



Uranium mining

Unveiling the impacts of the nuclear industry

Report written by Bruno Chareyron

with contributions from

Lidija Živčič, Tomislav Tkalec and Marta Conde



Uranium mining

Unveiling the impacts of the nuclear industry

Report written by:

Bruno Chareyron (CRIIRAD)

with contributions from:

Lidija Živčič and Tomislav Tkalec (FOCUS), Appendix 1

Lidija Živčič, paragraph 5.5

Marta Conde (ICTA), reviewing

Layout:

Lidija Živčič

Series editor:

Beatriz Rodríguez-Labajos

The contents of this report may be reproduced in whole or in part for educational or non-profit services without special permission from the authors, provided acknowledgement of the source is made.

This publication was developed as a part of the project Environmental Justice Organisations, Liabilities and Trade (EJOLT) (FP7-Science in Society-2010-1).

EJOLT aims to improve policy responses to and support collaborative research and action on environmental conflicts through capacity building of environmental justice groups around the world.

Visit our free resource library and database at www.ejolt.org, follow us on Facebook www.facebook.com/ejolt or follow tweets (@EnvJustice) to stay current on latest news and events.

The EJOLT project (2011-15) has received funding from the European Union's Seventh Framework Programme for research, technological development and demonstration under grant agreement no 266642. The views and opinions expressed in the website and in all EJOLT publications and documentaries including the Atlas reflect the authors' view and the European Union is not liable for any use that may be made of the information contained therein.

This document should be cited as:

Chareyron, B., Živčič, L., Tkalec, T., Conde, M., 2014. Uranium mining. Unveiling the impacts of the nuclear industry. EJOLT Report No. 15, 116 p.

Abstract

Uranium mining and milling comprise the first phase of the nuclear fuel cycle, and is one of the most polluting ones. The aim of this report is to give workers and communities basic information about radioprotection. The document deals with the radiological characteristics of materials and waste from the mines, principles of radiation protection, and methods of dose evaluation.

The report draws from on-site studies performed in Bulgaria, Brazil, Namibia and Malawi in the course of the EJOLT project and from previous studies performed by CRIIRAD in France and Africa over the last twenty years. It gives examples of the various impacts of uranium mining and milling activities on the environment (air, soil, water) and provides recommendations for limiting these impacts.

This report aims to contribute towards the development of the critical capacities of communities, so that they might have more information with which to face conflicts with states or companies in relation to uranium mining projects.

Keywords

radiological impact

uranium mining

uranium milling

nuclear power

environmental impact

uranium daughter products

health impact

radioprotection

Contents

Foreword	5
1 Uranium mining, an introduction	7
1.1 Utilization of natural uranium	7
1.2 Uranium mining techniques	8
1.3 Main uranium mines and companies	10
1.4 Evolution of world uranium production and demand	12
1.5 New mines and inferred uranium resources	13
2 Radioactivity of materials in uranium mines	15
2.1 Radioactivity of various materials in a uranium mine and mill	17
2.2 The concept of dose	21
2.3 How to evaluate external irradiation	22
2.4 How to monitor internal contamination	26
3 Environmental impacts	35
3.1 Radioactive contamination routes	37
3.2 Impacts of uranium mining and milling operations	43
4 Human health impacts	74
4.1 Health impacts of ionizing radiation	74
4.2 Radioprotection principles	75
4.3 Impacts on workers	78
4.4 Impacts on the population	82

5	Recommendations	86
5.1	Baseline studies	86
5.3	Cost evaluation	88
5.4	Training	88
5.5	Legislation	89
5.6	Environmental monitoring	92
5.7	Monitoring of health impacts	93
6	Conclusions	94
	Acknowledgments	95
	References	96
	Appendix: Situation of uranium mining on different continents	102
A1.1	Europe	102
A1.2	Asia	105
A1.3	Africa	107
A1.4	North America	109
A1.5	South America	111
A1.6	Australia	113
	References of Appendix	115

Acronyms and abbreviations

Bq	becquerel
BEIR	Committee on the Biological Effects of Ionizing Radiation [committee of the National Research Council of the USA which publishes a series of reports informing the US government on the effects of ionizing radiation]
CRIIRAD	Commission de Recherche et d'Information Indépendantes sur la RADioactivité
CSO	Civil Society Organizations
EC	European Communities
EIA	Environmental Impact Assessment
EJO	Environmental Justice Organizations
eV	electron-volts
IARC	International Agency for Research on Cancer
ICRP	International Commission on Radiological Protection
ISL	in situ leaching
J	Joule
LNT	Linear Non-Threshold (model)
mSv	milliSievert
μSv	microSievert
MOX	Mixed Oxide fuel
PWR	Pressurized Water Reactor
RERF	Radiation Effects Research Foundation
SEIA	Social and Environmental Impact Assessment
SEMP	Safety and Environment Management Plan
UAB	Universitat Autònoma de Barcelona
UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation
WHO	World Health Organization
WNA	World Nuclear Association

Foreword

The Environmental Justice Organizations, Liabilities and Trade (EJOLT) project is an initiative funded by the European Community that brings together a consortium of 23 academic and civil society organizations across a range of fields to promote collaboration and mutual learning among stakeholders who research or use Sustainability Sciences, particularly on aspects of Ecological Distribution. One main goal is to empower environmental justice organizations (EJOs), and the communities they support that receive an unfair share of environmental burdens to defend or reclaim their rights. This is done through a process of two-way knowledge transfer, encouraging participatory action research and the transfer of methodologies with which EJOs, communities and citizen movements can monitor and describe the state of their environment, and document its degradation, learning from other experiences and from academic research how to argue in order to avoid the growth of environmental liabilities or ecological debts.

The activities of EJOLT project are divided in different Work Packages (WPs). In particular, WP3 deals with nuclear energy. Within this theme, the present report informs about radiological impacts and risks. The report is designed to give scientific information and general information to citizens and NGOs confronted with the radiological environmental and health impacts of the first step of the nuclear fuel chain, namely uranium mining and milling.

The report is based on the experience of the CRIIRAD laboratory. CRIIRAD (*Commission de Recherche et d'Information Indépendantes sur la RADioactivité*) [Commission for independent research and information on radioactivity] is a non-governmental and non-profit organisation that works to improve information and protection of the public against ionizing radiation.

The contents of the report include the results of independent radiation surveys performed by CRIIRAD in France and Africa. These results encompass the outcomes of monitoring activities performed between 2011 and 2014, in the framework of the EJOLT project, with EJOLT members in Bulgaria (Za Zemiata), Namibia (Earthlife Namibia), Malawi (Citizens For Justice), and Brazil (Fundação Oswaldo Cruz, FIOCRUZ).

The aim of this report is not to give an academic view about uranium mining or the whole nuclear fuel chain. Rather it is to illustrate the main impacts, providing one or two examples for each category of impact. In so doing the report hopes to contribute to the development of the critical capacities of communities, so that they might have more information with which to face conflicts with states or companies in relation to uranium mining projects.

The report is organised into five main chapters. **Chapter 1** gives a general introduction to uranium mining, explaining the main techniques of extraction and the location of key mines. **Chapter 2** describes the radiological characteristics of materials and waste related to the mining and milling of uranium. It also gives basics information on the evaluation of doses in the case of external irradiation and internal contamination. **Chapter 3** analyses in detail the paths and processes in uranium mining that can pose a threat to the environment whilst **Chapter 4** does the same but looks at the impacts on health. Finally, **Chapter 5** outlines some recommendations, and **Chapter 6** concludes the report.

1

Uranium mining

An introduction

Uranium is a radioactive heavy metal, relatively abundant in the earth crust, used for military and civilian applications

1.1 Utilization of natural uranium

Uranium is a radioactive heavy metal relatively abundant in the earth's crust. Uranium mining constitutes the first step of the nuclear fuel cycle and it's used for military and civilian applications.

About 99.28 % by weight of all natural uranium is uranium-238. In contrast, uranium-235, the isotope required for the production of nuclear fission leading to a chain reaction, constitutes only 0.7 % of natural uranium. Uranium-235 is extracted through uranium mining and milling and then enriched to increase its proportion.

Nuclear fissions release a large amount of energy. In a typical nuclear reactor, the chain reaction is kept 'under control' and the heat produced by the nuclear fissions is used to produce vapour which will drive an electrical generator. In an atomic bomb the amount of fissile material (uranium-235 or plutonium) is calculated in such a way that the chain reaction will lead to an explosion.

1.1.1 Military applications

The first application of uranium was military for the development of atomic bombs using enriched uranium or plutonium. In both cases, the first step is to obtain uranium through the mining of economically viable ores.

From a historical perspective, one of the most famous mines is the Shinkolobwe mine in the Katanga province of the Democratic Republic of Congo (DRC). The United States of America used the uranium resources of Shinkolobwe to supply the Manhattan Project, responsible for building the first atomic bomb used during World War II.

Natural uranium has been used without enrichment, for manufacturing nuclear fuel for certain types of reactors, for example, the 'Uranium Naturel Graphite Gas' (UNGG) reactors in the case of France. The artificial plutonium accumulated in the irradiated fuel was extracted and reprocessed for the fabrication of atomic bombs in which plutonium was the fissile material. Other atomic bombs have been made with enriched uranium prepared using natural uranium. In these cases, uranium-

235 is the fissile material, with its proportion typically increased from 0.7 % to more than 80 %.

Uranium, more specifically depleted uranium, has also been used for defensive armour plating and armour-piercing projectiles. Such ammunition was used during the war against Iraq, in the Gulf war, and in the Balkans, where contamination with uranium particles has had consequences on the health of the exposed military forces and population (GRIP, 2001).

1.1.2 Civil applications

The main civil application of uranium is in the manufacturing of nuclear fuel used for the production of electricity in nuclear reactors. The current global demand for civil power requires about 70,000 tonnes of uranium per year. In 2012, about 86% was directly supplied by uranium mines (WNA, 2014).

Historically, uranium-rich minerals were needed because the industry sought another radioactive metal called radium-226, created by the natural disintegration of uranium. Radium-226 was used for the treatment of cancer and industrial applications. These days radium-226 is left as a waste product.

Other uses of uranium included colouring pigment for jewels, porcelain and glass. It was widely used for these purposes back in the 19th and early-to-mid-20th centuries, yet some people are still exposed at present to these products.

Being a very dense metal, uranium is also used as a counterweight in aircrafts, sailboat keels, or as biological protection for radiation shielding. In the case of the latter, e.g., it is used for containers to transport radioactive materials, for radiation shielding for industrial radiography equipment, or in medical radiation therapy.

1.1.3 The unfortunate presence of uranium in some products

Some materials that are not directly used in the nuclear industry do contain quite high concentrations of uranium, which may not be negligible for radioprotective purposes. This is the case for example in rare earth metals, some types of phosphate fertilizers, and in the processing of zircon-rich minerals. Some varieties of coal also contain quite high levels of uranium. Such materials are called Naturally Occurring Radioactive Materials (NORM) and Technologically Enhanced Naturally Occurring Radioactive Materials (TENORM). European regulations have recently begun to address this problem. See for example the Euratom 96-29 directive of May 1996 (Euratom, 1996) and the 2013/59 Euratom directive of December 2013 (Euratom, 2013).

Uranium is mined through conventional open pit mining, underground mines and in situ leaching

1.2 Uranium mining techniques

Uranium is mined through conventional open pit mining, underground mines and in situ leaching (ISL). In an **underground or open pit mine**, uranium mining companies first extract the rocks containing uranium using conventional mining techniques. Before the rocks are processed, a test is carried out to determine their uranium concentration in order to decide whether the uranium concentration merits processing this material.



Figs. 1-2

Open pit (Somaïr mine in Niger) and entrance to COMINAK underground mine (Niger)

Source: AREVA

The material extracted from the mine may therefore be considered ‘waste rock’ or ‘uranium ore’ depending on the uranium concentration. The value of the ‘cut-off’ depends on the accessibility of the uranium deposit, the technological strategies used for mining the uranium and the current market value of uranium concentrates.

After mining and separation of the uranium ore, the ore is crushed and subjected to chemical processing, or ‘**leaching**’, in order to extract the uranium atoms from the ore. Conventional mines usually have a mill located close to the mine where the ore is crushed, ground and then leached to dissolve the uranium oxides. The techniques used for leaching will be different depending on the uranium concentration in the ore. When the mean uranium concentration in the ore is ‘high’ (e.g., in France between 0.1-1 %), the material is subjected to intense crushing and processing in a mill (**dynamic lixiviation**) with a typical recovery usually **above 95 %**.

When the mean uranium concentration in the ore is low (e.g., in France between 0.03-0.06 %), leaching is not performed in a mill but carried out through **heap leaching**, also referred to as **static lixiviation**. Heap leaching entails the spraying of a leaching agent onto heaps of ore. As the leaching agent filters through the heap, the uranium enters the solution. This solution is then pumped to the chemical plant for additional processing. Heap leaching has a typical recovery of **60 to 80 %** of the uranium contained in the ore.

Heap leaching is much cheaper than milling and therefore enables the recovery of uranium from lower grade ores. In both cases, the waste generated by leaching produces ‘uranium tailings’. The residual radioactivity of the tailings will depend on the initial activity of the ore and the efficiency of the leaching process (generally around 70 to 80% of the initial activity).

Other uranium extraction sites use **in situ leaching (ISL)** where leaching solutions are pumped into the ore deposit underground through man-made bore-holes. The solution dissolves the uranium contained in the underground deposit and is pumped to the surface and processed. This technique avoids the creation of open-pits, but creates a risk of contaminating groundwater resources (Mudd, 2001). One of the most common leaching agents is sulphuric acid, but some mills and operations use carbonate leaching instead, depending on the chemical and mineralogical characteristics of the ore body.

Mining methods have changed over time. In 1990, 55% of the world production came from underground mines. This percentage shrank dramatically in the late 1990s but increased again with new mines opened in Canada and Australia (Olympic Dam).

The proportion of ISL has steadily increased, mainly as a result of new mines opening in Kazakhstan. According to the World Nuclear Association (WNA), an increasing proportion of uranium (presently 45%) is produced by ISL. A 2012 report by the WNA breaks down the methods used for uranium production, outlined in **Table 1**.

Method	Tonnes U	%
Conventional underground (except Olympic Dam)*	16,324	27.9
Conventional open pit	11,906	20.4
In situ leach (ISL)	26,263	45.0
By-product *	3,851	6.6

Table 1

Mining techniques used for uranium production

* Considering Olympic Dam as by-product rather than in underground category

Source: WNA, 2012

After it is leached, the uranium ore undergoes a process of ion exchange and is dried at high temperatures to obtain **yellow cake** powder (uranium concentrate). This yellow cake is then transported via truck, train or ship to other processing facilities, where it is purified and eventually enriched to increase the proportion of uranium-235 (the fissile isotope of uranium).

In order to manufacture nuclear fuel for energy production, it is usually then turned into a hard ceramic oxide (UO_2) for assembly into rods specifically designed for each type of reactor. The waste produced by uranium enrichment facilities is called depleted uranium, because the proportion of uranium-235 in it is lower than 0.7 %. Depleted uranium can be used with reprocessed plutonium extracted from spent fuel to produce MOX fuel, which is an alternative nuclear fuel.

1.3 Main uranium mines and companies

The situation of uranium mining across different continents is presented in **Appendix 1**, it includes closed mines, operating mines and ongoing projects. According to WNA, around 64% of the world's uranium production is from mines in Kazakhstan (36.5% of world supply from mines in 2012), Canada (15%) and Australia (12%).

Country	2005	2006	2007	2008	2009	2010	2011	2012
Kazakhstan	4,357	5,279	6,637	8,521	14,020	17,803	19,451	21,317
Canada	11,628	9,862	9,476	9,000	10,173	9,783	9,145	8,999
Australia	9,516	7,593	8,611	8,430	7,982	5,900	5,983	6,991
Niger (est)	3,093	3,434	3,153	3,032	3,243	4,198	4,351	4,667
Namibia	3,147	3,067	2,879	4,366	4,626	4,496	3,258	4,495
Russia	3,431	3,262	3,413	3,521	3,564	3,562	2,993	2,872
Uzbekistan	2,300	2,260	2,320	2,338	2,429	2,400	2,500	2,400
USA	1,039	1,672	1,654	1,430	1,453	1,660	1,537	1,596
China (est)	750	750	712	769	750	827	885	1,500
Malawi					104	670	846	1,101
Ukraine (est)	800	800	846	800	840	850	890	960
South Africa	674	534	539	655	563	583	582	465
India (est)	230	177	270	271	290	400	400	385
Brazil	110	190	299	330	345	148	265	231
Czech Republic	408	359	306	263	258	254	229	228
Romania (est)	90	90	77	77	75	77	77	90
Germany	94	65	41	0	0	8	51	50
Pakistan (est)	45	45	45	45	50	45	45	45
France	7	5	4	5	8	7	6	3
Total world	41,719	39,444	41,282	43,764	50,772	53,671	53,493	58,394
Tonnes U ₃ O ₈	49,199	46,516	48,683	51,611	59,875	63,295	63,084	68,864
Percentage of world demand*	65%	63%	64%	68%	78%	78%	85%	86%

Table 2

Production from mines by country (tonnes U) from 2005 to 2012

Note:

1) 'est' stands for 'estimate'

2) U₃O₈ is the oxide form of uranium typically contained in 'yellow cake'

Source: WNA Market report data

In 2012, eight companies marketed 88% of the world's uranium mine production. Details are given in **Tables 3** and **4** below. It is worth noticing that the uranium production of Kazakhstan increased by a factor of 5 from 2005 to 2012.

Company	Tonnes U	%
KazAtomProm	8,863	15
AREVA	8,641	15
Cameco	8,437	14
ARMZ - Uranium One	7,629	13
Rio Tinto	5,435	9
BHP Billiton	3,386	6
Paladin	3,056	5
Navoi	2,400	4
Other	10,548	18
Total	58,394	100

Table 3

Main uranium mining companies in 2012

Source: WNA Market report data

Mine	Country	Main owner	Type	Production (tU)	% of world
McArthur River	Canada	Cameco	underground	7,520	13
Olympic Dam	Australia	BHP Billiton	by-product/ underground	3,386	6
Ranger	Australia	ERA (Rio Tinto 68%)	open pit	3,146	5
Arlit	Niger	Somair/ AREVA	open pit	3,065	5
Tortkuduk (est)	Kazakhstan	Katco JV/ AREVA	ISL	2,661	5
Rossing	Namibia	Rio Tinto (69%)	open pit	2,289	4
Budenovskoye 2	Kazakhstan	Karatau JV/Kazatomprom-Uranium One	ISL	2,135	4
Kraznokamensk	Russia	ARMZ	underground	2,011	3
Langer Heinrich	Namibia	Paladin	open pit	1,955	3
South Inkai	Kazakhstan	Betpak Dala JV/ Uranium One	ISL	1,870	3
Inkai	Kazakhstan	Inkai JV/Cameco	ISL	1,701	3
Central Mynkuduk	Kazakhstan	Ken Dala JV/ Kazatomprom	ISL	1,622	3
Akouta	Niger	COMINAK/ AREVA	underground	1,506	3
Rabbit Lake	Canada	Cameco	underground	1,479	3
Budenovskoye 1&3	Kazakhstan	Akbastau JV/ Kazatomprom-Uranium One	ISL	1,203	2
Top 15 total				37,549	64

Table 4 The largest-producing uranium mines in 2012

Source: WNA

1.4 Evolution of world uranium production and demand

The world total uranium supply from mines is not sufficient to cover demand, as illustrated by the graph in **Fig. 3**.

