Life Cycle Inventory of generic uranium in-situ leaching

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Zürich, November 2011

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Title picture Wellfield of Beverley In-situ Leaching uranium mine in Australia.
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http://www.ga.gov.au/minerals/mineral-resources/uranium.html

1 In Situ Leaching description

Mining by in-situ leaching (ISL), or solution mining (Ger. *Untertage-Laugung*), involves treating the ore body where it is (in-situ) by injecting liquids underground and pumping them through the ore body to mobilise and recover the metals from the ore (leaching). For ISL, the ore body needs to be permeable to the liquids used, e.g. sand or sandstones, and should be located so that these liquids do not contaminate far-field groundwater. This means the deposit should be sandwiched between mechanically stable and hydrologically impermeable layers. So not any kind of deposit can be mined with ISL.

As leaching liquids, or so called lixiviants, either alkaline sodium carbonate or sulfuric acid are used. The former is used if large amounts of lime or carbonates are present in the ore body. The liquids contain also an oxidant like hydrogen peroxide, nitrate ions or sodium chlorate, to oxidise uranium U^{+IV} in UO_2 to the more mobile U^{+VI} to accelerate leaching. Liquids are pumped to the ore body by injection wells and regained by recovery or production wells. Uranium is recovered from the leach solution by ion exchange or solvent extraction and precipitation. After re-conditioning of the solutions, e.g. adding of acid-base reagents and oxidants, they are recycled in the injection wells.

ISL mining technology for uranium was independently developed in the former USSR and the USA in the early 1960s. The USSR used acid leaching, the USA predominantly alkaline leaching. ISL technology is currently frequently applied in the uranium production of the USA, Ukraine, Kazakhstan and partially in Australia.

Fig. 1.1 Injection and production wells of the ISL mine in Zarafshan, Uzbekistan. Source: IAEA 2001a.

2 ISL inventory

In former ecoinvent inventories prior to v3, uranium In-situ leaching was not included. Only open-cast or underground uranium mining was inventoried. In 2007 ISL made up 28% of the worlds uranium mine supply (Bartsch 2010). ISL produces yellowcake without milling and therefore replaces the functions of mining and milling.

A first coarse inventory of ISL mining is compiled here. As with other uranium mining/milling operations of ecoinvent, the functional unit is "1 kg of natural uranium product" i.e. 1kg yellowcake as U_{nat}. In the following "kg U" refers to this functional unit.

Energy demand

Energy is assumed to be supplied with diesel generators, inventorying with the rather large (i.e. environmentally advantageous) 10MW diesel generator in ecoinvent as a proxy.

ISL Operations	MJ diesel/kg U		Source
ISL Australia	253	1	WNA 2009-27
ISL Kazakhstan	440	1	WNA 2009-27
ISL Beverley, Australia	167	2	Heathgate 2006, p.45
ISL Beverley, Australia	172		Mudd & Diesendorf 2007
ISL This study	**253**		

1 Converted from electricity demand assuming 27% diesel generator efficiency

2 Figure for natural gas generator

Acid consumption

Sulfuric acid is used to dissolve the uranium in-situ (lixiviant). Oxidation agents are also needed oxidize in-situ uranium for solubility, e.g. hydrogen peroxide, but are neglected in the inventory, as being probably of low importance.

ISL Operations	kg sulfuric acid/kg U	Source
ISL Beverley, Australia	7.7	WNA 2009-27
ISL Kazakhstan	40 (<40 – 80)	WNA 2009-27
ISL This study	**20**	

Water consumption

ISL Operations	l water/kg U	Source
ISL Beverley, Australia	9123	Mudd & Diesendorf 2007
ISL This study	**9123**	

Radon emissions

Gaseous Radon-222 emits from holding ponds to the environment due to evaporation.

ISL Operations	kBq Rn-222/kg U		Source
ISL Beverley, Australia	43'100	1	IAEA 2005
ISL This study	**21'550**	2	

1 Given as upper estimate of 100 GBq per day, converted with annual production of 1000 t yellowcake in same production = 847 t U.

