have been discovered. As a result the specific CO_2 emission of uranium recovery and consequently of nuclear generated electricity

rises with time, steeply at low grades. The larger a uranium resource, the lower its grade, a common geologic phenomenon. At a grade of 130-100 g U/Mg ore the specific CO_2 emission of nuclear power surpasses that of gas-fired electricity generation, this is called the *CO_2 trap*.

Table 2

Lifetime data on the specific CO_2 emission of uranium mining + milling.

quantity	unit	advanced reactor	EPR design
input mass of natural uranium, $m(U_{nat})$	Mg	5748	17880
gross electricity production, E_{gross}	kWh	$219 \cdot 10^9$	$780 * 10^9$
total CO_2 emission, soft ores G = 0.1-0.05% U_3O_8	Gg	1551 - 3283	4823 - 10214
total CO_2 emission, hard ores, G = 0.1-0.05% U_3O_8	Gg	5937 - 12527	18467 - 39106
specific CO_2 emission, soft ores, G = 0.1-0.05% U_3O_8	g CO_2/kWh	7.1 - 15.0	6.2 - 13.1
specific CO_2 emission, hard ores, G = 0.1-0.05% U_3O_8	g CO_2/kWh	27.1 - 57.4	23.7 - 50.1

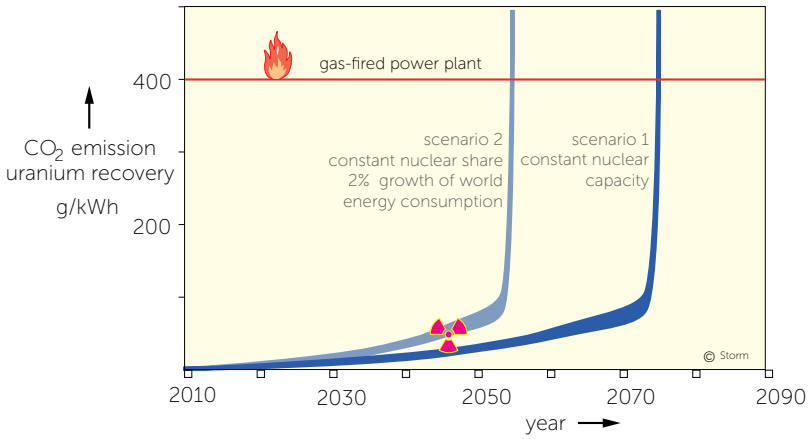

Figure 8

CO_2 trap: indication of the specific CO_2 emission by uranium mining + milling as function of the time, assuming that the richest available uranium ores are mined first. With time the mined ores are getting harder. In scenario 1 the nuclear capacity would remain at the current level (about 360 GWe). In scenario 2 the nuclear contribution to the global energy production would remain at the current level of 1.6%, implying an increasing global nuclear capacity.

References

Burnham et al. 1974,
Burnham JB, Brown RE, Enderlin W, Hanson MS, Hartley JN, Hendrickson PL, Paasch RK, Rickard WH, Schrenkhise RG & Watts RL,
Assessment of uranium and thorium resources in the United States and the effect of policy alternatives,
PN-238-658,
Battelle Pacific Northwest Laboratories, Richland, Washington: December 1974.

CSIRO 2004
Taylor G, Farrington V, Woods P, Ring R & Molloy R,
Review of environmental impatcs of the acid in-situ leach uranium mining process,
CSIRO Land and Water Client Report, August 2004,
CSIRO Land and Water, Clayton South, Vic 3169, Australia,
www.epa.sa.gov.au/pdfs/isl_review.pdf

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

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

ERDA-76-1
A National Plan for Energy Research, Development and Demonstration: Creating Energy Choices for the Future,
Volume 1, The Plan. p. 111-116, Appendix B: Net energy analysis of nuclear power production,
Washington DC: Energy Research and Development Administration, 1976.

Franklin et al. 1971
Franklin W D, Mutsakis M & Ort R G,
Total energy analysis of nuclear and fossil fueled power plants,
ORNL-MIT-138,
Oak Ridge National Laboratories and Massachusetts Institute of Technology, 23 November 1971.

GJO-100 1980
Statistical data of the Uranium Industry
GJO-100 (80)
Department of Energy, Grand Junction Office, Colorado, USA, 1980.

Huwyler et al. 1975
Huwyler S, Rybach L and Taube M,
Extraction of uranium and thorium and other metals from granite,
EIR-289, Technical Communications 123,
Eidgenössische Technische Hochschule, Zürich,
September 1975
Translated by Los Alamos Scientific Laboratory, LA-TR-77-42, 1977.

James & Simonson 1978
James HE & Simonson HA,
Ore-processing technology and the uranium supply outlook,
Paper in:
Uranium, supply and demand
Proceedings Third International Symposium by The Uranium Institute, London, July 12-14, 1978, pp 107-181.

James et al. 1978
James HE, Boydell DW & Simonson HA.
South African uranium industry plans for expansion
Nuclear Engineering International, November 1978, pp 42-45.