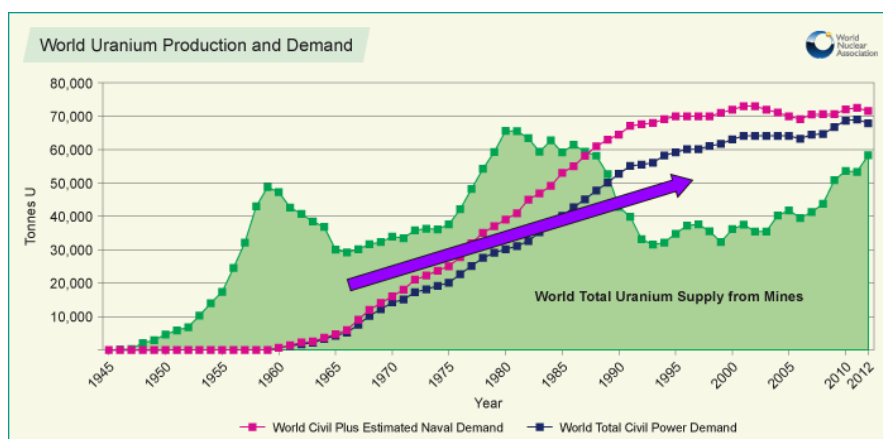


Fig. 3

World uranium production and demand

Source: WNA

In 2010 uranium mines produced 78% of global consumption. Secondary sources such as civil stockpiles, decommissioned nuclear weapons, reprocessed natural and enriched uranium and re-enriched depleted uranium tailings accounted for the remaining 22% (Conde and Kallis, 2012).

However the Fukushima nuclear disaster in Japan in March 2011 deeply affected the uranium market. Fifty nuclear reactors have been shut down in Japan, diminishing demand. Also the disaster stressed the risks associated with nuclear energy and therefore altered plans for future nuclear reactors around the world.

According to a May 2014 article in the magazine 'Uranium Investing News (Diniz, 2014), the tendency is not predicted to change in the short term. The article indicates, for the case of Japan:

"Of the many factors keeping the uranium market weak, oversupply is a top contender. [...]"

A Japanese court ruled against Kansai Electric Power carrying out a restart plan for two idled nuclear reactors, claiming that they are potentially vulnerable to earthquakes. According to the Financial Times, the decision by the judge in Fukui prefecture 'could disrupt an already complicated and politically charged effort to restart some of the 50 Japanese reactors that have been shut over safety concerns since the Fukushima disaster'. [...]"

As far as nuclear power is concerned, Japan's population remains sceptical and fairly divided, with opposition running about two-to-one based on recent polls. As Reuters noted, a March survey showed that roughly 80 percent of the people in Japan would prefer to see a gradual move away from atomic power".

Certainly, when it comes to the plans for investments in nuclear reactors many factors come into play. However, the scepticism of the Japanese population mirrors in the concerns of citizens from many of the countries where nuclear power is considered a viable energy source.

1.5 New mines and inferred uranium resources

In the 2000s, the price of uranium increased spectacularly until the economic crisis of 2007/08, from just USD 7 a pound in 2003 to USD 140 by June 2007. This translated into increased uranium exploration efforts, which soared between 2003 and 2009. Some 400 exploration companies formed or changed their orientation to raise USD 2 billion for uranium exploration (Conde and Kallis, 2012).

After this sharp increase, the price fell to USD 40–50 per pound, recovering to USD 73 just before the Fukushima accident, after which it fell again to USD 28 per pound where it has stabilised. Only recently it has gone up to USD 36 (UxC, 2014). This overall decrease in price has cancelled or at least delayed many projects such as the Trekkopje mine in Namibia or the Imouraren project in Niger. Despite this, some mines like Four Mile in Australia or Husab in Namibia are expected to open in the coming years.

According to the WNA, the country with the most known recoverable resources of uranium as of 2011 is Australia, which has 31% of reserves. **Table 5** shows resources from other countries, such as Kazakhstan, Russia and Canada.

Country	Tonnes U	Percentage of world (%)
Australia	1,661,000	31
Kazakhstan	629,000	12
Russia	487,200	9
Canada	468,700	9
Niger	421,000	8
South Africa	279,100	5
Brazil	276,700	5
Namibia	261,000	5
USA	207,400	4
China	166,100	3
Ukraine	119,600	2
Uzbekistan	96,200	2
Mongolia	55,700	1
Jordan	33,800	1
other	164,000	3
World total	5,327,200	100

Table 5

Reasonably Assured Resources plus Inferred Resources

Note: Reasonably Assured Resources plus Inferred Resources, to USD 130/kg U, 1/1/11, from OECD NEA & IAEA, Uranium 2011: Resources, Production and Demand ("Red Book"). The total to USD 260/kg U is 7,096,600 tonnes U, and Namibia moves up ahead of Niger

Source: WNA

It is difficult to know if nuclear energy production will actually grow in the coming years and decades, as more questions are raised, including:

- safety issues, particularly after the Three Mile Island (1979), Chernobyl (1986) and Fukushima (2011) nuclear accidents;
- the effects of low doses of radiation on the workers and population;
- proliferation issues;
- the lack of appropriate solutions for the management of radioactive waste produced by nuclear reactors and in all phases of the nuclear fuel cycle (including radioactive waste rocks and tailings from uranium mines and mills);
- the actual cost of nuclear electricity compared to other energy production solutions, when taking into consideration the cost of dismantling, upgrading the safety of the reactors, waste management and dealing with the consequences of nuclear accidents. See more on this issue in EJOLT report 12 (Raeva et al., 2014).

2

Radioactivity of materials and waste of uranium mines

All natural uranium isotopes (uranium-238, uranium-234, uranium-235) are radioactive. This means that the nucleus of these atoms are unstable. Such atoms will naturally **decay** and become a new atom or **daughter-product**. The daughter products of uranium atoms are themselves radioactive. In the case of uranium-238 for example, the process of decay will lead to the creation of 13 other radioactive daughter products, ultimately creating a stable isotope of lead (lead-206).

The characteristics of the radioactive daughter products of uranium-238 are presented in **Table 6**. They all are metals (thorium-234, thorium-230, radium-226, lead-210, polonium-210, etc.) except one, radon-222, which is a radioactive gas.

Radionuclide	Half life		Decay Mode	Main X or gamma emission	
				Energy (keV)	Intensity (%)
Uranium-238	4.47 billion	Years	alpha	16.16	4.1
Thorium-234	24.1	Days	beta	63.3	3.8
Protactinium-234 ^m	1.17	Minutes	beta	1,001	0.65
Uranium-234	245,000	Years	alpha	53.2	0.12
Thorium-230	75,400	Years	alpha	67.7	0.38
Radium-226	1,600	Years	alpha	186.1	3.28
Radon-222 (gas)	3.8	Days	alpha	510	0.07
Polonium-218	3.1	Minutes	alpha		
Lead-214	26.8	Minutes	beta	351.9	37.1
Bismuth-214	19.9	Minutes	beta	609.3	46.1
Polonium 214	0.16	Milliseconds	alpha	798	0.01
Lead 210	22.3	Years	beta	46.5	4
Bismuth 210	5	Days	beta		
Polonium 210	138.4	Days	alpha	803.1	0.001
Lead 206	Stable element (no decay)				

Table 6

Main characteristics of uranium-238 decay products

Source: CRIIRAD and Browne and Firestone

During this process of disintegration, different energetic radiations are emitted: alpha particles, beta particles; gamma rays and sometimes neutrons. These radiations are called '**ionizing radiation**' because they carry enough energy to separate electrons from other atoms and molecules, thereby ionizing them.

Each radioactive atom has a given probability to disintegrate. This probability is determined by the '**half-life**' of the radioactive substance. The half-life is the time required for half of the radioactive atoms to undergo radioactive decay.

The half-life of uranium-238 is 4.5 billion years, equivalent to the age of our planet. When the Earth was 'created', the activity of uranium-238 in the earth's crust was about twice as high as its present value. About 50% of the heat given off by the earth is generated by the radioactive decay of elements contained in the earth's lithosphere and mantle, such as uranium and thorium, and their decay products.

As indicated in **Table 6**, these radionuclides emit various types of ionizing radiation. Eight emit alpha particles. Six emit beta particles. In addition to the emission of alpha and beta particles, some of the disintegrations lead to the emission of electromagnetic radiation: X rays and gamma rays. Most of the gamma emissions from the uranium-238 decay chain come from two decay products of radon-222: lead-214 and bismuth-214.

Gamma radiations are very penetrating. They can travel tens of metres (and more) through the air and irradiate people even when the radioactive material remains outside the human body (this is called external irradiation). It is necessary to install significant amounts of dense material like concrete or lead between a source of gamma radiation and potentially exposed people in order to significantly lower the amount of gamma radiation

Alpha radiations are relatively less penetrating. They can be totally stopped by a sheet of paper or a plastic bag, but are particularly dangerous when the radioactive material is ingested or inhaled (this is called internal contamination). In this case alpha particles are emitted directly inside the body.

The presence of natural uranium and its decay products in the earth's crust – and therefore in numerous building materials made out of natural minerals – is the main source of exposure of mankind to ionizing radiation from natural sources. This is especially due to the diffusion of **radon gas** from the soil and materials containing uranium, and its accumulation in the air inside buildings and dwellings.

This radiological hazard is now well documented at the international level, notably by the International Commission on Radiological Protection (ICRP), the World Health Organization (WHO), the International Agency for Research on Cancer (IARC, 1988), and Euratom. Different regulations have been set up to determine recommendations and action levels in order to lower radon concentrations inside buildings and to reduce cancer risks. Unfortunately, the action levels are set at levels which tolerate quite a high risk of cancer death.

In order to evaluate the level of risk to human beings induced by the radioactivity present in our environment, two steps are usually necessary. The first one is to be aware of the amount of radioactivity. This point is discussed in **section 2.1** below

where we give examples of the typical radioactivity of different materials dealt with in uranium mines and mills.

The second step is to monitor the amount of energy (the 'dose') deposited in the human body by ionizing radiations emitted by radioactive substances present in soil, air, water or food. The concept of dose is introduced in **section 2.2**. As the dose may be delivered by external irradiation or internal contamination, examples of these mechanisms are given in **sections 2.3** and **2.4** respectively.

2.1 Radioactivity of various materials in a uranium mine and mill

The level of radioactivity of a substance is given by its activity. The **activity** is the amount of atoms undergoing a radioactive decay in a given amount of time. One **becquerel (Bq)** is defined as the activity of a quantity of radioactive material in which one atom decays per second. The activity may be given in Bq/kg (for samples of soil, sediments or food), Bq/m³ (air), Bq/l (water), Bq/cm² (contaminated surface), etc.

Each radionuclide has a given level of radioactivity per amount of atoms or weight. This number is called the 'specific activity'. The specific activity of uranium-238 is about 12,500 Bq/g (12.5 Bq/kg).

Uranium-238 and its daughter products have their own half-lives ranging from 0.16 milliseconds to 4.47 billion years. In the earth's crust and in undisturbed uranium ore, the uranium-238 decay chain is in **equilibrium** which means that the amount of daughter atoms decaying is replaced by new ones created by the disintegration of the father atoms. In this case, the total activity is simply equal to the activity of the father of the decay chain (namely uranium-238) multiplied by the number of daughter products in the decay chain (namely 14, as shown in **Table 6**).

As soon as a chemical process is used to separate uranium from its daughter products, this equilibrium is modified. This is what occurs in a uranium mill where uranium is separated from thorium-230 and radium-226. For example, when obtaining yellow cake in the milling process, the activity of uranium-238 will be much higher than that of radium-226.

When calculating the radioactivity of solid materials in a uranium mine or mill, it is therefore important to distinguish between the mining process in which uranium-238 is still in equilibrium with its daughter products (natural ore or waste rocks) and the milling process in which ore is processed and leads to various disequilibrium in waste (tailings) or in the commercial product (yellow cake).

As indicted above, about 99.3 % of the uranium found in the earth's crust is uranium-238. For this reason, the next sections do not deal with uranium-235. It should be noted that after mining and milling, uranium concentrate may be sent to a uranium enrichment plant where the proportion of uranium-235 will be increased by a few percent (for manufacturing fuel for Pressurized Water Reactor (PWR) reactors) and even a few tens of percent (for manufacturing atomic bombs or special fuel for specific reactors like the ones used in nuclear submarines, etc.). In

One becquerel (Bq) is defined as the activity of a quantity of radioactive material in which one atom decays (becomes a new atom) per second

this case the contribution of uranium-235 and its own daughter products has to be taken specifically into consideration.

The amount of uranium-238 in the soil or rocks can be monitored undergoing a chemical analysis, using for example fluorimetry or mass spectrometry. In this case, the results are expressed as a concentration (for example, mg/kg, g/kg, etc.). The amount of uranium can also be monitored using the amount of radiation contained in the soil through different types of radiological analyses including gamma spectrometry or alpha spectrometry. In this case the results are given as an activity (usually in Bq/kg).

Using the specific activity mentioned above, it is possible to calculate the activity of uranium-238 in a given material if the concentration of uranium is known. The activity (Bq/kg) is equal to the concentration (g/kg) multiplied by the specific activity (12,500 Bq/g).

2.1.1 Radioactivity of natural uranium in the soil

The typical activity of uranium-238 in the earth's crust is **40 Bq/kg** (becquerels per kilogram). Uranium-238 decays naturally into thorium-234. During this process, one alpha particle is emitted. It means that with a sample of one kilogram of typical soil, 40 atoms of uranium-238 disintegrate per second, emitting 40 alpha particles and creating 40 new atoms of thorium-234. Thorium-234 itself is radioactive and will emit beta radiation and give birth to 40 atoms of Protactinium-234^m, which are radioactive, etc.

The total activity of the whole uranium-238 decay chain in a typical sample of soil will therefore be **560 Bq/kg** (14 radionuclides multiplied by 40 Bq/kg). This shows that to properly evaluate the total radioactivity¹ of materials containing natural uranium, it is necessary to take into consideration all 13 daughter products.

The uranium content in fact varies widely depending on the type of rock and the geology of the area. For example, the concentration of uranium is usually higher in granite rocks (typically **200 Bq/kg**).

2.1.2 Radioactivity of waste rock and uranium ore

The uranium concentration in the material to be mined varies widely and so does the activity of the waste rock and the ore to be processed. In the case of France, for example, uranium activity in **waste rock** is typically of a few thousands Bq/kg². At the beginning of the 1990s, due to a general decrease in the market price of uranium, the **cut-off** used to distinguish 'waste rocks' and 'ore' was increased to 0.04%. Previously, the value had been 0.01% in the case of open pit mines and 0.02% in the case of underground mines. With such concentrations, the typical

For properly evaluating the total radioactivity of materials containing natural uranium it is necessary to take into consideration all the 13 daughter products

¹ The contribution of the eleven radionuclides contained in the uranium-235 decay chain is neglected here. Taking into consideration the natural isotopic ratio of the activities: uranium -238 / uranium-235 of 21.7 %, one can calculate that the contribution of uranium-235 and its decay chain to the radioactivity of natural uranium is below 5%. This would not be true with enriched uranium manufactured at uranium enrichment plants.

² IRSN, "Fiche N°1", L'extraction de l'uranium en France : données et chiffres clés, 12 février 2009.

activity of uranium-238 in waste rocks can reach **1,250 to 5,000 Bq/kg**. Presently in France there are no more uranium mining activities.

In fact, the actual activity of waste rock can be much higher. Usually, samples of ore are mixed with waste rocks. Screening methodologies used to evaluate the radioactivity of the mined material may not be able to distinguish 'waste rocks' and 'uranium ore'. Therefore, their results are not 100 % reliable.

Table 7 below illustrates examples of uranium-238 concentration (by weight), uranium-238 activity (Bq/kg) and the total activity of the uranium-238 decay chain of 'waste rocks' and ore samples. In some countries, uranium ore is still mined with uranium concentrations below 0.04 % and uranium-238 activities below **5,000 Bq/kg**. This is the case for example with the Rössing³ open pit mine in Namibia.

Area or uranium mine	Country	Uranium-238 concentration (%)	Uranium-238 concentration (g/kg)	Uranium-238 activity (Bq/kg)	Total activity of Uranium-238 decay chain (Bq/kg)
A / Normal rocks					
Typical earth crust	World average	0.00032	0.0032	40	560
B / Waste rocks (typical Uranium 238 concentration above which the material is processed)					
Open pit mining (before the beginning of the 90's)	France	0.01	0.1	1,250	17,500
Underground mining (before the beginning of the 90's)	France	0.02	0.2	2,500	35,000
Open pit and underground mining (after the beginning of the 90's)	France	0.04	0.4	5,000	70,000
C / Uranium ore					
Rössing	Namibia	0.03	0.32	4,000	56,000
Imouraren (Project)	Niger	0.066	0.66	8,250	115,500
Caetité	Brazil	0.30	3	37,500	525,000
COMINAK	Niger	0.40	4	50,000	700,000
North Saskatchewan (Cigar Lake)	Canada	20	200	2,500,000	35,000,000

Table 7

Uranium concentration, uranium-238 activity and total activity of uranium-238 decay chain in some uranium ores and waste rocks

Source: CRIIRAD

At its open pit project in Imouraren⁴ (Niger), AREVA is planning to mine uranium with a mean activity of **8,250 Bq/kg**. In the case of the Caetité uranium mine in Brazil (open pit) and the COMINAK⁵ uranium mine in Niger (underground mine), the uranium concentrations in the ore are higher with 0.3% and 0.4% respectively, which means uranium-238 activities of **37,500 Bq/kg** and **50,000 Bq/kg**.

At some mines, the uranium concentration is extremely high. In Cigar Lake, north Saskatchewan (Canada), some uranium ores have concentrations of 20% which means a uranium-238 activity of **2,500,000 Bq/kg**⁶. In this case, uranium is

³ Rössing web site, April 2014, year 2008 to 2012, year 2008 data used here <http://www.rossing.com/performance.htm>.

⁴ AREVA web site, April 2014 : <http://www.aveva.com/FR/activites-623/imouraren-sa-une-nouvelle-etape-dans-un-partenariat-historique.html>.

⁵ AREVA web site, April 2014 : <http://www.aveva.com/FR/activites-602/cominak-exploitant-de-la-plus-grande-mine-d-uranium-souterraine.html>.

⁶ AREVA web site, April 2014 (<http://www.aveva.com/FR/activites-619/exploitation-extraire-le-minerai-d-uranium.html>).

The total radioactivity of the tailings is usually above 40,000 Bq/kg in the case of heap leaching and above 100,000 Bq/kg in the case of tailings from mills

extracted using automated methods in order to limit the exposure of workers to ionizing radiation.

In all the examples above, one has to remember that the total activity of the uranium-238 decay chain is 14 times higher than the activity of uranium-238 alone. In a sample of uranium ore with uranium-238 activity of 37,500 Bq/kg, the total activity of the uranium-238 decay chain will be 37,500, multiplied by 14, which produces 525,000 Bq/kg. This means that, every second, in each kilogram of such material, more than 500,000 radioactive atoms are disintegrating and emitting alpha, beta and gamma radiation.

2.1.3 Radioactivity of tailings

The residual radioactivity of uranium tailings will depend on the initial activity of the ore and the efficiency of the leaching process. **Table 8** below gives examples of calculations of the residual radioactivity of the tailings.