2 Figure reduced by 50%

Radiation doses for mine employees

The mine employees are closely exposed to radiation from uranium and other isotopes and are therefore monitored. Some data of radiation exposure of ISL employees in Beverley, Australia, is available from (Taylor et al. 2004, p.33). Average dose to employees was 0.68 mSv/yr in 2003. Total workforce at Beverley in 2004 was 179 employees. Thus the annual collective dose is estimated to be

0.122 person.Sv per operation year. Uranium production in Beverly was 607'627 kg U_{nat} (Taylor et al. 2004, p.5). So per kilogram U_{nat} a collective dose to workers of $2 \cdot 10^{-7}$ person.Sv is caused. This data from Beverly 2003 is used for ISL in general. The conversion of collective radiation doses in LCIA methods is described below.

Injection and recovery wells

No data was found for the specific infrastructure of an ISL field. An estimate of the probably most important part – the injection and recovery pipes – was based on a assumed 20m-edge, hexagonal wellfield pattern geometry with central recovery well, wells running 120m deep and 10 kg steel per metre of piping, 15 m ore aquifer height with 0.168% U_3O_8 ore grade and 75% overall recovery, resulting in 32 kg U recovered per m^2 surface area and **0.108 kg steel pre kg uranium recovered**. Due to use of sulfuric acid as lixiviant high-alloyed steel is assumed. No re-use or recycling of steel is assumed.

The significance of the energy for drilling the wells (0.0108 drill-meters per kg recovered uranium) was checked with an inventory figure for drilling shallow geothermal heat wells from ecoinvent 1996 (ESU 1996, p.X.12) of 39.3 MJ diesel per meter, resulting in 0.46 MJ/kg U, which appears negligible compared to the overall process energy of 253 MJ/kg U.

Remediation

Remediation in ISL wellfields consists – if done at all – by flushing the depleted underground with water until acceptable groundwater concentrations are attained. No detailed inventory of this process was compiled. Instead the following process with simplified assumptions and estimates is assessed:

- The initial groundwater concentrations in the wellfield are assumed to be identical to the initial leachate concentrations in uranium tailings, as established in (Doka 2008, p.10).
- After 2 years of mining per field, remediation takes 5 years and a pumped remediation water volume of $25m^3$ per kilogram produced uranium is estimated.
- The concentration of pollutants decreases exponentially to 10% of the initial value in that time.
- Leachate treatment will separate pollutants with an efficiency of 90%.
- The separated pollutants are disposed in a residual material landfill.
- Direct process energy intensity for remediation is identical to uranium production, as the methods are similar: pumping and separation. Process energy for remediation is therefore 2.5 times the process energy of mining (5 years ÷ 2 years).

The ecoinvent residual landfill model is then used to estimate emissions from the landfilled waste (Doka 2003). Any further fate of the remediated underground is neglected here, although it cannot be guaranteed that no pollutant emissions to adjacent groundwater or the surface occur, especially in the long run.

Land transformation and occupation

Per square meter of surface area an amount of 32 kg natural uranium is produced, as calculated above; see 'Injection and recovery wells'. Hence, per kilogram uranium product 0.0312 m^2 mine field area is necessary. Occupation duration is seven years (2 operation, 5 remediation) and land occupation is thus 0.22 m^2a (as mineral extraction site).

Resource extraction and recovery

The inventory is based on an overall generic recovery for acid ISL of 75% as given in (Red Book 2003, p.265). Non-recovered uranium is assumed to remain underground, but is assumed to be worthless uranium leftover in an exploited deposit. Therefore it is inventoried as resource extraction for the impact assessment.