Kistemaker 1975
Kistemaker J,
Energie-analyse van de totale kernenergie cyclus gebaseerd op licht water reactoren,
FOM Instituut voor Atoom- en Molecuulfysica, Amsterdam,1975, (in Dutch)
prepared for Landelijke Stuurgroep Energieonderzoek (LSEO)
LSEO 682

Kistemaker 1976
Kistemaker J,
Aanvulling op: Energie-analyse van de totale kernenergiecyclus gebaseerd op lichtwater reactoren,
LSEO 818, juli 1976 (in Dutch).

Mortimer 1977
Mortimer N D,
The Energy Analysis of Burner Reactor Power Systems,
PhD dissertation, Milton-Keynes Open University, UK,
December 1977.

MPR-2776 2005
Bubb J, Carroll D, D'Ollier R, Elwell L & Markel A,
DOE NP2010 Nuclear power plant construction infrastructure assessment,
prepared for Department of Energy, Washington DC,
MPR-2776,
21 October 2005,
www.ne.doe.gov/

Mudd 1998
Mudd G,
An environmental critique of in situ leach mining: The case against uranium solution mining,
A research report for Friends of the Earth (Fitzroy) with The Australian Conservation Foundation, July 1998,
www.sea-us.org.au/scifacts.html

Mudd 2000
Mudd G M,
Acid in-situ leach uranium mining: 2 - Soviet Block and Asia,
paper for: Tailings and Mine Waste '00,
Fort Collins, CO, USA, January 23-26 2000,
proceedings AA Balkema, Rotterdam, pp.527-536.
‹2000-TMW-AcidISL-FSU-Asia.pdf›
http://users.monash.edu.au/

Mudd 2011
Mudd G,
Uranium mining & CO2 accounting,
AusIMM Uranium Conference, Perth, 8 June 2011
file: 2011-06-08-AusIMM-U-Mining-v-Grade-v-CO2.ppt
www.ausimm.com.au/uranium2011/

Mudd & Diesendorf 2007
Mudd GM & Diesendorf M,
Sustainability Aspects of Uranium Mining: Towards Accurate Accounting?
2nd International Conference on Sustainability Engineering and Science,
Auckland, New Zealand, 20-23 February 2007.
www.nzsses.auckland.ac.nz/

Mutschler et al. 1976
Mutschler PH, Hill JJ, & Williams BB,
Uranium from the Chatanooga shale, Some problems involved in development,
PB-251-986,
Bureau of Mines, Pittsburg, USA, February 1976.

Orita 1995
Orita Y,
'Preliminary assessment on nuclear fuel cycle and energy consumption',
Part of: Assessment of greenhouse gas emissions from the full energy chain for nuclear power and other sources,
Working material, International Atomic Energy Agency, Vienna, Austria, 26 28 September 1995.

Rombough & Koen 1974
Rombough C T & Koen B V,
The total energy investment in nuclear power plants,
Technical Report ESL-31
Energy Systems Laboratories, College of Engineering, The University of Texas at Austin, November 1974.

Rombough & Koen 1975
Rombough C T & Koen B V,
Total energy investment in nuclear power plants,
Nuclear Technology, Vol 26 May 1975, pp 5-11.

Ross & Guglielmin 1968
Ross AH & Guglielmin LG,
Milling technology of uranium ores
Nuclear Applications, vol 5, nr 11, November 1968, pp 311-318.

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.

Simonson et al. 1980
Simonson HA, Boydell DW & James HE,
The impact of new technology on the economics of uranium production from low-grade ores
paper in:
Uranium and nuclear energy
Proceedings Fifth International Symposium by The Uranium Institute, London, July 2-4, 1978, pp 92-180.

SRI 1975
Manpower, materials, equipment and utilities required to operate and maintain energy facilities,
PB 255 438,
Stanford Research Institute (SRI), Menlo Park, CA, March 1975,
prepared for Bechtel Corporation, San Francisco CA and National Science Foundation.

WISE-U 2015
Impacts of uranium in-situ leaching
WISE Uranium Project,
updated 9 Jan 2015
‹ Impacts of uranium in-situ leaching ›
http://www.wise-uranium.org/uisl.html
retrieved Sept 2018

WNA-eroi 2016
Energy return on investment,
World Nuclear Association, updated November 2016
http://www.world-nuclear.org/information-library/energy-and-the-environment/energy-analysis-of-power-systems.aspx
retrieved June 2017

WNA-mining 2016
Uranium mining overview,
World Nuclear Association, uodated February 2016
‹ Uranium mining overview - World Nuclear Association.pdf ›
http://www.world-nuclear.org/information-library/nuclear-fuel-cycle/mining-of-uranium/uranium-mining-overview.aspx
retrieved 11 April 2018

WNA-Ugeol 2015
Geology of uranium deposits,
World Nuclear Association, February 2015
‹ Geology of uranium deposits - World Nuclear Association.pdf ›
http://www.world-nuclear.org/information-library/nuclear-fuel-cycle/uranium-resources/geology-of-uranium-deposits.aspx
retrieved 11 April 2018