Uranium-238 concentration in the ore (%)	Uranium-238 activity in the ore (Bq/kg)	Total activity of uranium-238 decay chain in the ore (Bq/kg)	Uranium recovery (%)	Residual uranium-238 activity in the tailings (Bq/kg)	Residual thorium-230 activity in the tailings (Bq/kg)	Total residual activity of uranium-238 decay chain in the tailings (Bq/kg)	Residual activity of uranium-238 decay chain in the tailings compared to initial radioactivity (%)
A / Uranium ore processed by Heap Leaching							
0.03	3,750	52.500	60	1,500	3,750	43,500	83
0.03	3,750	52.500	80	750	3,750	40,500	77
0.06	7,500	105.000	60	3,000	7,500	87,000	83
0.06	7,500	105.000	80	1,500	7,500	81,000	77
B / Uranium ore processed in a conventional mill							
0.1	12,500	175.000	95	625	12,500	127,500	73
1	125,000	1.750.000	60	50,000	125,000	1,450,000	83

Table 8

Residual radioactivity in the tailings depending on uranium concentration in the ore and leaching technique

Source: CRIIRAD

During leaching, between **60 and 95 % of the uranium is removed** (i.e., uranium-238, uranium-234 and uranium-235). In the case of the uranium-238 decay chain for example, this 'extraction' will partially remove the two uranium isotopes belonging to the decay chain, namely uranium-238 and uranium-234. In the tailings, as uranium-238 is partly removed, the activity of its two short-lived daughters, thorium-234 (24 days) and protactinium-234^m (1.17 minutes) will decrease.

About 100 % of the daughter products from thorium-230 to polonium-210 (10 daughter products) are left in the tailings with the same activity as in the unprocessed ore. One can thus calculate that the residual activity left in the tailings is equal to 70 % (and sometimes 80 %) of the initial activity of the ore.

The total radioactivity of the tailings is usually above 40,000 Bq/kg in the case of heap leaching and above 100,000 Bq/kg in the case of tailings from mills. In some cases the radioactivity of the tailings may even exceed 500,000 Bq/kg.

The total activity in the uranium concentrate 'yellow cake' will be between 29.6 and 38 million Bq/kg

2.1.4 Radioactivity of uranium concentrate 'yellow cake'

After the leaching process and the chemical treatment of the solutions containing uranium, the final step consists of the precipitation of the uranium into a dry powder called 'yellow cake' in which uranium usually takes an oxide form (U_3O_8). With a typical purity of 70 % to 90 % of U_3O_8 , it is possible to calculate the uranium-238 activity in the yellow cake at between 7.4 million Bq/kg and 9.5 million Bq/kg (see **Table 9**).

U_3O_8 concentration in the yellow cake (%)	Uranium-238 concentration in the yellow cake (%)	Uranium-238 concentration in the yellow cake (g/kg)	Uranium-238 activity in the yellow cake (Bq/kg)	Total activity of uranium-238 decay chain in the yellow cake if "new" material (Bq/kg)	Total activity of uranium-238 decay chain in the yellow cake after a few month (Bq/kg)
70%	59%	594	7,400,000	14,800,000	29,600,000
80%	68%	678	8,500,000	17,000,000	34,000,000
90%	76%	763	9,500,000	19,000,000	38,000,000

Table 9 Radioactivity of 'yellow cake'

Source: CRIIRAD

However, the total⁷ activity of the uranium-238 decay chain in the concentrate will be higher taking into consideration the additional activities of uranium-234 (which is the same as the uranium-238), and thorium-234 and protactinium-234^m, continuously regenerated by their father atom (uranium-238).

Both activities will be in equilibrium in less than 8 months. After this time, the total activity in the uranium concentrate will be between 29.6 and 38 million Bq/kg. The total activity will therefore depend on the time elapsed since the uranium is extracted through leaching.

2.2 The concept of dose

Ionizing radiations carry large amounts of energy which is released in the cells of exposed human bodies. It is useful to compare the energy of ionizing radiation to the typical energy of visible light from the sun (a few electron-volts or eV). The energy of solar rays is sufficient to create skin problems and even increase the risk of skin cancer. Ionizing radiations are much more powerful.

For example, one alpha particle emitted by one uranium 238 atom carries more than 1 million times more energy (typically 4,196,000 eV) than visible light from the sun. Bismuth-214 is emitting various gamma rays with different energies. About 16% of them have an energy of 1,760, 000 eV.

The '**absorbed dose**' is the amount of energy deposited in the human body by ionizing radiation (energy absorbed per unit mass). The health effects of ionizing radiation will depend on many factors. These include the absorbed dose, the type

⁷ This calculation does not take into consideration the additional activity of natural uranium-235 (and some of its daughter products) nor the possible residual contribution of thorium-230, radium-226 and other uranium-238 daughter-products that may stay in the concentrate depending on the 'selectivity' of the leaching and purification process.



The unit of effective dose is expressed in milliSievert (mSv) or microSievert (μSv)

of radiation delivering the dose (alpha, beta, gamma, etc.), the affected organs, the age of the exposed person, and the time distribution (for example, whether the dose is delivered all at once or over time).

In the official model developed by the ICRP, some of these factors are taken into consideration. For example special factors are introduced for the conversion of the absorbed dose into an '**equivalent dose**' depending on the type and quality of radiation. Then equivalent doses to each organ are used to calculate the **effective dose**, which is the sum of the weighted equivalent doses in all the tissues and organs of the body from internal and external exposure.

The unit of effective **dose** is expressed in milliSievert (mSv) or microSievert (μSv).

1 milliSievert (1 mSv) = 1,000 microSievert (1,000 μSv).

The health impacts of low doses of ionizing radiation include the increase of various types of cancers, genomic instability, and life-shortening and negative impacts on all bodily functions. Even at low doses, ionizing radiation increases the risk of cancer.

In order to evaluate the total effective dose it is necessary to take into consideration external irradiation and internal contamination. These concepts are described in the next two sections.

2.3 How to evaluate external irradiation

When radioactive substances are located outside the human body with no direct contact, some of the radiation emitted may travel through the air, penetrating the human body through the skin. This is called **external irradiation**.

External irradiation is caused mainly by **gamma radiation**. These powerful electromagnetic waves travel tens and even hundreds of metres in the air, depending on their energy. This is the reason why high uranium concentration in the soil can be detected using airborne monitoring with planes or helicopters equipped with gamma radiation detectors.

Dose rate monitors are used to monitor the amount of external irradiation, usually expressed as a **dose rate in microSievert per hour (μSv/hour)**. The dose rate decreases as the distance from the source of radiation increases. The typical value of ambient dose rate one metre above ground is slightly below **0.1 μSv/h** at sea level, when the concentration of natural nuclides in the soil is equivalent to the mean value of the earth's crust.

2.3.1 Theoretical evaluation of external irradiation emitted by the soil

If the amount of radioactive substances in the soil (expressed in Bq/kg) is known, it is possible to predict the dose rate emitted by the soil using specific conversion factors that give the dose rate associated with a given activity of the soil (Bq/kg). Such calculations may be useful when it is not possible to make actual measurements. For example, an NGO may want to predict the impact of mining

External irradiation is caused mainly by gamma radiation, electromagnetic waves able to travel tens of metres and even hundreds of metres

activities on the surface of radioactive soil where uranium activity is described in an environmental impact study.

In the earth's crust, and therefore in natural soil, there are 4 radioactive elements: uranium-238 and its 13 daughter products, uranium-235 and its 10 daughter products, thorium-232 and its 10 daughter products and potassium-40 (it's daughter product is not radioactive).

With regard to natural uranium, the contribution of uranium-235 can be neglected due to emphasis on uranium-238. In this case, the gamma dose rate can be evaluated using the activity of uranium-238, thorium-232 and potassium-40, assuming that the decay chains are in equilibrium and using specific conversion factors plotted in the second column of **Table 10** below.

These calculations can be used when radioactivity has a uniform distribution over large areas. **Table 10** gives examples of dose rate values calculated taking into consideration the activity of natural radioactive elements in the soil.

Radionuclide	Conversion factor (nGy/h per Bq/kg)*	Natural soil with mean activity		Waste rocks with 4,000 Bq/kg of ²³⁸ U		Uranium ore with 40,000 Bq/kg of ²³⁸ U	
		Activity in the soil	Dose rate 1 m above ground	Activity in the soil	Dose rate 1 m above ground	Activity in the soil	Dose rate 1 m above ground
		(Bq/kg)	(μSv/h)	(Bq/kg)	(μSv/h)	(Bq/kg)	(μSv/h)
Uranium-238 / Radium-226	0.386	40	0.015	4,000	1.544	40,000	15.440
Thorium-232	0.523	40	0.021	40	0.021	40	0.021
Potassium-40	0.038	400	0.015	400	0.015	400	0.015
Total doserate (μSv/h)			0.052		1.58		15.5
Cumulated exposure							
After 2 000 hours (μSv/year)			103		3,160		30,952
In the case of permanent exposure of 8760 hours (μSv/year)			452		13,842		135,571

Table10

Evaluation of the gamma dose rate one metre above ground depending on uranium 238 activity in the soil

* In the case of gamma rays, the absorbed dose in Gray (Gy) is equivalent to the Equivalent dose in Sievert (Sv). One nanoGray per hour (nGy/h) is equivalent to 0,001 μSv/h"

Source: CRIIRAD

In the case of natural soil in which the activities of radioactive elements (uranium-238, thorium-232 and potassium-40) are equal to the mean activity of the earth's crust (40 Bq/Kg; 40 Bq/kg and 400 Bq/kg respectively), the dose rate due to 'telluric radiation' (i.e., radiation coming from the soil itself) is about **0.05 μSv/h**.

At sea level, the contribution of external irradiation from **cosmic radiation** coming from space would add about 0.037 μSv/h. In this case, the total dose rate from telluric and cosmic sources is **about 0.1 μSv/h**. With higher uranium-238 activities in the soil, the dose rates are much higher, for example:

- 1.58 μSv/h in the case of waste rock with uranium-238 activity of 4,000 Bq/kg;
- 15.5 μSv/h in the case of ore with uranium-238 activity of 40,000 Bq/kg.

The risk to the health of people or workers staying on the soil will depend on the cumulative dose, which is calculated taking into consideration the dose rate and the amount of time spent per year. Such annual doses are estimated in **Table 10** in the case of an annual exposure of 2,000 hours and of a permanent exposure of 8,760 hours, assuming that people are standing⁸ on the soil.

For example, in an area where natural rocks have uranium-238, thorium-232 and potassium-40 activities close to the mean values monitored in the earth's crust, the typical dose rate due to telluric radiation is 0.05 µSv/h. This produces an annual dose of 103 microSievert for an individual spending 2,000 hours on that site.

If waste rock from a uranium mine – with a mean uranium-238 activity of 4,000 Bq/kg – is used for filling this area, the ambient dose rate may increase to 1.58 µSv/h. For people spending 2,000 hours per year on site, the annual dose from external irradiation⁹ would be 3,160 microSievert. In this case the additional dose due to the inappropriate management of waste rock would be:

$$3,160 - 103 = 3,057 \text{ microSieverts per year}$$

This figure is clearly above the annual dose limit of 1,000 µSv/year for the public.

2.3.1 How to monitor external irradiation

Many different types of materials from a uranium mine are radioactive and increase the ambient dose rates for people or workers in the vicinity of such material. External irradiation may be significant in the following cases:

a) with naturally radioactive rocks that are extracted from the mine. They will be managed as waste rock or uranium ore.

b) with different types of waste and materials contaminated by mining and milling activities. The purpose of uranium extraction is to concentrate uranium, and therefore concentrate the radioactivity contained in the natural rocks. This contamination includes:

- Tailings from heap leaching activities and mills.
- Uranium concentrate ('yellow cake').
- Contaminated equipment used in mines and mills (pipes, pumps, drums, vehicles, filters used for filtration of air or liquid effluents, etc.).
- Material (including top soil and bioindicators) contaminated by the deposit of radioactive dust from the mine, mill, waste rock dumps or tailings dams, etc.
- Material (including sediments, soil, aquatic vegetation) contaminated by water or liquid effluents from mines or mills.

⁸ If, instead of standing on the soil, people are laying on the soil, the dose rate is much higher and the cumulated dose will increase accordingly.

⁹ A comprehensive evaluation of the impact would require calculating the dose due to internal contamination (see next section).

The dose due to external irradiation can be monitored using different methods:

- The cumulative dose may be evaluated using electronic **monitoring posts** that perform continuous monitoring, or by passive detectors that will give an average value. Passive monitors are usually changed after one month, or a quarter of a year. The results may be expressed as microSieverts per month or per hour.

These are the methods used by mining companies. The problem however is that the places where monitoring posts are located may not be representative of actual radiation rates if locations are selected by companies or their subcontractors without independent control.

- **Portable monitors** like calibrated Geiger-Mueller counters or other radiation monitors like scintillometers may also be used to monitor dose rates ($\mu\text{Sv/h}$). These monitors are easily accessible and easy to use. Some Geiger-Mueller counters are available at a typical cost of about 200 Euros. Professional radiation monitors may cost several thousand Euros. This is a strategy that local NGOs or citizens can implement for independent assessments of the exposure of the public leaving near uranium mines.

The use of portable monitors enables the drawing of detailed maps of radiation emitted inside or outside buildings and at different distances from potentially contaminated material (soil, scrap, waste, etc.) and people.

Annual exposure can then be evaluated by multiplying the dose rate monitored at a given place by the number of hours spent at this place during one year. If the dose rates are very different at different locations, it is necessary to take into consideration the actual dose rates and the amount of time spent at each location and to add the contributions of all different locations.

- For the evaluation of **individual doses of workers** the mining companies also use **passive monitors** or **electronic dosimeters**. Passive monitors have to be sent to a specialized laboratory for dose evaluation. The results are usually not given to workers directly but sent to the radiation protection unit or the company doctor. The advantage of electronic dosimeters is that the values of the dose rate and the cumulated dose can be seen directly by the worker on the monitor. This enables better transparency and reactivity.

Depending on the predicted annual occupational exposure of workers, an individual monitor may be provided for each worker or only to a selection of workers belonging to the same group. In this case, the individual dose of all the workers belonging to the same group will be calculated using the mean dose of those with an individual monitor.

It should be noted that some workers do not use their individual monitors consistently in order to lower their official cumulative dose. This is due to the fact that if their doses are too high they will not be allowed to continue working in the same position, and may lose their specific allowance for risk or even be dismissed.

When the radioactive atoms manage to penetrate inside the human body the terminology 'internal contamination' is used

2.4 How to monitor internal contamination

Radioactive substances may also come into contact with the human body, causing contamination. '*External contamination*' occurs, for example, in the case of the deposition of radioactive material on the skin. A fraction of the radioactive atoms may migrate through the skin and lead to an internal contamination.

'*Internal contamination*' occurs when radioactive atoms manage to penetrate the human body. Internal contamination may occur through the ingestion of contaminated food or water, or the inhalation of contaminated air (radon gas, radioactive dust). In the case of internal contamination the dose is usually calculated in two steps.

1. Evaluating the amount of radioactive material (amount of becquerels) ingested or inhaled.
2. Applying an appropriate dose factor ($\mu\text{Sv/Bq}$) to calculate the dose taking into consideration the type of radionuclide, its chemical properties and the age of the exposed individual.

The evaluation of doses due to internal contamination is usually much more complex than the evaluation of external irradiation. Some examples are given below in the cases of ingestion and inhalation.

2.4.1 Contamination through ingestion

In order to evaluate the doses induced by ingestion of contaminated food, the first step is to obtain a detailed and reliable analysis of the activity (Bq/l or Bq/kg) of all radioactive substances present in samples of water or food that people consume.

In the case of the evaluation of the impact of a uranium mine, a comprehensive evaluation requires the monitoring of 14 radionuclides belonging to the uranium-238 decay chain and 11 belonging to the uranium-235 decay chain. Sometimes the uranium ore also contains non-negligible levels of thorium-232 (11 radionuclides in the decay chain).

The samples have to be sent to specialised laboratories. The typical cost of analysis can range from a few tens of Euros (for example for the monitoring of uranium concentration using mass spectrometry) to a few hundred Euros (for the monitoring of uranium-238, thorium-230, radium-226, radon-222, lead-210, polonium-210, etc.).

Once the activities of all relevant radionuclides in each food or water sample are known (Bq/kg or Bq/l), it is possible to calculate the dose induced by the consumption of a given weight or volume of this material using appropriate dose coefficients ($\mu\text{Sv/Bq}$). **Table 11** below plots dose coefficients for the public dictated by the ICRP (ICRP, 2012).

Radionuclide	A1 Dose coefficient for a 5 years old child ($\mu\text{Sv/Bq}$)	A2 Dose coefficient for an adult ($\mu\text{Sv/Bq}$)	R= A1/A2 Ratio Child/ Adult	C Activity (Bq/l or Bq/kg)	D1 = A1*C Dose ($\mu\text{Sv/l}$ or $\mu\text{Sv/kg}$) for a 5 years old child	D2=A2*C Dose ($\mu\text{Sv/l}$ or $\mu\text{Sv/kg}$) for an adult
Uranium-238	0.080	0.045	1.8	2	0.160	0.090
Thorium-234	0.013	0.0034	3.8	2	0.026	0.007
Protactinium-234 ^m	0.0017	0.00051	3.3	2	0.003	0.001
Uranium-234	0.088	0.049	1.8	2	0.176	0.098
Thorium-230	0.31	0.21	1.5	2	0.620	0.420
Radium-226	0.62	0.28	2.2	2	1.240	0.560
Lead-214	0.00052	0.00014	3.7	2	0.001	0.000
Bismuth-214	0.00036	0.00011	3.3	2	0.001	0.000
Lead-210	2.2	0.69	3.2	2	4.400	1.380
Bismuth- 210	0.0048	0.0013	3.7	2	0.010	0.003
Polonium-210	4.4	1.2	3.7	2	8.800	2.400
Total dose : $\mu\text{Sv/l}$ or $\mu\text{Sv/kg}$					15.44	4.96

Table 11

Effective dose coefficients in the case of ingested radionuclides from the uranium-238 decay chain

Source: ICRP, 2012, available at <http://www.icrp.org/publication.asp?id=ICRP+Publication+119>

Columns A1 and A2 give the effective dose coefficients in the case of ingestion of the main radionuclides of the uranium-238 decay chain and two age groups (a 5 years old child and an adult). The ICRP (2012) details dose coefficients for 5 age groups.

It is easily observable that the dose coefficients are very different from one radionuclide to another. For example, the most radiotoxic nuclide in the uranium-238 decay chain is polonium-210. In the case of an adult, its dose coefficient (1.2 $\mu\text{Sv/Bq}$) is 26.6 times higher than uranium-238 dose coefficient (0.045 $\mu\text{Sv/Bq}$) and 10 900 times higher than bismuth-214 dose coefficient (0.00011 $\mu\text{Sv/Bq}$).

Polonium-210 is probably the most radiotoxic substance on earth. A high dose of polonium-210 was used to poison and kill former Russian Federal Security Service (FSB) member, Alexander Litvinenko in London in November 2006.

The high variability of dose coefficients is due to the fact that different radionuclides emit different types of radiation with different energies. They also have different chemical properties and different biological half-lives¹⁰. Some may accumulate partially in some organs in the long term and deliver the dose for years and decades after initial contamination, others may be eliminated through urine and faeces more quickly.