Tab. 2.1 Inventoried unit process exchanges for in-situ leaching per kg natural uranium produced

Technosphere inputs				
sulphuric acid, liquid, at plant	RER	kg	20	
diesel, burned in diesel-electric generating set (1)	GLO	MJ	253.3	
steel, electric, chromium steel 18/8, at plant	RER	kg	0.108	
water, decarbonised, at plant	RER	kg	9123	
diesel, burned in diesel-electric generating set (2)	GLO	MJ	633.3	
collective radiation dose (3)		person.Sv	2E-07	
Natural resources				
Uranium, in ground		kg	1.33	
Transformation, from unknown		m2	0.03122	
Transformation, from to extraction site		m2	0.03122	
Occupation, mineral extraction site		m2a	0.2185	
Transformation, from mineral extraction site		m2	0.03122	
Transformation, to unknown		m2	0.03122	
Air emissions, low-population density				
Radon-222		kBq	21'550	
Groundwater emissions from residual landfill			**Short-term**	**Long-term**
Sulfate		kg	16.48	137.1
Nitrate		kg	4.449	19.11
Phosphate		kg	0.0005546	0.3322
Boron		kg	0.00001271	0.001595
Chloride		kg	0.5642	1.408
Fluoride		kg	0.003066	0.0535
Silver, ion		kg	0.000000001506	0.0000009023
Arsenic, ion		kg	0.009171	0.000000000009171
Barium		kg	0.000000005962	0.000003571
Cadmium, ion		kg	0.000000002852	0.000001709
Cobalt		kg	0.000001721	0.001031
Chromium VI		kg	0.00003021	0.00009544
Copper, ion		kg	0.000000232100	0.000139
Mercury		kg	0.000000002673	0.000001601
Manganese		kg	0.000002124	0.001272
Molybdenum		kg	0.02616	0.0001206
Nickel, ion		kg	0.000001434	0.0008592
Lead		kg	0.000000009267	0.000005551
Antimony		kg	0.0008849	0.001624
Selenium		kg	0.00225	0.004131
Vanadium, ion		kg	0.00003496	0.01095
Zinc, ion		kg	0.0000001204	0.00007209
Beryllium		kg	0.0000002251	0.0001348
Strontium		kg	0.000003648	0.002185
Titanium, ion		kg	0.00001582	0.009475
Silicon		kg	0.000151	0.06701
Iron, ion		kg	0.000001357	0.000813
Calcium, ion		kg	0.0003298	0.1975
Aluminum		kg	0.0002917	0.1747
Potassium, ion		kg	0.05014	0.1277
Magnesium		kg	0.0001479	0.0886
Sodium, ion		kg	1.168	1.944

1 Diesel consumption for mining process

2 Estimated diesel consumption for remediation process

3 Only from radiation exposure of mining employees, not to the general public

3 Employee radiation doses in LCIA

The original ecoinvent data v2.2 includes only emissions of radioactive pollutants to the environment. Radiation doses which affect directly the employees in plants are originally not assessed.

Doses of radiation exposure of mine workers are sometimes published in mSv (millisievert) per individual and per year. Multiplied by the number of affected workers exposed, so called collective doses for a group of people result. The physical unit is usually given as person-Sievert (or man-Sievert). Collective dose data can be converted into a human health burden in the LCIA stage. The ReCiPe'08 as well as Eco-indicator'99 Impact Assessment methods asses radioactive emissions, but originally only burdens of the remote regional and intenational public are modelled and very local effects are excluded (Goedkoop et al. 2000, Goedkoop et al. 2009). However those methods already include a conversion of collective doses from person-Sievert to environmental burden units. This conversion can also be applied to collective doses of workers.

Tab. 3.1 Converting collective radiation doses into environmental burden points for ReCiPe'08 and Eco-indicator'99 Impact Assessment methods.

	Human health damage per collective dose [1] DALY/person.Sv	Environmental burden points per health damage pts/DALY	Environmental burden points per collective dose [2] pts/ person.Sv
ReCiPe'08	1.17	19'796	23'161
Eco-indicator'99	1.5	25'970	38'955

1 Human health damages are expressed in disability-adjusted life years DALY

2 Though conceptually similar, the resulting points of the two methods ReCiPe'08 and Eco-indicator'99 shall be kept separate, as they are not exchangeable.

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