It should be noted also that the dose coefficients are usually much higher in the case of children compared to adults. The ratio '5 years old Child'/adult' plotted in

¹⁰ The *biological half-life* is the time an organism takes to eliminate one half the amount of a compound or chemical.

In order to evaluate properly the impact of uranium mining activities, it is necessary to take into consideration all the daughter-products of uranium-238 that are present in the food and water impacted by the mining operations, and not only the father of the decay chain (uranium- 238)

column R, ranges from 1.5 to 3.8. The radio-sensitivity of younger children and babies is even higher.

The dose coefficients plotted here are official values given by the ICRP. But independent researchers point out the fact that the biophysical models used to calculate these factors are not representative of complex biological and physical mechanisms and lead to an underestimation of the actual dose and subsequent risk (ECCR, 2010).

In order to calculate the dose, it is necessary to multiply the effective dose coefficient ($\mu\text{Sv/Bq}$) by the amount of ingested becquerels for each of the radionuclides (see columns D1 and D2 in **Table 11**). The example in **Table 11** deals with the ingestion of one litre or one kilogram of food with a given contamination of 2 Bq/kg for each radionuclide of the uranium-238 decay chain. The consumption of one kilogram of this food or water will lead to an internal dose of 15.4 microSieverts for a 5 year old child and 4.96 microSievert for an adult.

Thus, it is possible to use the typical amount of food or water ingested per year to calculate the annual dose. In the example above, if the typical amount of food ingested in one year is 10 kilograms instead of one kilogram, the dose will simply be 10 times higher; i.e., 154.4 and 49.6 microSievert per year respectively. In this example, more than 50 % of the dose is due to polonium-210 and lead-210, the most radiotoxic radionuclides in the uranium-238 decay chain.

This example shows that in order to properly evaluate the impact of uranium mining activities, it is necessary to take into consideration all the daughter-products of uranium-238 that are present in the food and water impacted by mining operations, and not only the father of the decay chain, i.e. uranium-238 itself. In fact, in the example described in **table 12** below, uranium-238 is responsible for less than 2% of the dose.

In general, in water or food, the uranium-238 decay chain is not in equilibrium. An example of such a disequilibrium is given in **Table 12** below in the case of a sample of underground water.

Therefore, in order to properly evaluate the doses, it is necessary to actually monitor all the radionuclides of the decay chain, or at least, to make reasonable assumptions regarding the activity of some radionuclides when the activity of their father or daughter products is known. For example, in many cases, the activities of uranium-238, thorium-234, protactinium-234^m and uranium-234 are similar. This is usually also the case for the activities of radium-226, lead-214, bismuth-214, as well as for lead-210, bismuth-210, and polonium-210.

For radioprotective purposes, if reasonable assumptions cannot be made, it is recommended to make assumptions that will lead to an overestimation of the dose.

Item	A2	C	D2=A2*C
	Dose coefficient for an adult (μSv/Bq)	Activity (Bq/l)	Dose (μSv/l) for an adult
Activity			
Gross alpha activity		0,19	
Gross bêta residual activity		0,53	
Radionuclides			
Uranium 238	0,045	0,021	0,001
Thorium 234	0,0034	0,021	0,000
Protactinium 234m	0,00051	0,021	0,000
Uranium 234	0,049	0,021	0,001
Thorium 230	0,21	0,000	0,000
Radium 226	0,28	0,053	0,015
Lead 214	0,00014	0,053	0,000
Bismuth 214	0,00011	0,053	0,000
Lead 210	0,69	0,509	0,351
Bismuth 210	0,0013	0,509	0,001
Polonium 210	1,2	0,036	0,043
Total dose (without radon 222): μSv/l			0,41
Radon 222	0,01	1.230	12,3
Total dose (including radon 222): μSv/l			12,71
Annual dose (μSv) if annual consumption of 2 liters/day			9.286
Contribution of different radionuclides to the total dose			
Radon 222 contribution			96,8%
Lead 210 contribution			2,8%
Uranium 238 contribution			0,0074%

Table 12

Detailed monitoring of a sample of underground water used for human consumption in France and evaluation of the dose in case of ingestion

Source: CRIIRAD

2.4.2 Dissolved radon in water

A significant problem lies in the fact that radon-222 activity in water is usually not monitored by mining companies or radioprotection authorities. Radon-222 is a gas that can be dissolved in water circulating through uranium bearing rocks or percolating on waste rock piles or other solid waste containing uranium or radium 226.

In the case of **water** used for human consumption; the dose limit recommended by the WHO is set to 100 microSievert per year (**0.1 milliSievert per year**), but radon-222 dissolved in water is not taken into consideration for the evaluation of this dose.

In fact, the WHO recommends the monitoring of dissolved radon in water but does not set sufficient limits, advising a safety value of 1,000 Bq/l. Only recently a European Directive set a lower limit of 100 Bq/l for radon-222 activity in drinkable water. During the preparation of this Directive, CRIIRAD recommended the limit not to exceed 10 Bq/l and the European Parliament agreed to set a limit of 20 Bq/l, but the final decision was **100 Bq/l**. (EURATOM 2013/51).

One of the most significant problems is the fact that radon-222 activity in water is usually not monitored by the mining companies or radioprotection authorities

In order to assess the radiological content of water samples, different analytical methods can be used. In some cases uranium is monitored alone using **fluorimetry or mass spectrometry**. Its concentration is expressed in micrograms per litre ($\mu\text{g/l}$). Knowing that the specific activity of uranium-238 is about 0.0125 Bq/ μg , one can calculate its activity in water. Often the activity of uranium-234 will be close to that of uranium-238, so the activity of the former can be estimated using uranium-238 activity for a preliminary evaluation. This is not sufficient to evaluate the activity of other uranium-238 daughter products like radium-226, radon-222, lead-210, and polonium-210. This is because their activity and/or contribution to the dose may be much higher and should be monitored specifically using appropriate techniques (gamma and/or alpha spectrometry, liquid scintillation counting, etc.).

A common method of monitoring the quality of water used for human consumption consists of **determining gross alpha activity** and gross beta activity in the water. This is usually done using alpha spectrometry and liquid scintillation techniques.

In the case of France, for example, if gross alpha activity is above 0.1 Bq/l, or residual gross beta activity above 1 Bq/l, further monitoring of the water should be carried out. This is because depending on the type of radionuclide emitting the alpha or beta radiation, the annual dose may exceed 0.1 milliSievert. This additional monitoring is carried out in a laboratory that monitors a list of natural and artificial radionuclides in order to calculate more precisely the total dose for the consumer.

This methodology is not appropriate for many reasons including the fact that in some cases, the limit of 0.1 milliSievert per year may be exceeded even if the gross alpha and gross beta activities are below the limits mentioned above (this may be the case with lead-210 for example).

But perhaps the greatest weakness of this method is the fact that it does not take into account the contribution of radon-222. If the gross alpha activity is high, one might assume there is a large amount of dissolved radon in the water, as radon-222 is an alpha emitter. But most of the analytical methodologies used to monitor the gross alpha activity entail the evaporation of the water. The dissolved radon-222 present in the sample therefore escapes through the air and is not taken into consideration when the sample is measured. In some cases, this will entail an enormous underestimation of the dose to the consumer.

Below and in **Table 12** we illustrate how such underestimation is possible, showing some results of the monitoring of underground water used for human consumption in a village in France. The dose coefficients plotted in column A2 are the values recommended by the ICRP (ICRP, 2012), except for radon-222 for which the dose coefficient is derived from UNSCEAR (UNSCEAR, 1993).

The gross alpha activity of this sample was established by a laboratory agreed by the French Nuclear Safety Authority and using a methodology recommended at international level (NF ISO 10704). It was determined to be 0.19 Bq/l. As this value is above 0.1 Bq/l, additional monitoring was carried out in order to monitor the activity of main natural alpha emitters. The detailed analysis shows that alpha

CRIIRAD recommends the systematic independent monitoring of radon-222 on samples of water collected in the environment of uranium mines

activity is mainly due to uranium-238 (0.021 Bq/l), uranium-234 (0.021 Bq/l), radium-226 (0.053 Bq/l) and polonium-210 (0.036 Bq/l).

CRIIRAD laboratory analysed radon-222 activity and confirmed that gross alpha monitoring did not include radon-222, the activity of which is very high (1,230 Bq/l). In fact, **radon-222** is responsible for **96.8 % of the dose** in the case of ingestion of this water by an adult. The contribution of lead-210 is 2.8 %. The contribution of uranium-238 in this example is below 0.008 %. CRIIRAD therefore recommends the systematic independent monitoring of radon-222 on samples of water collected in the environment of uranium mines.

2.4.3 Contamination through inhalation of radioactive dust

As with ingested radionuclides, the evaluation of doses in the case of inhalation of radionuclides is usually performed in two steps. The first step requires the monitoring of the activity of all relevant radionuclides in the air (Bq/m³). This is done through air samples. The samples are then analysed in a laboratory using appropriate analytical techniques (usually alpha spectrometry or gamma spectrometry). Knowing the amount of air inhaled, it is possible to calculate the incorporated activity for each radionuclide (Bq/year).

Then different dose coefficients (μSv/Bq) must be used for different age groups in order to convert the Bq/year into an annual effective dose (μSv/year). **Table 13** below plots dose coefficients (μSv/Bq) for an adult of the general population, as dictated by ICRP (ICRP, 2012). It is necessary to take into consideration the ability of the substance introduced in the lung to be dissolved in the blood and therefore circulate through the body to other organs.

The ICRP recommends 3 categories of solubility: Fastly soluble (F), Moderately soluble (M) and Slowly soluble (S). In the case of uranium, most of hexavalent compounds like UF₆, UO₂F₂, UO₂(NO₃)₂ belong to class F. Less soluble compounds like UO₃, UF₄, UCl₄ and most of the other hexavalent compounds belong to class M. Very insoluble compounds like UO₂ and U₃O₈ belong to class S (Euratom,1996). In **Table 13** dose coefficients (if available) are associated with these 3 different groups (F, M, S).

Uranium 238 decay chain	Dose coefficients μSv/Bq			
	Class F	Class M	Class S	Maximum
Uranium-238	0.50	2.9	8.0	8.0
Thorium-234	0.0025	0.0066	0.0077	0.0077
Uranium-234	0.56	3.5	9.4	9.4
Thorium-230	100	43	14	100
Radium-226	0.36	3.5	9.5	9.5
Lead-214	0.0028	0.014	0.015	0.015
Bismuth-214	0.007	0.014	-	0.014
Lead-210	0.90	1.1	5.6	5.6
Bismuth-210	0.0011	0.093	-	0.093
Polonium-210	0.61	3.3	4.3	4.3
Subtotal uranium-238 decay chain (if in equilibrium)	102.94	57.43	50.82	136.93

Table 13

Dose coefficients in the case of inhalation for an adult, depending on the solubility

Source: ICRP, 2012 and EURATOM 96/29 Directive

The global dose coefficient when inhaling 1 Bq of natural uranium 238 taking into consideration its own daughter-products with the addition of uranium 235 and its daughter products is 170 $\mu\text{Sv/Bq}$

Comparison with artificial radionuclides

It is useful to note that the radiotoxicity of the natural radionuclides contained in the uranium-238 decay chain is quite high for some substances, including thorium-230, uranium-238, uranium-234, radium-226, lead-210 and polonium-210. Their dose coefficients may exceed 4 microSievert per Becquerel, even reaching 100 microSievert per Becquerel for thorium-230. This means that the annual dose limit of 1,000 $\mu\text{Sv/year}$ can be reached by inhaling only 10 becquerels of thorium-230.

Uranium mining companies frequently declare that uranium, since it is a natural substance, is 'not dangerous'. This is incorrect. When comparing with the radiotoxicity of well-known artificial radionuclides such as caesium-137 (Tchernobyl, Fukushima) or plutonium-238, in fact uranium-238 dose coefficients are 100 to 300 times higher than caesium-137 ones (0.039 $\mu\text{Sv/Bq}$, class S).

Thorium-230 dose coefficients are typically only 10 % lower than plutonium-238 ones (110 $\mu\text{Sv/Bq}$, class F). This means that a given amount of becquerels¹¹ of natural thorium-230 will deliver a dose comparable to the same amount of becquerels of plutonium-238. In order to calculate the dose from inhalation of dust containing uranium and its daughter products, it is necessary to consider the contribution of all radionuclides.

Evaluation of the global dose coefficient when inhaling dust from a uranium mine

The last line in **table 13** above gives the total dose coefficient in the case of inhalation of 1 Bq of uranium-238, assuming that all other daughter products are in equilibrium with uranium-238 itself. This is usually the case with dust from mining activities (blasting), from crushing, and from the waste rock dumps. This is because in such cases no chemical extraction has taken place (no separation between uranium and radium in a mill or through heap leaching).

When the solubility is unknown, for radiation protection purposes, it is recommended to make evaluations using the coefficients with the highest values. In this case, a preliminary evaluation can be made using 136.9 $\mu\text{Sv/Bq}$ of inhaled uranium-238 in equilibrium with its daughter products.

In order not to confuse the reader we do not mention the contribution of uranium 235 and its decay products. The dose coefficient in the case of the inhalation of one Becquerel of uranium-235 in equilibrium with its daughter products is (for an adult) about 717 $\mu\text{Sv/Bq}$. This value is calculated using the highest coefficient for each radionuclide. When dealing with natural uranium, which is the case in a uranium mine and mill, the 'uranium-238 activity' / 'uranium-235 activity' ratio is about 21.7. Therefore, when considering 1 Bq of uranium-238, the amount of uranium-235 is 0.046 Bq (1Bq /21.7) and the dose coefficient becomes $717/21.7 = 33 \mu\text{Sv/Bq}$.

¹¹ The main difference will be the fact that much more thorium-230 (in mass) will be required to obtain the same amount of becquerels as with plutonium-238.

The global dose coefficient when inhaling 1 Bq of natural uranium-238, taking into consideration its own daughter-products with the addition of uranium-235 and its daughter products is therefore $136.9 + 33 = 170 \mu\text{Sv/Bq}$. We use this figure to give one example of the methodology that may be used to make a preliminary evaluation of doses through the inhalation of dust from a uranium mine.

Example of calculation of dose when inhaling dust from a uranium mine based on uranium concentration in the air

In Brazil, near the Caetité uranium mine, the mining company is monitoring dust in the environment. According to official data, during year 2011, the mean value for uranium-238 concentration in dust was $88 \mu\text{Bq/m}^3$ (microBecquerel per cubic metre of air). This measurement was taken at a monitoring post named Tamandua, located 2.1 km downwind of the open pit (North/North-West) (INB, 2014). The natural (background) activity of uranium-238 in the air can be evaluated using the results of monitoring posts located in more remote localities like Maniaçu about 10 km West/South-West ($18 \mu\text{Bq/m}^3$).

In this example, a preliminary evaluation of the impact of the mining operation is $88 - 18 = 70 \mu\text{Bq/m}^3$ of additional uranium-238 dust in the air. For an adult, the typical breathing rate is $0.8 \text{ m}^3/\text{h}$ (higher values should be taken in case of specific activities). For a permanent stay (8,760 hours per year), the air intake would be $7,008 \text{ m}^3$. The mean added activity of uranium-238 in the air being $70 \mu\text{Bq/m}^3$, the annual intake will be 0.49 Bq of uranium-238 ($7,008 \text{ m}^3$ multiplied by $70 \mu\text{Bq/m}^3$). The annual dose will be therefore 83 microSieverts ($0.49 \text{ Bq} \times 170 \mu\text{Sv/Bq}$), which is not negligible.

The actual calculation of the impact would in fact require more detailed data including: the detailed radiological composition of the air (not only uranium), the granulometry of the dust (a fraction of the uranium in the air may not be inhalable if attached to aerosols with a large size), and an evaluation of the different levels of contamination in the open air and inside dwellings (depending on the habits of the inhabitants). However, these calculations are useful for a preliminary assessment.

Another point of concern is whether the data provided by the company is accurate. During an on-site mission performed near the mine, CRIIRAD noticed that the air samplers were not operating in a continuous manner, raising the question of the validity of the samples (Porto, 2014a).

2.4.4 Contamination through inhalation of radon gas in the air

The amount of radon-222 in the air is usually given as a concentration of radon gas (Bq/m^3) which is monitored separately from the radioactivity of dust itself.

In fact, most of the dose to the lungs is not due to radon itself but to its short-lived daughter products, especially polonium-214 and polonium-218 which are alpha emitters like radon (see **table 6** above). The equilibrium factor F allows for the consideration of the relative activities of all of the short-lived alpha emitters created by the disintegration of radon-222 atoms.

Living in a dwelling with radon concentration above 30 Bq/m³ may induce a risk of cancer corresponding to an annual dose in excess of 1 milliSievert

Another useful concept is the **potential alpha energy (PAE)**. One Becquerel of radon-222 in equilibrium with its daughter products is equivalent to a PAE of 5.56 nJ/m³ (nanjoule per cubic metre of air).

The official conversion factors recommended by the ICRP 60 (1990) are:

1.43 mSv per mJ.h.m⁻³ for workers

1.1 mSv per mJ.h.m⁻³ for the general public.

The unit mJ.h.m⁻³ gives the cumulated energy (mJ= milliJoules) incorporated through the inhalation of radon.

Knowing that 1 Bq of radon 222 in equilibrium with its daughter products is equivalent to a PAE of 5.56 nJ/m³ one can calculate that 18 Bq/m³ of radon-222 in equilibrium with its decay products is equivalent to a PAE of 100 nJ/m³. Exposure for a whole year to such concentrations would deliver a dose of about 1 milliSievert.

Taking into consideration more realistic conditions for people in their dwellings, i.e., a typical equilibrium factor of 0.4 and a presence of 7,000 hours per year, the correspondence will be:

57 Bq/m³ of radon 222 indoor is equivalent to 1 mSv/year

According to new evaluations proposed by the ICRP 115 (2011), living in a dwelling with radon concentration above 30 Bq/m³ may induce a risk of cancer corresponding to an annual dose in excess of 1 milliSievert.

For more accurate evaluations of the annual dose due to radon, it is necessary to take into consideration the actual equilibrium factor and exposure duration. The equilibrium factor may be very different in the outside air and in the air inside dwellings.

3 Environmental impacts

At the surface of planet earth, on all continents, there are natural levels of radiation in the soil, water, air, flora and fauna. Uranium-238, uranium-235 and their daughter products are present in all rocks and soil. These natural radionuclides are also naturally present in the lower atmosphere (dust from the soil) along with radon-222 which permanently emanates from the rocks and soil. They are also present in surface and underground waters in contact with this soil and rocks as well as in the crops, flora and fauna and therefore in the food chain.

The radiation emitted by these radionuclides is called natural background radiation. When uranium ore is buried underground – at a depth of few tens or even few hundreds of metres – the radiation levels at the surface of the soil remain low and usually have the same order of magnitude of natural radiation levels. Exceptionally, some areas of a limited extension (a few square metres) can be found where the ore reaches the ground surface. Otherwise, the protection offered by the soil is usually sufficient to reduce the risks for people living in the area. Indeed, alpha and low energy beta particles are stopped by a thin layer of soil (much less than 1 cm.). Even penetrating gamma radiation does not cross a layer of soil of a few metres deep. Most of the radon gas remains trapped inside the soil because of its short half-life (3.8 days), many of the gas atoms will disintegrate inside the soil during their migration before reaching the biosphere.

When uranium is mined, uranium ores are brought to the surface. Uranium ores have high uranium content. A typical ore with a uranium concentration of 0.2 % has a uranium-238 activity of about 25,000 Bq/kg. The total activity calculated including all the uranium 238 daughter products and the uranium-235 decay chain therefore exceeds 360,000 Bq/kg, while the mean activity of the earth's crust is below 2,000 Bq/kg. Such material should be managed with a great deal of caution due to the risks of exposure to ionizing radiation.

In terms of underground water quality, the amount of nuclides may remain low if the minerals containing uranium are trapped in impermeable layers. The radiological situation changes, as soon as uranium extraction begins.



In **section 3.1** of this chapter we examine in detail these impacts, first looking at the paths of contamination through water, and then through the atmosphere (dust and radon):

- Uranium mining will increase the amount of uranium and its daughter products in surface and/or underground water. Some of them are very radiotoxic when ingested (Chareyron and Castanier, 1994). Lead-210 and polonium-210 for example are among the most radiotoxic elements.
- Radioactive dust is transferred to the atmosphere by mining operations, extraction and crushing of the ore, uranium milling, and management of waste rock and tailings.
- Radon gas is transferred to the atmosphere by the vents of underground mines and by diffusion from radioactive rocks and tailings (Chareyron and Castanier, 1994).

In **section 3.2** the threats uranium extraction poses to the environment are examined. The impact begins with very first step of the process, namely uranium prospecting.

All the production processes of mining operations, from extraction and crushing of ore to uranium milling and production of yellow cake, transfer radionuclides into the biosphere. This should be taken into account when calculating the dose of workers and affected populations.

Radioactive waste is produced by uranium mines in many different forms, increasing the ambient dose rates for workers and people living in the vicinity of these materials. These include solid waste (waste rocks, tailings, contaminated equipment, etc.) and liquid effluents which are not properly managed and are usually disposed of without proper confinement, allowing for airborne and water contamination. The biggest impacts come from waste rock and tailings.

Huge quantities of radioactive waste rock (rocks not treated in the mill), with activity exceeding the normal natural activity of the earth's crust by one to two orders of magnitude accumulate in uncovered waste rock dumps. They are also sometimes dispersed into the environment and may be used for landfill, road construction or even building (Chareyron, 2002b).

Large amounts of radioactive tailings are generated by milling operations and generally stored without proper confinement (Chareyron and Castanier, 1994). They contain all the radioactive metals of the uranium decay chain which have not been extracted in the mill, especially thorium-230 and radium-226 whose half-lives are 75,000 years and 1,600 years respectively (with typical total activities exceeding 100,000 and even 500,000 Bq/kg). In some cases they are discharged directly into the environment, or re-used.

It should be stressed that even decades after shutting down uranium mines and mills, the radioactive contamination of the environment remains. This is due to the fact that uranium-238 half-life is very long (4.5 billion years). Uranium-238 will always be present in the different types of waste, decaying into its daughter products.



Of major concern is the possible contamination of surface and underground waters, transportation through the air of dust, radon gas and gamma radiation, and the stability of the tailings dams themselves, as they have failed on several occasions.

Contaminated liquid effluents furthermore pose a considerable risk due to limitations in their treatment before they are discharged into the environment. Even when the effluents are transferred to containment pools for evaporation, the risk of spills remains.

In **section 3.2.6** we will examine the risks linked to the management and transportation of yellow cake, the product obtained from the uranium extraction process. Finally, in **section 3.2.7** other impacts related to the production of yellow cake will be explored such as the use of chemicals, of water resources and the use of fossil fuels and greenhouse gas emissions. This last point is particularly relevant in the climate change debate and the role of nuclear as a 'clean' source of energy.

3.1 Radioactive contamination routes

3.1.1 Water contamination

The water in contact with the uranium ore body is able to carry some of the radioactive elements initially contained in the rocks, either in their soluble or insoluble forms. Many factors affect the mechanisms of transfer of the radioactive elements from the rocks into the water including: chemical characteristics of the water and the ore body, temperature, permeability and granulometry of the rocks.

Uranium mining will drastically increase the contamination of the water. Some of the reasons for this are given below.

The digging of the mine, trenches and tunnels increases the surface of exchange between the water and the rocks as the solid rock is fractured, crushed, etc.

In the case of open pit mining, companies must move millions of tonnes of radioactive rock, allowing the radioactive metals in the rocks and ore to be more readily mobilised, and increasing the risk of groundwater and surface water contamination. For example, Rössing (Namibia) moved 31.7 million tonnes of waste rock in 2012 in order to process 12 million tonnes of ore and produce 2,699 tonnes of uranium oxide (Rössing, 2014).

Uranium extraction exposes groundwater to the air, which may bring about chemical reactions that can affect the characteristics of the water; and increase the transfer of sulphates and radioactive heavy metals. This mechanism is known as Acid Mine Drainage.

The radioactive material is exposed at the surface of the soil under the influence of rain. This is the case for most waste rock dumps. In order to keep the mine dry, huge amounts of contaminated water have to be pumped out. Sometimes, the contaminated water is not treated and is discharged directly into the environment.

This was systematically the case in the early years of uranium mining. This is still

At many places, the sediments, aquatic plants and soil from river banks downstream from uranium mines have such a contamination that they should be disposed as "radioactive waste"

the case today at some mines either because there is no legislation and control or because the standards applied to decide if a treatment is necessary or not are very poor.

Even when a treatment is performed, the standards applied enable the discharge of waters with a significant residual contamination and available treatment methodologies are not efficient enough to totally remove the radioactive heavy metals (see **section 3.2.5.2**). The surface and/or underground waters will then contaminate the aquatic environment. This can occur in the very long term even after the closure of the mine.

The contaminated waters of former uranium mines (and also tailing deposits, uncovered waste rock deposits, etc.) will then induce the accumulation of radioactive metals in sediments, fauna and flora, plants of rivers, ponds, and lakes. This is a problem that has not yet been properly addressed by companies.

Contamination of the soil, river and lake sediments

In many places, the sediments, aquatic plants and soil from river banks downstream of former uranium mines are so contaminated (uranium-238 activity or the activity of some of its daughter-products exceeding 10,000 Bq/kg) that they should be disposed of as 'radioactive waste'. Some examples are given in **Tables 14** and **15** below.

The accumulation of uranium-238 and/or radium-226 downstream of uranium mines is usually more intense for surface soil sampled from the river banks than from river sediments (one order of magnitude in this example) as shown in **Table 15** below.

Sample type	Sample, Location	Year	Uranium-238 (Bq/kg dry)	Radium-226 (Bq/kg dry)	Lead-210 (Bq/kg dry)
Sediment	Brook, upstream	2006	76	77	123
Sediment	Ditch, near Lake, downstream	2003	49,900	1,191	1,387
Sediment	Ditch, near Lake, downstream	2006	144,000	430	2,150
Sediment	Lake, downstream	2004	126,000	735	3,533

Table 14

Radioactivity of sediments upstream and downstream Saint-Pierre mine (France) (year 2003, 2004, and 2006)

Note: Saint-Pierre mine is located in Cantal (France). Uranium extraction took place from 1956 to 1985. The mining companies were SCUMRA, then Total Compagnie Minière. The site is now under COGEMA-AREVA's responsibility (Chareyron 2004, 2005a; Chareyron and Constantin Blanc 2007a)

Source: CRIIRAD

Sample type	Sample, Location	Year	Uranium 238 (Bq/kg dry)	Radium 226 (Bq/kg dry)	Lead 210 (Bq/kg dry)
Sediments	River, upstream	1996	87	85	109
Marshy soil	Downstream tailings pond	2001	7,900	18,400	7,500
Sediments	River, 25m downstream water discharge	2001	510	770	390
Soil	River bank 25 m downstream discharge	2001	5,900	10,600	4,100
Deep sediment (20/30 cm)	Dam, 12 km downstream	1996	4,048	1,928	1,613
Sediment	Dam, 12 km downstream	2006	4,700	1,630	1,680

Table 15 Radioactivity of sediments and soil upstream and downstream Les Bois Noirs uranium mine (year 1996, 2001 and 2006)

Note: Les Bois Noirs mine is located in the Loire department (France). Uranium has been extracted there from 1955 to 1980 by the CEA and then COGEMA-AREVA. (Chareyron 2002b, Chareyron 2008b).

Source: CRIIRAD

Contamination of the biota near rivers

Bioaccumulation of radioactive metals can be extremely high in the biota. In some cases, the contamination of aquatic plants by radium 226 downstream of uranium mines can exceed 100,000 Bq/kg dry

Bioaccumulation of radioactive metals can be extremely high in the biota. In some cases, the contamination of aquatic plants by radium-226 downstream of uranium mines can exceed 100,000 Bq/kg dry (**Table 16** below). Such levels show clearly that mine water treatment systems are not operating properly, and/or that the requirements of the authorities are not strict enough.

The problem of bioaccumulation is usually not taken into consideration by mining companies, nor by the administration in charge of environmental monitoring and regulatory control.

It should be noted as well that radioactive metals contained in liquid effluents can be transported tens of kilometres from the mines. At Les Bois Noirs mine (France), uranium accumulation in sediments 12 km downstream of the mine is still 54 times above the natural value monitored upstream (**Table 15**). Uranium and radium accumulation in aquatic mosses are 4 to 6 times above background value 30 km downstream of the discharge pipe of the mine (**Table 16**).

Sample type	Sample, Location	Year	Uranium-238 (Bq/kg dry)	Radium-226 (Bq/kg dry)	Lead-210 (Bq/kg dry)
Fontinales	river, upstream	2001	109	144	323
Fontinales	Drain, downstream tailings pond	2001	32,400	113	1,250
Fontinales	river, 25 m downstream the discharge pipe	2001	9,000	93,600	1,430
Fontinales	river 1.5 km downstream	2001	3,500	37,800	600
Fontinales	river, 9 km downstream	2001	1,900	5,500	480
Fontinales	river, 30 km downstream	2001	450	990	210
Fontinales	inside discharge pipe	2006	3,400	143,000	6,000
Fontinales	river < 1 km downstream	2006	10,200	147,000	2,400

Table 16 Radioactivity of aquatic mosses upstream and downstream Les Bois Noirs uranium mine (France) (Year 2001 and 2006)

Source: CRIIRAD, Chareyron 2008.

Many different operations conducted during uranium mining activities are producing a lot of radioactive dust: blasting the rocks inside the mine, loading and unloading the trucks with the rocks, crushing the ore, transporting various types of materials on unpaved roads

3.1.2 Airborne contamination through dust

Many different operations conducted during uranium mining activities produce a large amount of radioactive dust. Examples include blasting the rocks inside the mine, loading and unloading the trucks with rocks, crushing the ore, and transporting various types of materials on unpaved roads.

This dust contains radioactive elements that can be carried long distances by the wind. For example, particles of sand from the Sahara desert are transported by the wind across the Mediterranean Sea and can travel more than one thousand kilometres. Examples of environmental contamination through dust deposition are given in **section 3.2.3.3**.

3.1.3 Airborne contamination through radon

General observations

Radon-222 is a radioactive gas produced by the disintegration of radium-226 associated with uranium-238. Uranium extraction results in an increased concentration of radon in the atmosphere. There are a number of reasons for this that include the exposure to the air of rocks with a high concentration of uranium and radium-226 (in both open pit and underground mines); the storage in the open of heaps of ore at the pitheads and near the uranium extraction plants; excavation and drilling; the pumping of groundwater; the storage in the open of mine spoil from underground and open pit mines; the storage in the open of tailings (waste from uranium extraction); and the ventilation of the underground galleries.

Even though the physical half-life of radon is relatively short (3.8 days), this radioactive gas can cover tens or even hundreds of kilometres before it disintegrates totally. After one week, the radioactivity of radon gas is still about 27% of its initial value. It takes 38 days for its radioactivity to fall to a thousandth of its original level.

Radon is an emitter of **alpha** particles, and its disintegration is accompanied by the creation of short half-life heavy metals (polonium-214 and polonium-218) which also emit alpha particles. Inhalation of this radioactive gas and its decay products thus leads to the irradiation of the respiratory system.

Radon is classed as **carcinogenic** to humans and is reckoned to be the second commonest cause of fatal lung cancer after tobacco. The increased incidence of lung cancer among uranium miners has been known for decades. Recent epidemiological studies have confirmed that inhalation of radon increases the risk of lung cancer even at very low doses and even in the context of exposure at home (Darby, 2005).

After inhalation, a proportion of radioactive isotopes enters the bloodstream and may reach other organs besides the lungs. Some researchers think that other pathologies may be caused by exposure to radon, in particular leukaemia.

The disintegration of radon leads to the formation of heavy metals two of which have a relatively long half-life: **polonium-210** (an alpha emitter with a half-life of

Radon is classed as carcinogenic to man and is reckoned to be the second commonest cause of fatal lung cancer after tobacco. The increased incidence of lung cancer among uranium miners has been known for decades

138.5 days) and **lead-210** (a beta and gamma emitter with a half-life of **22.3 years**).

In the vicinity of uranium extraction zones, significant quantities of radon are emitted into the atmosphere and can progressively lead to an abnormal accumulation of lead-210 and polonium-210 on soil and vegetation surfaces. This accumulation can lead in turn to internal contamination of the local population through ingestion of contaminated food. Indeed, polonium-210 and lead-210 are among the most radiotoxic radionuclides by ingestion.

In the environment of uranium mines, radon (and its daughter products) is one of the highest contributors of the internal dose to workers and the communities living nearby.

Knowledge of radon concentrations around mining zones, both in the outdoor air and within buildings, is thus fundamental to assess the health risks posed to local populations. Reliable measurements require a sufficient number of sampling locations over a long duration on account of the high variation in concentrations over time, in terms of both hourly (daily cycle) and annual (seasonal variation) timescales. These measurements can be carried out using different techniques (charcoal canisters, passive detectors, active samplers, etc.).

Air vents of underground mines

Among the various industrial sources of radon, particular attention should be given to the impact of the air vents of underground mines, which can emit large amounts of radon into the atmosphere.

In order to lower the amount of radon and radon daughter products inhaled by miners, underground mines have to be vented. Fresh air is pumped down to the mine tunnels whilst extracting air from the shafts whose radon concentration will increase as it is flowing close to the uranium bearing rocks.

In 1991, the yearly discharge of radon to the atmosphere at the Fanay uranium mines (**France**) was, according to AREVA, 249,000 Billion Becquerels (Chareyron and Castanier, 1994). Usually, mining companies do not give figures related to this impact.



Figs. 4-5

**COMINAK mine
air vents near
Akokan city**

Source: CRIIRAD,
C Chamberland
and M. Roche,
2007

The annual reports of AREVA's COMINAK underground mine in **Niger** do not mention the annual discharge of radon to the atmosphere (COMINAK, 2009). But as a result of approaches taken in 2004, CRIIRAD received the following information from AREVA:

"The concentrations of radon emitted from the air vents (ventilation is mandatory under article 32 of the regulation of 8/01/2001, which also defines maximum radon concentrations acceptable in the workplace) are very variable, depending on:

- *the nature of the zone being mined*
- *the ventilation of the zone (airflow after it has been mined)*
- *weather conditions.*

*The concentrations measured range from **3,600 to 18,000 Bq/m³** with an average of **10,000 Bq/m³** at the level of the outlet itself. The impact of this ventilation is reflected in the measurement of added doses and has no effect on the population."*

Such radon-222 activities are several orders of magnitude higher than the usual natural radon concentration in the atmosphere (typically about 10 Bq/m³). Moreover, AREVA's radon monitoring in 2008 in the open air in the city of Akokan – located next to COMINAK mine (the area designated 'Akokan gendarmerie') – shows an annual added dose of 1.36 millisieverts, 90% of which is due to radon-222. This impact is well above the maximum annual dose limit of 1 milliSievert per year (Chareyron, 2010a).

Radon diffusion from radioactive material stored at the surface of uranium mines

Even when there is no pumping system, the natural 'passive' diffusion of radon from the soil to the atmosphere is a source of additional radon in the environment of uranium mines. According to UNSCEAR (UNSCEAR, 1988), the typical natural exhalation of radon from the surface of the earth's crust is about **20 mBq/m²/s**. But when the material left on the soil or close to the surface contains higher levels of uranium (waste rocks, uranium ore) or radium 226 (tailings), the radon exhalation rates are much higher.

For example, near the village of Saint-Pierre (France) a mine and a mill was in operation between 1956 to 1985. Even though the site had been officially reclaimed, CRIIRAD monitored in 2006 high levels of radon exhalation ranging between 76 to 5,383 mBq/m²/s. The highest levels were monitored on soil contaminated with tailings, uranium ore and other types of waste (Chareyron, 2007c).



Fig. 6

Monitoring of radon exhalation at Saint-Pierre (France)

Source: CRIIRAD, 2006



The diffusion of radon from the contaminated material stored at the surface of uranium mining areas increases the radon concentration in the open air. According to UNSCEAR, the mean radon-222 activity in the open air is about **10 Bq/m³** above land (and much lower above the oceans). The values are usually much higher near uranium mines.

For example, in the case of the former uranium mine in Saint-Pierre (France), radon emission from radioactive waste left on the soil increased the concentration of radon in the open air from 30 Bq/m³ monitored at reference locations remote from the mine, to 500-650 Bq/m³ on the property of the mine (Chareyron, 2007c).

Radon accumulation inside buildings

In some instances radioactive waste rock or mine tailings have been used for the construction of buildings, increasing the amount of radon in the buildings drastically. Examples are described in **sections 3.2.2.2** and **3.2.3.2** below in the case of the re-use of waste rock and tailings.

Recently, in France, very high levels of radon were monitored in a private house in the village of Bessines-sur-Gartempe (Limousin) where a family was caring for children. This house was a former petrol station built in the 1960s on waste rock and tailings from a COGEMA-AREVA uranium mine. Using helicopter monitoring surveys, in 2009-2010 AREVA detected high gamma radiation levels above this house. But the mining company did not immediately monitor radon inside the house.

The Radiation Protection Authorities¹² were informed only in March 2014 of the detection of very high radon concentrations inside the house (between 9,000 and 19,000 Bq/m³). The authorities decided to relocate the family¹³. Such values are extremely high compared with the average monitored in this department (about 204 Bq/m³) and with the WHO recommendation of 100 Bq/m³ inside houses. Spending 7,000 hours per year in such a house would correspond to an annual dose of from 157 to 300 times the annual dose limit of 1 milliSievert per year.

When the drill reaches the mineralized areas, radioactive fluids (contaminated water) and solids (mud, crushed rocks, core samples) are brought to the surface

3.2 Impacts of uranium mining and milling operations

3.2.1 Impacts of prospecting activities

The first steps of prospecting activities, such as monitoring of radiation in surface waters or existing wells, mapping of ambient gamma radiation of the soil, and monitoring of open air radon activity do not modify radiation in the biosphere. However, when initial prospecting activities indicate the presence of underground uranium deposits, companies necessarily launch more destructive sampling activities. These include digging trenches and exploration tunnels, and performing

¹² Press Release of the prefecture of Haute Vienne, March 27th 2014.

¹³ France Bleu, May 20th, 2014, "Bessines : des taux de radioactivité très élevés dans la maison de la nounou" (<http://www.francebleu.fr/environnement/radioactivite/les-mesures-dans-la-maison-evacuee-bessines-montrent-des-taux-de-radioactivite-tres-eleves-1538837>).

drilling activities in order to evaluate the extent and quality of uranium deposits. These activities increase radiation in the biosphere.

Trench digging removes the protective layer of soil covering the rock. In the course of a mission performed in Brazil in April 2014, CRIIRAD monitored dose rates about 10 times above natural values at different locations along an exploration trench 4 metres wide and hundreds of metres long in Juazeiro (Bahia State) (Porto, 2014a).

When the **drill** reaches the mineralized areas, (i.e., the underground layers bearing uranium deposits), radioactive fluids (contaminated water) and solids (mud, crushed rocks, and core samples) are brought to the surface. For example, independent monitoring activities performed at the soil surface at an AREVA prospecting area in Imouraren (Niger) revealed gamma radiation rates 5 to 9 times above natural background radiation on top of small heaps of radioactive material left after drilling activities (Chareyron, 2008a).



Figs. 7-8

Impact of prospecting activities in Niger / AREVA Imouraren project (C. Chamberland et M. Roche, April 2007)

Source: CRIIRAD

After drilling operations, mining companies take **core samples** of underground rock in order to send them to specialized laboratories for detailed chemical and/or mineralogical analysis. The preliminary treatment of the radioactive core is usually partially done on site in prospecting camps. These activities expose workers to radiation, and radioactive material is sometimes left at the camp. For example, in Cameroon, a Cameroonian NGO discovered radioactive rocks in the camp of the Mega uranium company, in a village close to Poli. The dose rate of the rocks was above 10 $\mu\text{Sv/h}$, saturating the portable radiation monitor. The amount of uranium-238 reached 2 million Bq/kg (Chareyron, 2014a).



Fig. 9

Village near Poli (Cameroon) where radioactive rocks were left at Mega Uranium prospecting camp

Source: David Bayang, 2008

CRIIRAD visited private **laboratories** in Bamako (Mali) and Swakopmund (Namibia) where core samples were crushed and treated, later to be sent to analytical laboratories overseas. The exposure of workers to ionizing radiation was not properly monitored.

On occasion these drilling activities have direct consequences on **water resources**. Drilling can profoundly modify the circulation of underground waters and interrupt the flow of natural springs. This occurred in the case of prospecting activities a few decades ago in Limousin (France). When drilling penetrates deep **aquifers**, water flows through the artificial hole. This water may then carry toxic chemicals (like heavy metals, different anions and cations) and radionuclides.

In Falea, Mali, uranium prospecting activities were carried out by the Canadian company, Rockgate. Villagers complained that three cows died after drinking the water that flowed for several days from the hole of a drill. By November 2011, more than 440 holes had been drilled in this area. A traditional well had also been abandoned after wastewater from a nearby drill flowed into the well. The mining company is now bringing water by truck in a tank to supply the villagers (Chareyron, 2011a).

During prospecting, the local population is also subjected to various other negative impacts. Companies do not hesitate to drill in the middle of fields or near houses. Sometimes drilling is performed at night, meaning that inhabitants are exposed to noise and powerful lights and are unable to sleep properly. Prospecting work is carried out extensively in many areas of the world. In Africa alone thirty-five countries have already granted exploration licenses (Wise uranium, 2014).

3.2.2 Impacts of radioactive waste rock from mines

3.2.2.1 Waste rock dumps

In the case of conventional uranium mining (open pit or underground mines) much of the material (soil, rocks) has to be removed before reaching the ore body.

The material is tested for gamma radiation in order to establish the average uranium content. When the level of radiation is below a given value, which means the uranium content is not high enough; the material is called 'waste rock' and usually stockpiled in a waste rock dump.



Fig. 10

Aerial view of a Rössing waste rock dump

Source: Google Earth, CRIIRAD

The average uranium activity in such waste rocks may be typically one hundred times above the mean value of the earth crust. Moreover, samples of uranium ore are usually mixed with the waste rocks giving even higher radiation doses

The average uranium activity in such waste rock is typically one hundred times above the mean value of the earth's crust. Moreover, samples of uranium ore are usually mixed with waste rock, producing even higher radiation doses. This is due to the fact that the screening methods for monitoring the radiation of the material extracted from the mine gives only a global assessment. For example, monitoring is usually performed on trucks loaded with several tens of tonnes of rock. If several kilograms of rock with high uranium concentration are mixed into the middle of the load, high gamma radiation rates can remain undetected.

The uranium mining activities of Rössing produce huge amounts of waste rock (31.7 million tonnes in 2012). CRIIRAD carried out a radiological study of the surrounding area of the Rössing uranium mine in Namibia (Chareyron, 2014b) as part of the EJOLT project. CRIIRAD and Earthlife Namibia discovered that one of the waste rock dumps is located on the banks of the Khan River (at the intersection with Dome Gorge) without appropriate fencing and without any confinement. In **Figure 10** above, the waste rock has a blue colour distinct from the natural substratum, with the blue line indicating the Khan River bed. The river flows underground except during annual heavy rains.

CRIIRAD preliminary measurements were able to illustrate the radiological impact of the waste rock dumps through different pathways explained further below: gamma radiation, transfer of radionuclides to the atmosphere, surface sediments and underground water.

Airborne contamination

During the same sampling campaign, **Gamma and beta-gamma dose rates** measured with an electronic dosimeter at close range was well above background values: 37 $\mu\text{Sv/h}$ for the gamma dose (Hp10) compared to a local background value of 0.19 $\mu\text{Sv/h}$. The measurement for the beta-gamma dose to the skin (Hp 0.07) was 130 $\mu\text{Sv/h}$, about 1,300 times above typical background values.

Gamma radiation is very powerful and can travel through air at distances of tens of metres from the source. At a distance of 150 metres from the waste rock dump, the ambient dose rate was still about 50 % above the natural background rate.



Figs. 11-14

View of a waste rock dump at Dome Gorge, and monitoring of gamma radiation

Source: CRIIRAD and Earthlife Namibia, 2011



Waste rock contains high levels of uranium in equilibrium with its daughter products. This includes radium-226, which continuously disintegrates and produces the **radioactive gas radon-222**. A preliminary monitoring of radon gas activity in the ambient air near the waste rock confirmed high values of 722 Bq/m³ (mean value) when the monitor was located on the rocks.

The waste rock dumps are not covered so radon is continuously emitted by the rocks, and transferred to the atmosphere, contaminating the area.

Water contamination – sediments samples

The finest fraction of radioactive rock is washed away, **contaminating the sediments** of the Khan River. Due to the alpha emissions of uranium and its daughter-products, the mineral is progressively destroyed by radiation. The fact that the rock is now in contact with air and rain also changes the chemical reactions at the surface of the rock, facilitating the dissolution of some of the radioactive heavy metals contained in the rock.

This is illustrated by the laboratory analysis of sediments (**Figure 15**) in which uranium-238 activity is 1,200 Bq/kg and radium-226 activity is 1,400 Bq/kg. These values are 10 times above those measured in sediments collected in the Khan River upstream from Rössing mine.



Fig. 15

Sampling of fine sediments at the bottom of a Rössing waste rock dump

Source: CRIIRAD, 2011

Water contamination – water samples

The rain can also transfer the most mobile nuclides and chemicals to underground waters. For this reason, CRIIRAD performed sampling of underground water from boreholes located in the Khan riverbed upstream, and immediately downstream, from the waste rock dump.

The analysis of the water samples showed a significant increase in the concentration of various chemicals downstream of the waste rock dump (see **section 3.2.7.1**). However, the highest impact concerned **uranium** (factor 2,155) whose concentration was **431 µg/l downstream, while it was only 0.2 µg/l upstream**. The WHO recommended uranium concentration limit in drinkable water is now 30 µg/l.



In many countries, radioactive waste rocks from the uranium mines have been re-used for road construction and even for building activities

According to Rössing's SEIA (Social and Environmental Impact Assessment), the external irradiation from the waste rock dumps *"is not considered as members of the public will not have access to such areas during mine operation"* (Rössing, 2011).

However as indicated in other sections of the same SEIA report: *"The Khan River is an important tourist view corridor and should not be subjected to landscape modifications. The existing vista does include close views of the existing waste rock dumps"* (Rössing, 2011).

From a radiological point of view, access to the waste rock dump should be restricted. At a meeting with Rössing management in April 2012, CRIIRAD and Earthlife asked that a fence be built around the waste rock dump in order to lower the risk of the public being exposed to radiation. Acknowledging this demand, Rössing stated that *"a fence has been erected to prevent unauthorised access into the mining licence area"* (Response from Rössing, January 16th 2013).

Spending only 20 minutes at the bottom of the waste rock dump in contact with some of the rocks can produce a dose in excess of the trivial level of 10 microSieverts. These results also show that the workers inside the mine are continuously exposed to radiation from the ore bodies and waste rock. People should also be prevented from bringing home radioactive rock because in this case the duration of the exposure may be much longer than a few minutes.

In order to evaluate the global risk for the public and workers, two other exposure pathways should be taken into consideration: the internal exposure to radioactive dust and radon gas; and the risk of ingestion of radionuclides in case of direct contact with the rock.

The appropriate disposal of radioactive waste rock should be further addressed by Rössing. Waste rock should be deposited in a place that is at minimum confined below the rocks and covered with layer of clay or some other material to limit erosion, lixiviation by rain, radon emissions, etc.

This issue is extremely important, especially considering the fact that Rössing expansion projects will potentially create approximately 250 million tonnes of additional waste rock requiring disposal (Rössing, 2011). Contamination will be everlasting since uranium 238 has a half-life of 4.5 billion years (Chareyron, 2014b). Similar problems recorded by CRIIRAD exist in France, Bulgaria, and Niger.

3.2.2.2 Re-use of radioactive waste rock

In many countries, radioactive waste rock from uranium mines have been re-used for road construction and even for building activities.

France

CRIIRAD demonstrated that several places near a French uranium mine were contaminated, including the car park of a restaurant, the yard of a farm, several sawmill buildings, and several kilometres of path and roads (Chareyron 2002b).

In one case, a sawmill was built several decades ago directly on radioactive waste rock taken from the mine. Due to gamma radiation and radon gas accumulation, the radiation dose inside the building exceeded the annual maximum permissible dose for members of the public by a factor of 20. In 2003, the mining company AREVA had to pay to return 8,000 m³ of radioactive waste rock to the former open pit (Chareyron 2002b).



Figs. 16-17

Sawmill built on radioactive waste rock from a uranium mine, France

Source: CRIIRAD

As of November 2014, discussions with the mining company, local NGOs and the government are on-going, to decide if radioactive rock used at other places would or would not be removed (other saw mills, private houses, recreation centre, etc.).

Gabon

In Mounana, Gabon, the houses of workers of the COMUF-AREVA mine were built with radioactive material from the mine. Monitoring of gamma radiation performed in 2009 by a French journalist revealed high gamma radiation doses in 4 dwellings (from 0.4 μ Sv/h to 0.87 μ Sv/h at the soil surface and 0.24 to 0.51 μ Sv/h one metre above ground). CRIIRAD calculated that the cumulated external irradiation for the inhabitants of 3 of these dwellings was above the annual dose limit of 1 mSv/year. Taking into consideration the additional dose due to the inhalation of radon 222 and the ingestion of contaminated food, would give much higher results (Chareyron, 2009a).

CRIIRAD wrote a letter to AREVA and to the Radiation Protection authorities of Gabon in order to obtain the results of official radiation monitoring efforts. Neither AREVA nor the Ministry of Mines and Energy of Gabon provided the reports. CRIIRAD eventually procured an unauthorised copy of an official report (CNPPRI, 2007) written by the Radiation Protection authorities. According to this report, in Mounana, more than 100 dwellings are affected. The additional dose due to external irradiation was found to be above 4,000 μ Sv/year in several of them, reaching up 15,400 μ Sv/year. This compares to a maximum annual dose limit of 1,000 μ Sv/year. There is no doubt that when considering the contribution of internal exposure the inhabitants are submitted to much higher doses. Very surprisingly, a report (VEIT, 2010) commissioned by the European Parliament and published in 2010 concluded that *“apparently no radioactive material had been used for construction”*.

Bulgaria

In the course of the EJOLT project, CRIIRAD and Za Zemiata found in 2011 that radioactive waste rock was present in areas easily accessible to the public in Bulgaria. These areas are near the Seslavytzi village and Buhovo town, around 25 km from Sofia.

The dose rate monitored for example on picnic tables used by tourists visiting the Seslavytzi monastery was 0.35 $\mu\text{Sv/h}$. The radiation came from radioactive waste rock located less than 1 metre from the tables. A dose rate of 0.88 $\mu\text{Sv/h}$ was monitored one metre above the rocks. Some waste rock showed high radiation doses in the area of 110 $\mu\text{Sv/h}$. Such a dose rate is about 500 times above a typical natural background dose. A child bringing samples of such radioactive rocks home would receive non-negligible doses.

On the main waste rock pile located about 100 metres from the monastery, the dose rate monitored 1 metre above ground was between 0.6 and 0.9 $\mu\text{Sv/h}$. Gamma radiation was coming from uncovered radioactive waste rocks. The dose rate to the skin on such samples was 50 $\mu\text{Sv/h}$ (about 250 times above the typical natural background dose). The same was the case with the waste rock piles of Seslavytzi former uranium crusher (0.88 $\mu\text{Sv/h}$ one metre above ground and 20 $\mu\text{Sv/h}$ on the rocks).

In Buhovo city, the dose rate of radioactive waste rock lying on the soil of a landfill located between a school and the hospital was 0.46 $\mu\text{Sv/h}$ (1 metre above ground) and more than 4 $\mu\text{Sv/h}$ on the rocks.

In many places, very radioactive samples of uranium ore from mines are kept by local people or former workers who are unaware of the often significant radiological hazards

3.2.2.3 Re-use of radioactive minerals

Often, highly radioactive samples of uranium ore from mines are kept by local people or former workers who are unaware of the often significant radiological hazards. The CRIIRAD laboratory for example discovered in France that residents near the Les Bois Noir former uranium mine were keeping a sample of uranium ore with a dose rate of 1 milliSievert per hour at the surface of the stone (Chareyron, 2002a). This figure is about 5 000 times the local background level.

The gamma dose rate was 18.3 microSievert per hour at a distance of one metre. Staying at a distance of 1 metre for just 10 minutes per day exceeds the annual maximum permissible dose for members of the public i.e. 1 milliSievert per year (Euratom, 1996).



Figs. 18-19

Very radioactive rock from a former uranium mine kept in the garden of a Citizen in France

Source: CRIIRAD, June 2012

3.2.3 Impacts of radioactive tailings from the mills

After the uranium ore has undergone a milling process to obtain yellow cake, large amounts of radioactive waste in the form of tailings have to be disposed of. As explained in **section 2.1.3**, the radiological content of these tailings is about 70-80% of the original radiological content of the uranium ore and currently exceeds 100,000 Bq/kg.

In the past, tailings have been discharged directly into the environment, and even re-used in places accessible to the public. But even when they are disposed of at the mine or mill site, usually in tailings dams, a transfer of radioactive substances takes place as a result of inadequate disposal.

The issue of how to control tailings dams has not yet been dealt with adequately, nor have proposed solutions taken into consideration their radioactivity, and the radiotoxicity and long half-lives of the radioactive substances contained within them. The contamination of the atmosphere and water through the transfer of radionuclides described above in the case of the waste rock also occurs with tailings dams. In this section, the problem of the poor management of tailings is examined using examples from France (where about 50 million tonnes of tailings are stored), Gabon, Niger and Namibia.

3.2.3.1 Direct discharge of tailings into the environment

In the past, mining companies were accustomed to discharging radioactive tailings directly into the environment.

This is what COMUF, a subsidiary of the French company COGEMA (now AREVA), did in Gabon (Africa). In the city of Mounana, COMUF extracted more than 6 million tonnes of uranium ore from the early 1960s until 1999. From 1961 to 1975, about 2 million tonnes of radioactive tailings from the mill were discharged into the Ngamaboungou River.

Independent monitoring performed by a French journalist in 2009 showed high radiation levels in the forest near the banks of the river. The gamma dose rate reached 4 $\mu\text{Sv/h}$ one metre above the soil's surface and saturated the radiation monitor on contact with the radioactive mud ($> 10 \mu\text{Sv/h}$).

The analysis of a mud sample performed by the CRIIRAD laboratory showed that the radiation was coming from tailings. The uranium-238 activity was 640 Bq/kg while the thorium-230, radium-226 and lead-210 activities were 18,200 Bq/kg, 11,000 Bq/kg and 11,600 Bq/kg respectively (Chareyron 2009a).

These past practices are still responsible for the long term contamination of the environment.

3.2.3.2 Re-use of tailings

Taking into consideration their radioactivity, tailings should be considered radioactive waste and managed accordingly. The examples detailed below show that as a result of poor practice, tailings are sometimes re-used by citizens and mining companies.



France

In France, in 1988, CRIIRAD discovered that tailings had been re-used by a citizen in a village (in Limousin) located near the COGEMA-AREVA uranium mines. He was advised to use this 'sand' by a mine worker. He used it to form the concrete slab of his kitchen. Radon-222 activity in his dwelling was measured at 2,500 Bq/m³ (the present WHO recommendation is not to exceed 100 Bq/m³) and CRIIRAD advised him to dismantle the slab, which he did.

Later, a former employee of the mining company said that it would be impossible to make concrete with tailings due to their chemical characteristics. CRIIRAD returned to the village in 1998 and found a small piece of the original concrete that the citizen had used to seal the wash-hand basin in his bathroom. The analysis confirmed that the concrete contained tailings. The uranium-238 activity was 900 Bq/kg, while thorium-230, radium-226 and lead-210 activities were 6,100 Bq/kg, 6,800 Bq/kg and 6,300 Bq/kg respectively (Chareyron, 1998).

Namibia

In Namibia CRIIRAD monitored abnormal levels of gamma radiation in the **parking lot of the Rössing mine**¹⁴. The dose rate (0.9 µSv/h) was about 6 times above the natural background rate (0.15 µSv/h) (Chareyron, 2014b).

This radiation was due to the presence of radioactive tailings from the Rössing mill. The analysis of top soil performed by CRIIRAD showed a radium-226 / uranium-238 ratio of 2.5. Uranium-238 activity in the sample was 730 Bq/kg while radium-226 activity was 1,800 Bq/kg.

In a letter dated January 16th 2013 sent to the local NGO Earthlife Namibia, Rössing managing director stated: *"Although the Radiation Safety Section at Rössing did not know that tailings have been used in the parking area, the 'elevated levels' are indeed known to the Radiation Safety Section, and Rössing maintains they are no cause of concern as they do not result in significant additional exposure to anyone"*.

CRIIRAD is concerned that the Rössing Radiation Safety Section is not making efforts to ascertain why levels of gamma radiation are about 6 times above normal in a parking area. This demonstrates a failure in the application of radiation protection principles. The first principle of the ICRP (International Commission on Radiological Protection) is that the exposure of people to radiation should be maintained as low as reasonably achievable. This is due to the fact that there is no safe limit of exposure to ionizing radiation. The higher the value of accumulated dose, the higher the risk of developing cancer in the long term. It is internationally agreed that a trivial dose is a dose below 10 microSievert per year (Euratom, 1996). In the case of Rössing's parking lot, spending 5 minutes per day during 200 working days leads to an additional exposure in excess of 10 microSieverts. This is considered 'significant exposure' according to the ICRP. When adding the

¹⁴ A video showing these measurements is available at the URL below:
<http://www.criirad.org/actualites/dossier2012/namibie/mines.html>

contribution of internal exposure by inhalation of radon emitted by tailings and by inhalation of radioactive dust, the impact is even higher.

In the same letter, Rössing confirms that they do not plan to decontaminate the parking lot. The letter states: *“There is no plan for any modification of the area.”* And *“Occupational exposures of workers in the area are monitored continuously and are consistently below 2 mSv per annum, all pathways included”*.

CRIIRAD also presumes the radiation received by the workers on the parking is not taken into consideration in Rössing’s dose evaluation, since the workers receive their radiation monitors after passing through the gate of the facility.

There are moreover additional concerns that tailings or other radioactive material could have been used to build additional facilities within the mine, again affecting the principle of diminishing exposure to radiation. An independent monitoring team should be allowed inside the mine to carry out a survey (Chareyron 2014b).

3.2.3.3 Impact of tailings dams

A common practice for disposing of tailings is to put them back into former underground galleries or open pits, or to construct artificial ‘dams’. The main problem is that sites are not selected in a way that guarantees the confinement of the radioactive material. The chances of airborne contamination and contamination of underground and / or surface waters is thus increased.

Airborne contamination

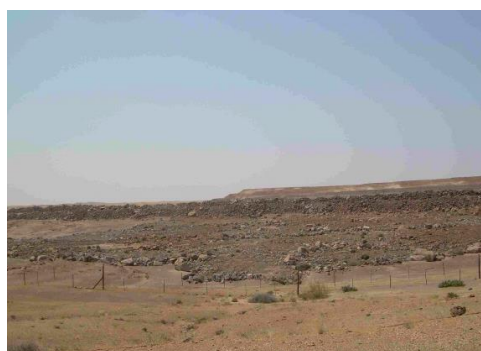
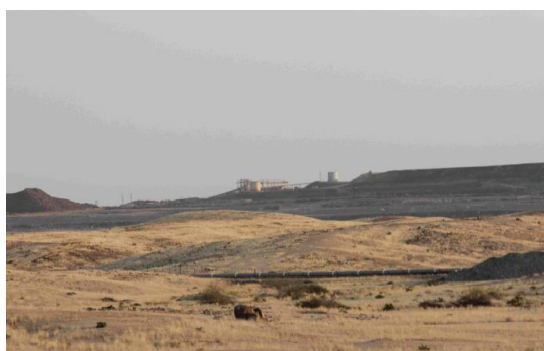
Niger

In Niger, about 50 million tonnes of radioactive tailings are stored in the open air, near the SOMAÏR and COMINAK mills, a few kilometres away from the towns of Arlit and Akokan (with approximately 112 000 inhabitants). Radon gas and radioactive dust can be scattered by the powerful winds of the desert (Chareyron 2003, 2005b, 2008a).

Namibia

The storage of tailings in the open air without appropriate cover is also commonplace in Namibia at the Rössing uranium mine.

CRIIRAD did some sampling and discovered that the finest fraction of tailings dumped in the Rössing tailings dam is blown away by the wind and has contaminated the surrounding environment (Chareyron 2014b).



Figs. 20-21

**View of Rössing
tailings dam**

Source: CRIIRAD,
September 2011

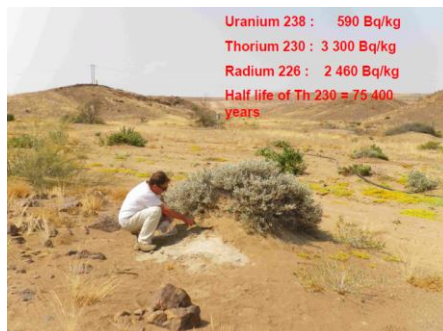
Radium-226 activities range between 960 Bq/kg and 7,400 Bq/kg (compared to a natural value of about 100 Bq/kg in this area) in soil samples collected up to 2 km away from the tailings' dam fence. Contaminated topsoil also contains high levels of thorium 230 (8,600 Bq/kg compared to a natural value of 100 Bq/kg). As can be seen in **Figures 24** and **25** the contaminated dust is fine and can therefore be easily inhaled. An example of this contamination can be seen in the Figures below that show contaminated dust accumulated underneath a small bush.



Figs. 22-23

CRIIRAD team monitoring gamma radiation in the environment of Rössing tailings dam

Source: CRIIRAD, September 2011



Figs. 24-25

CRIIRAD team monitoring gamma radiation in the environment of Rössing tailings dam and sampling top soil contaminated by radioactive dust from the dam

Source: CRIIRAD, September 2011

In all four samples of top soil, the radium-226 / uranium-238 ratio is between 2.3 and 5. The uranium-238 residual activity in the contaminated soil is lower than the radium-226 activity, indicating that the material dispersed by the wind is not made of dust from natural uranium bearing rocks but consists of tailings (radioactive waste from the mills) where uranium-238 has already been extracted from the ore.

This issue has not been properly addressed by Rössing. In a letter responding to Earthlife Namibia queries dated January 16th 2013, Rössing states: “No health risk is associated with the dust plume, which will be cleaned up as part of mine closure. Dust emissions are monitored continuously as part of the public exposure protection programme”.

If a clean-up of the dust is put off until mine closure in a few decades, the contamination will persist until then. Some of the radionuclides contained in the dust are extremely radiotoxic, such as thorium-230, especially in the case of inhalation (see **section 2.4.3** above).

The lack of confinement of such radiotoxic substances is not acceptable. The tailings dam should be appropriately confined, covered with a layer of clay or another material to limit erosion, lixiviation and emissions of dust and radon.

CRIIRAD scientists are not the only ones concerned with the impact of this radioactive plume. This point was also raised by Krugmann (2010) in the Strategic Environmental Assessment associated with the 'Central Namib Uranium Rush': *"Windblown dust from the dry parts of the tailings presents a significant environmental concern in the vicinity of the tailings. As the dust deposition plume around the Rössing tailing impoundment indicates tailings dust deposition can take place within a radius of 5-10km even in the direction of the strongest winds"*.

Regarding the dust monitoring activities performed by Rössing in the town of **Arandis**, located 6 kilometres away from the tailings dam, the company published a graph on its website in which monthly concentrations of inhalable particulates in the air (PM 10) are given from July to December 2010. All values are below 20 $\mu\text{g}/\text{m}^3$. The results seem extremely low compared to a 'standard', a limit plotted on the graph, the value of which is set by Rössing at 0.15 mg/m^3 which is 150 $\mu\text{g}/\text{m}^3$. By Rössing's standards the affected population may be under the impression that there are no risks posed by exposure to this dust.

In fact, the WHO standard for inhalable particulates is 20 $\mu\text{g}/\text{m}^3$ for 'annual average concentration' and 50 $\mu\text{g}/\text{m}^3$ for 'Maximum 24 hour concentration'. It should be noted also that during the 1990s, the WHO stated that no safe thresholds could be determined for particulate exposures (WHO, 2005). In the case of the population living in the environment of uranium mines, the hazards caused by these particulates are enhanced by the fact that they contain radioactive substances (Chareyron 2014b).

Water contamination

France

About 1.5 million tonnes of tailings are known to have been dumped in a former open pit at AREVA's Bellezane mine located in the department of Haute-Vienne (Limousin, France), where uranium was extracted from 1975 to 1992 by COGEMA-AREVA.



Fig. 26

Tailings dumped into Bellezane former open pit (France)

Source: CRIIRAD

The CRIIRAD laboratory discovered that the finest fraction of the radioactive material would be able to reach the underground galleries beneath the pit, contaminating underground waters that are still being pumped and treated by AREVA

Moreover, the mine water treatment plant is not efficient enough to prevent the accumulation of uranium 238 and its daughter products in the sediments of the river and meadows located downstream, as illustrated in **Table 17** below (Chareyron and Castanier, 1994; Chareyron, 2006a).

Sample / Mine	Sample, Location	Year	Uranium 238 (Bq/kg dry)	Radium 226 (Bq/kg dry)	Lead 210 (Bq/kg dry)
Sediment	river, upstream	1993	73	60	68
Sediment / BZN	river, downstream	1993	36,167	1,971	1,928
Sediment / BZN	river, 1.5 m, downstream	2004	63,000	13,400	2,770

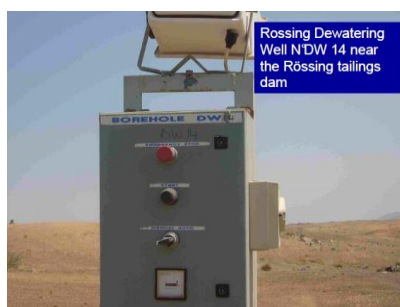
Table 17 Radioactivity of sediments and soil upstream and downstream of Bellezane uranium mines (year 1993, 2004)

Source: CRIIRAD

Namibia

In Namibia, the Rössing uranium mine has a network of dewatering wells and trenches designed to pump contaminated water back to the tailings dam (see **Figs. 27-30**). During 2012, Rössing collected 2.38 million m³ of seepage (Rössing 2014). The uranium concentration in the underground water samples collected by CRIIRAD in 2011 downstream of Rössing's tailings dam was very high (554 to 3,174 µg/l compared to 0.2 µg/l upstream).

The impact of the present and future leakages occurring below the tailings dam would have to be studied in detail as the extension of the contaminated plume and the durability in time of the pumping system has not been properly documented in Rössing's SEIA.



Figs. 27-30

Dewatering wells and trenches designed to pump back contaminated water to the Rössing tailings dam, Namibia

Source: CRIIRAD, 2011

The waste rock and the 200 million tonnes of tailings will in the long term constitute a source of chemical (especially sulphates) and radioactive contamination for the Khan River basin.

Surprisingly, the modelling performed by experts paid by Rössing (Aquaterra, 2011) indicates that it will take 50 to 1,000 years for the contaminated plume to enter the Khan River. These studies should be reviewed by independent experts as CRIIRAD monitoring results show that contamination with sulphates, uranium and other chemicals is already detectable in the underground water sampled in boreholes in the Khan River bed (Chareyron, 2014b).

Risk of dam failure

The walls of the dams constructed for storing the tailings or other liquid or solid waste from uranium extraction or conversion plants can develop cracks and break. In case of the failure of such dams, large amounts of radioactive material can contaminate the areas located downstream.

This occurred in **France** in 2004 at the COMURHEX AREVA uranium conversion plant. About 30,000 m³ of radioactive mud and slurry escaped and contaminated the nearby plains (Chareyron, 2006b).



Fig. 31

Reconstruction of a damaged dam used to store radioactive solid effluents from a uranium conversion plant

Source: AREVA, France, 2006

In the case of **Namibia**, CRIIRAD observes that no scientific report had addressed the question of the long term stability of the dam in Rössing's expansion plans (Rössing, 2011).

In a letter to Earthlife Namibia dated January 16th 2013, the Managing Director of Rössing states: "A stability study is in place for the present facility for a number of years. The risk of failure is very low". CRIIRAD views this letter by Rössing as an acknowledgement that there actually is a risk of failure. This risk will probably increase with the expansion project when about **200 million tonnes of tailings** accumulate in the tailings facility. This is acknowledged in their expansion project (Rössing, 2011: 33) in which they state that "Geotechnical stability: is expected to be sufficient but requires further confirmatory analysis".

CRIIRAD believes that the Namibian authorities should ask for a detailed technical report on these issues, including a review by a team of independent scientists.

3.2.4 Impacts of contaminated equipment

3.2.4.1 Re-use of contaminated scrap metal

The dispersal and re-use of contaminated scrap metal from the mines and mills is also a significant source of radiation exposure for workers and the general public. Examples from Niger are detailed below.

Niger

During 2003, the CRIIRAD laboratory conducted independent surveys in Niger upon request of a local NGO (AGHIRIN'MAN). CRIIRAD discovered that radioactive scrap metal had been sold in the city of Arlit located next to the mine. One piece was a pipe from the uranium mill. It was sold without appropriate decontamination and the activity of radium-226 in the crust inside the pipe exceeded 200 000 Bq/kg. Such a practice cannot be justified.

The mining company COGEMA (now known as AREVA) stated that before 1999, no radiation limit had been used for scrap metal recycling. Later, a dose limit of 1 microGray per hour at a distance of 50 cm was applied (this figure is practically equivalent to 1 $\mu\text{Sv/h}$). The use of these pieces inside houses – which is common in African countries – would exceed the annual maximum permissible dose for members of the public with exposure (at a distance of 50 cm) of just 3 hours per day during 365 days per year. The evaluation of the total radiological impact would require consideration of internal contamination by ingestion and inhalation (Chareyron, 2003, 2005b).

Radioactive materials have been detected over the period 2003-2012 in Arlit as detailed below. In 2007 contaminated scrap was discovered by AGHIRIN'MAN and CRIIRAD inside private houses and at scrap merchants (Chareyron 2008a).

In June 2009, M. Almoustapha Alhacen, president of the local NGO AGHIRIN'MAN discovered radioactive pipes used for drilling in Arlit. The gamma dose rate was 49 times above natural value on the material. At a distance of 50 centimetres, the gamma dose rate was still 1.7 $\mu\text{Sv/h}$ to be compared to a natural value of 0.1-0.2 $\mu\text{Sv/h}$ in this area (Chareyron, 2009c).



Fig. 32

Contaminated pipes (Arlit, Niger)

Source: AGHIRIN'MAN, June 2009

Again, AGHIRIN'MAN discovered in 2012 that more than 1,600 tonnes of scrap from the mines had been sold, of which 1,000 tonnes were found at a scrap merchant's place in Arlit in September 2012. Using a scintillometer provided by CRIIRAD, AGHIRIN'MAN showed¹⁵ that the gamma radiation on the contaminated material reached values 9 times above natural background rates.



Figs. 33-34

**Contaminated scrap
(Arlit, Niger)**

Source: AGHIRIN'MAN,
September 2012

Brazil

In Brazil, the state owned company *Industrias Nucleares do Brasil* (INB-URA) operates a uranium mine and mill in the state of Bahia. The contaminated equipment is stored in the open air (pumps, drums, valves, etc.) inside the mines (see **Figs. 35-36** below). Some of this equipment has been decontaminated and recycled before being given by INB to local communities. The workers however have doubts about the quality of decontamination and the accuracy of the radiation monitoring of the material before it leaves the facility. They say that the training of some of the radioprotection operators consists of a 30 minute meeting with their supervisor.

CRIIRAD believes the company should provide guarantees on the methodology applied for checking the residual contamination of the recycled material. It should also make the standards applied (residual contamination limits in Bq/cm² and residual dose rate on contact of the equipment in µSv/h) available to the public, (Chareyron, 2014d).



Figs. 35-36

**Provisory storage of
contaminated equipment
at INB-URA (Caetité,
Brazil)**

Source: INB-URA worker

¹⁵ See CRIIRAD press release at <http://www.criirad.org/actualites/dossier2013/niger/CP-ferrailles-niger01-2013.pdf>.

3.2.4.2 Re-use of contaminated tissue

The dispersion of contaminated scrap metal is not the only problem. Other pieces such as contaminated liners or tissues are re-used outside mining facilities for various uses. Examples from Niger and France are described below.

Niger

In Arlit, Niger, in June 2009, M. Alhacen, president of the local NGO (AGHIRIN' MAN) performed independent radiation monitoring and discovered that radioactive liners that had been formerly used for the radioactive effluents ponds of AREVA's mills were being sold in the market.



Figs. 37-38

Contaminated pieces of tissue (Arlit, Niger)

Source: AGHIRIN' MAN, June 2009

Radiation levels were more than 100 times above normal on contact with this contaminated material. At a distance of 2 and 3 metres, the gamma dose rate was between 2.6 and 3.6 $\mu\text{Sv/h}$. Staying 4 hours in the vicinity of this material implies a non-negligible dose (more than 10 microSieverts). If re-used inside a dwelling, the annual dose limit of 1,000 microSievert per year will be exceeded by spending only one hour per day during the whole year at a distance of 2 metres. When considering the additional dose due to internal contamination, especially with the inhalation of radon produced by the contaminated material, the evaluation of the risk is even higher.

CRIIRAD wrote a letter to the CEO of the mining company AREVA denouncing this situation but obtained no response (Chareyron, 2009c). Instead, M. Alhacen, who is also a worker in one of the mines (SOMAÏR), received a letter from SOMAÏR in July 2009 asking him to justify why he made public his findings.

France

Recently in France, highly radioactive filters from a former uranium mill were discovered in the house of a former mine worker. The contaminated material was discovered in August 2013 while the local NGO 'Collectif des Bois Noirs' was monitoring gamma radiation in the village (while looking for places where waste rock may have been re-used). In the street in front of this house, high gamma radiation rates were measured and reached a value 80 times above natural

background on contact with the door. The house was no longer inhabited as the family was in the process of selling it.

AREVA was asked to evacuate the material. At the beginning of 2014 AREVA put the most contaminated filters in a plastic bag. Then, during a second mission, the material was put in a drum to await evacuation by the French agency in charge of the storage of radioactive waste (ANDRA).

Monitoring performed by CRIIRAD in April 2014 showed that:

- even when the most active filter was stored in the drum inside the house, the dose rate was still 2 to 3 $\mu\text{Sv/h}$ on the door; and 0.7 to 0.9 $\mu\text{Sv/h}$ in the street (about 1.5 metres from the door),
- another contaminated filter was left at the bottom of a window (see **Figs. 39-40** below). It had been used to improve the tightness of the window. The dose rate on this second filter was up to 84 $\mu\text{Sv/h}$ and still 2.5 $\mu\text{Sv/h}$ at a distance of one metre.



Figs. 39-40

Radioactive filters from a uranium mill discovered at the bottom of the window of a house in France

Source: CRIIRAD, B. Chareyron, April 2014

CRIIRAD urged the radioprotection authorities to organise the evacuation of both filters, and to launch detailed studies on the contamination of the house and of its former inhabitants. The former worker had died of leukaemia years ago and his daughters had lived for years in this house, also exposed to external irradiation and internal contamination. The filters contain high levels of radium-226 therefore permanently producing radon-222. This case shows that the workers of the mine had no proper training regarding the dangers of the material they were dealing with. But even 3 decades after the closure of the mine, the local population is still exposed to high risks (Chareyron, 2014c).

3.2.5 Inappropriate management of liquid effluents

3.2.5.1 Untreated contaminated waters discharged in the environment

In order to maintain the mine dry, the water that naturally accumulates has to be pumped out while the mine is in operation. When pumping is stopped, water floods the mine and naturally flows into the environment. In both cases, this water is contaminated with uranium and its daughter products. Depending on local legislation, this water may be discharged directly into the environment or be treated before it is discharged (at least using settling ponds for allowing the

deposition of radioactive heavy metals in the sediments at the bottom of the pond).

France

The Puy de l'Age mine (formerly an open pit mine) is located in the department of Haute-Vienne (Limousin, France). The mine was reclaimed by COGEMA-AREVA in 1993 and the water treatment unit was dismantled after the authorities declared in 1996 that reclamation efforts had been sufficient.



Figs. 41-42

Settling pond of the former water treatment system at Puy de l'Age mine and contaminated meadow located downstream

Source: CRIIRAD, 1993, 2003b

However, the water flowing from the closed mine is still contaminating the meadow located downstream (Chareyron and Castanier, 1994; Chareyron, 2003b). CRIIRAD showed that the meadow's soil was contaminated with uranium-238 (20,000 Bq/kg) and its daughter products like radium-226 (33,000 Bq/kg). These values are 20 times above the limit dictated by Euratom Directive 96/29, for determining if waste from a nuclear facility should be considered radioactive and be managed accordingly. Results are plotted in **Table 18** below.

Sample / Mine	Sample, Location	Year	Uranium-238 (Bq/kg dry)	Radium-226 (Bq/kg dry)	Lead-210 (Bq/kg dry)
Sediment	river, upstream	1993	73	60	68
Sediment	river, downstream	1993	13,470	28,740	7,282
Soil of the meadow	meadow, downstream	2003	20,000	33,000	11,500

Table 18 Radioactivity of sediments and soil upstream and downstream 'Puy de l'Age' uranium mine (year 1993, 2003)

Source: CRIIRAD results

Bulgaria

In 2011, in the course of the EJOLT project, CRIIRAD and Za Zemiata tested the quality of the water flowing from former uranium mines in Bulgaria. Even decades after the closure of the mines, the water still carries high concentrations of radioactive substances (uranium) and chemicals, including heavy metals and toxic substances such as arsenic.

The standards for acceptable contamination of the discharged effluents from uranium mines are determined by the national or local authorities and are usually too high to properly protect the environment

Samples taken downstream of the Kremikovtzi uranium mine showed a uranium concentration of 1,653 µg/l in a drain at the lowest horizontal former gallery of the mine. The WHO standard for uranium in drinkable water was set in 2011 to a provisory value of 30 µg/l. The water flowing from the Kremikovtzi mine also had high levels of sulphates and numerous metals (arsenic, iron, manganese, molybdenum, nickel, antimony) as well as also cobalt and chromium (Chareyron, 2012c). The situation of this mine is well known by the authorities, as a mine water drainage treatment plant has been planned but not yet been built.

3.2.5.2 Weak standards and inefficient water treatment facilities

The standards for acceptable contamination of discharged effluents from uranium mines are determined by national or local authorities, and are usually in excess of those required to adequately protect the environment.

In France, contaminated water from uranium mines can usually be discharged without treatment when the uranium concentration is below 1.8 mg/l or 1 800 µg/l (which is 22.5 Bq/l) and the radium-226 activity is below 0.37 Bq/l (soluble form). In some cases, if the dilution offered by the rivers receiving the effluents is considered sufficient, a limit of 3.7 Bq/l may even be accepted. Even with such very permissive limits, mining companies face technical difficulties in designing and operating efficient water treatment plants in the very long term. This is the case even for powerful international companies like AREVA.

For example, at Les Bois Noirs former uranium mine (Rhône-Alpes region, France), the company could not guarantee that the radium-226 content of treated water was in conformity with the limit of 0.37 Bq/l determined by the local administration. Only recently has water treatment been modified to make radium-226 activity compliant with limits (0.3 Bq/l was the mean value monitored by AREVA for year 2012).

However, these limits are too high and do not take into account the impact of bioaccumulation of radioactive heavy metals in the sediments and aquatic flora and fauna. In fact, the radioactive metal present in the water discharged by the mine water treatment facility is progressively accumulating in plants (aquatic mosses) growing in the watercourse downstream of the treatment facility. CRIIRAD monitored a radium-226 contamination of 160,000 Bq/kg dry in plants sampled in October 2012. This is 690 times above the natural concentration monitored in the same species collected upstream the mine (233 Bq/kg dry).

The samples of aquatic mosses collected downstream the mine thus qualifies as radioactive waste. The impact on the local population will depend on local habits. In some areas, the aquatic flora may be used for human consumption, and fertilisation of crops. The contamination of aquatic flora will indeed contaminate the animals that consume such plants.

The standards applied to waters discharged from uranium mines should be urgently reviewed, but national authorities are reluctant to lower the discharge limits in light of the fact that efficient water treatment methods would be too costly (Chareyron, 2014e).

As with the tailings dams, the settling ponds or basins designed to collect the contaminated waters or liquid effluents from uranium mines and mills are sometimes overflowing or breaking

3.2.5.3 Spills

As with the tailings dams, the settling ponds or basins designed to collect contaminated waters or liquid effluents from uranium mines and mills overflow or break from time to time.

Brazil

Such problems have been frequent at the settling pond of INB-URA mine in Brazil (Porto, 2014a). In the course of the EJOLT project, CRIIRAD and FIOCRUZ discovered abnormal radiation levels and the contamination of the soil in the valley located downstream of the settling pond (Chareyron, 2012d).

Niger

In Niger, in December 2010, cracks appeared in the walls of three basins designed to permit the evaporation of contaminated effluents from the SOMAÏR-AREVA mine. As a result about 50 million litres of slurry contaminated with radioactive substances (uranium concentration of 180 mg/l) and chemicals (including nitrates) were spilled into the environment. About 150,000 tonnes of contaminated soil on a surface of 20 hectares had to be removed by SOMAÏR. The local population complained that several camels died after drinking the contaminated liquids (AGHIRIN'MAN, 2011).



Figs. 43-44
Spill of contaminated slurry at Somaïr-AREVA Mine, Niger

Source: AGHIRIN'MAN, December 2010

3.2.6 Impact of management and transportation of uranium concentrate ('yellow cake')

As explained above, uranium concentrate, usually called 'yellow cake' has a very high uranium concentration. The biggest risk at this stage of the process is external irradiation and internal contamination of workers.

3.2.6.1 External irradiation

The workers and people living near stored yellow cake are submitted to external irradiation, even when the uranium concentrate is contained in metallic drums for transport to the purification-conversion plant.

It is useful to note that mining companies or some experts commissioned by the companies are accustomed to denying any risk of external irradiation.

Namibia

In the case of Namibia for example, the SEA (Strategic Environmental Assessment) carried out for the Ministry of Mines and Energy for the 'uranium rush' occurring in the Central Namib states that

“ a further health concern relates to the transportation of final product (yellowcake). As with any hazardous chemical, the transportation of this low radioactive material requires monitoring and surveillance all the way from the mine to the exit port. There is no danger to the general public from this activity because the metal drums containing the yellowcake are effective barriers to the emanation of any radiation. However, if there was a transportation accident and members of the public were directly in contact with yellowcake or if material was stolen, emergency measures would have to be taken (as with any other hazardous chemical)” (SAIEA, 2010).



Fig. 45

A worker monitoring radiation on yellow cake drums

Source: Rössing

.....
Uranium concentrate usually called 'yellow cake' has a very high uranium concentration. The biggest risk at this stage of the process is external irradiation and internal contamination of workers

Metal drums containing yellowcake are **not** an effective barrier to the emanation of radiation.

When CRIIRAD visited Rössing uranium mine in Namibia (April 2012), the radiation protection expert of the company confirmed¹⁶ that the typical dose rate on contact of the drums was between 20 $\mu\text{Sv/h}$ and 2 $\mu\text{Sv/h}$ at a distance of 1 metre from the drums. These values are respectively 100 hundred times and 10 times higher than the local natural background radiation of 0.2 $\mu\text{Sv/h}$.

Niger

The French mining company AREVA gives the same kind of message to the public. In a documentary (Hennequin, 2009) broadcasted on French television, an engineer from AREVA is interviewed in front of yellow cake drums from a mill in Niger (see Figure 46 below). He says: “*There is no radioactivity on contact since there is a metal sheeting which guarantees harmlessness*”.

¹⁶ Information given to B. Chareyron (CRIIRAD) by Dr Gunhild Von Oertzen (RUL) at a meeting on 16th April 2012 (Uranium Institute).



Fig. 46

AREVA engineer in front of yellow cake drums in Niger

Source: Documentary (Hennequin, 2009)

This would be true if yellow cake contained only pure alpha emitters like uranium-234 and uranium-238, but the material also contains uranium-235 and two daughter products of uranium-238, namely thorium-234 and protactinium-234^m, which emit powerful gamma radiation. This radiation is able to pass through metal and travel tens and even hundreds of metres in the open air.

The actual dose rate measurements performed by AREVA subsidiaries in Niger confirm that the radiation from the drums is not negligible, as showed by the results¹⁷ plotted in **Table 19** below.

Type of monitoring	Minimum (μSv/h)	Comparison to background radiation	Maximum (μSv/h)	Comparison to background radiation
Drums				
Dose rate on contact	5	25	12	60
Dose rate 1 metre from the drum	2	10	4	20
Truck loaded with the drums				
Dose rate on contact of the truck	12	60	19	95
Dose rate 2 metres from the truck	1.2	6	4.7	24

Table 19

Dose rate monitored by AREVA subsidiaries in Niger near yellow cake drums

Source: AREVA

The dose rate on the drums varies from 5 to 12 μSv/h, which is about 25 to 60 times above the local natural¹⁸ background rate. At a distance of 1 metre from the drums, the dose rate is still 2 to 4 μSv/h, which is below the official limit¹⁹ of 100 μSv/h, but 10 to 20 times above natural background.

On contact with the trucks loaded with the drums, the dose rate is 12 to 19 μSv/h, which is below the official limit of 2 000 μSv/h, but is 60 to 95 times above natural background. At a distance of 2 metres from the trucks loaded with drums, the

¹⁷ Results given by AREVA in writing to SHERPA, a French NGO cooperating with CRIIRAD on the issue of the impact of uranium mining in Niger.

¹⁸ The natural background is different at different locations. We use here a value of 0.2 μSv/h monitored by CRIIRAD in the mining city of ARLIT even if lower values have been monitored in different parts of the city.

¹⁹ We mention here the recommendations of the IAEA (year 1996, revision 2000).

dose rate is 1.2 to 4.7 $\mu\text{Sv/h}$. This is below the official limit of 100 $\mu\text{Sv/h}$, but is 6 to 24 times above natural background radiation.

In the case of Niger, local NGOs have been fighting for the improvement of safety measures for years. They complain that the drivers of trucks were carrying citizens from Arlit to Niamey (capital city of Niger). The distance between these two cities is about 800 kilometres and the journey takes about 11 hours. The accumulated exposure of the passengers can thus exceed 200 microSieverts for one trip, which is one fifth of the annual dose limit for the public. AREVA's subsidiaries eventually promised to ask the companies in charge of transportation not to allow drivers to continue to carry passengers.

The external irradiation from yellow cake is in general a problem that has not been properly addressed by the mining companies.

France

All uranium concentrates (yellow cake) to be further processed in France are received at the COMURHEX-AREVA plant in Malvesi, near Narbonne city (south of France). This yellow cake can come from different uranium mines located abroad, such as Niger, Canada, and Kazakhstan.

At this chemical plant, uranium concentrates go through a purification and pre-conversion process (production of UF_4) prior to further conversion (into UF_6) and enrichment (these two steps may be performed at the Tricastin nuclear site in France). The drums are stored in the open air in a park with a capacity of 25,000 tonnes of uranium.

In 2006, at the request of a family that was living close to the plant, the CRIIRAD laboratory monitored gamma radiation in the environment of this facility (see **Figs. 47-48**). The gamma radiations emitted by the drums were detected at a distance above 280 metres from the fence²⁰, including in front of the house of the family.



Figs. 47-48

Monitoring of gamma radiation near uranium concentrate park at Comurhex Malvesi plant (France)

Source: CRIIRAD, 2006

²⁰ A video showing the flux of gamma radiation at the fence in January 2014 is available at <http://www.criirad.org/installations-nucl/malvesi/malvesi-comurhex.html>.

The official data initially presented to the public by AREVA showed no impact at the fence of the facility. After independent monitoring by CRIIRAD, the company had to publish new results that indeed showed an impact (Chareyron, 2006b).

In such facilities, workers are exposed to gamma radiation, including subcontractors in charge of the security of the sites.

Brazil

In the case of the INB-URA uranium mine in Caetité (Brazil), the guardroom is located close to the radioactive drums (see **Figure 49**). The guard is very probably exposed to non-negligible gamma radiation doses although an appropriate safeguarding of his cabin would significantly lower this exposure to radiation.



Fig. 49

Drums containing yellow cake near guard cabin in Brazil (INB-URA)

Source: INB-URA worker

3.2.6.2 Internal contamination

The workers involved in the final steps of the uranium concentration process (drying of the uranium powder, filling of the drums, sampling of uranium concentrate for quality control issues) are usually among the most highly exposed in uranium mines and mills because they are potentially exposed to high concentrations of radiotoxic substances (several tens of millions of Bq/kg).

Some of the exposed workers are subject to internal contamination and suffer from different pathologies. Cases have been reported for example in France (Lamireau, 1995) and Namibia (Chareyron, 2011b).

3.2.7 Other environmental impacts

In previous chapters of this report, we have described only some of the radiological impacts of uranium mining and milling activities on the environment.

In fact, water and airborne contamination also transfer various non-radioactive chemicals either naturally associated with the ore, or used for the chemical process.

The use of water resources (including in areas where water is particularly scarce), is also impacted, as are the use of fossil fuels and the production of greenhouse gases at more or less all steps of the uranium extraction process.

When analyzing the impact of uranium mining activities, people should not think about uranium and its daughter products only

3.2.7.1 Chemicals

When analyzing the impacts of uranium mining activities, it is therefore important to consider much more than just uranium and its daughter products.

Other elements contained in rock

Different elements are contained in natural rock and ore depending on their geological history. For example uraninite (UO_2) is associated with thorinite and uranothorianite, which contain a great deal of thorium. Thorium is a radioactive metal with high radiotoxicity. Below we explore cases in different countries.

Malawi

In the course of the EJOLT project, CRIIRAD monitored soil samples taken from areas surrounding uranium mines in Malawi (Kayelekera), and Brazil (Caetité). Tests revealed non-negligible amounts of **thorium-232**.

In Malawi, the thorium-232 activity of the natural soil sampled in the vicinity of the uranium mine (2,160 Bq/kg) was 3 times above the uranium-238 activity (Chareyron, 2012a).

Brazil

In Brazil, the radioactive dust deposited on the soil in the vicinity of waste rock and tailings dumps of INB-URA, had a thorium-232 activity 2 times above the uranium-238 activity (Chareyron, 2014d). However, monitoring performed by the mining company of the radioactivity of aerosols in the air does not seem to include the impact of thorium-232. In addition, the monitoring of radon in the air deals with radon-222 (uranium-238 decay chain) but not radon 220 (thorium-232 decay chain) (INB, 2014).

Niger

Other uranium deposits contain arsenic, copper, lead, manganese, molybdenum, selenium, and silver. Usually uranium mining companies do not effectively monitor the environmental impact of all these elements, or, when they do, they do not share the results with the public.

For example, in Niger, the measurements conducted by AREVA on underground water used for human consumption include: sodium, potassium, calcium, magnesium, chlorides, sulphates, phosphates, nitrates, silicon and iron. Their results raise two series of questions outlined below.

First, some parameters are exceeding WHO recommendations. This is the case for example with nitrates. However, this information is not made public, as AREVA states in its press releases: *“Bacteriological (monthly), radiological (half-yearly) and chemical (yearly) analyses show the absence of contamination”*.

Second, the results obtained by CRIIRAD after the analysis of samples collected by Greenpeace in November 2009, confirmed that the amount of **nitrates** exceeded WHO recommendations in some samples. It also revealed in some samples the presence of other substances at levels markedly higher than those recorded at the reference site (namely **ammonium ions, nitrites, bromides,**

manganese, molybdenum, selenium and tungsten). In some cases, the measured concentrations of these substances exceeded WHO recommendations (Chareyron, 2010b).

Namibia

The analysis of water samples showed a very significant increase in the concentration of various chemicals downstream of the waste rock dump at the confluence of the Dome Gorge and the Khan River, when compared to upstream values.

An increase was detected for fluoride, nitrates and sulphates whose concentrations were below detection limits upstream. The impact was particularly high for sulphates (1,302 mg/l downstream). Sulphates and nitrates are an indicator of the leaching of waste rock.

The data also showed an increase for arsenic, zinc, boron, radon-222, vanadium and zinc (factor of 9 to 35), molybdenum (factor 85), selenium (factor 131) (Chareyron, 2014b).

Chemicals used by the uranium mining companies

It must not be forgotten that uranium mining and milling requires large quantities of chemical products, with specific problems connected to their transportation, storage, and disposal, creating specific pollutions.

Niger

For example in 2002, the COMINAK-AREVA mine used the following consumables: sulphur (11,768 tonnes), cement (5,160 tonnes), sodium chloride (3,799 tonnes), sodium carbonate (2,955 tonnes), ammonium nitrate (1,487 tonnes), oils (893 m³), magnesium (637 tonnes), solvents (364 m³), explosives (325 tonnes), caustic soda (211 tonnes), sodium chlorate (79 tonnes), conveyor belts (3 kilometres), as well as tyres, metal, and batteries (Chareyron, 2008a).

Local NGOs complain that these chemicals and materials are sometimes stored in villages and cities surrounding the mines without any precautions.

In Niger, the local NGO AGHIRIN'MAN wrote to the governor in October 2011 to stress the risks incurred by the population:

“For some time we noticed that chemicals used for the uranium extraction facilities in the area of Arlit are managed in a way which is not compliant with the regulations of our country. Some of these materials are dangerous for public health and security. This is the case for nitrate (used for the explosives), magnesia (a toxic chemical), corrosive carbonate, sulphur and sulphuric acid from Nigeria transported to Arlit mills.” (AGHIRIN'MAN 2011).

Figs. 50-51 show bags containing sodium carbonate to be used at the SOMAÏR uranium extraction site. The NGO AGHIRIN'MAN and the municipality of ARLIT discovered that suppliers were storing it in Arlit city houses, and asked that the material be moved away from the inhabitants. The material is now provisorily stored in the open air before being supplied to the mining company.



Figs. 50-51

Chemicals stored in the surroundings of Arlit city, Niger

Source:
AGHIRIN'MAN annual
report 2011

Malawi

During the transportation of the chemicals accidents occur.

The Paladin sustainability report published in 2012 mentions a spill of a one-tonne bag of sulphur that fell from a truck approximately 23kms from the Kayelekera mine (Malawi), and a spill of around 10,000 litres of diesel due to a diesel tanker overturning approximately 1km from the mine gate. In each case the company states that *“all spilled material was cleaned up, removed and the area remediated to ensure no residual impact”* (Paladin 2012).

However chemicals are still evident on the soil, as **Fig. 52** shows. The entrance of the Kayelekera mine is a high traffic area through which many trucks pass to deliver materials and chemicals for the operation of the Paladin mine.



Fig. 52

Trucks at the entrance of Paladin mine in Kayelekera, Malawi

Spilled material (white material inside the red circle) can be seen on the road

Source: CRIIRAD, May 2012

3.2.7.2 Use of water resources

Uranium mining and milling require large quantities of water. This is a significant concern especially in places where this resource is scarce.

Country	Mine	Company	Fresh water withdrawal (million m ³ /year)	Reference, year
Namibia	Langer Heinrich	Paladin	1.9	(Paladin 2012), 2011/2012
Malawi	Kayelekera	Paladin	0.8	(Paladin 2012), 2011/2012
Namibia	Rössing	Rio Tinto	3.1	(Rössing 2014), 2012
Niger	Cominak	AREVA	4.4	(Cominak 2009), 2009
Niger	Somaïr	AREVA	4.6	(Somaïr 2010), 2010

Table 20

Fresh water withdrawal rates by uranium mining companies in Africa

Source: AREVA, Rössing, Paladin

In the desert region of Arlit in Niger, SOMAÏR and COMINAK (AREVA's subsidiaries) pump fresh water from the Tarat aquifer, which is a non-renewable source.

SOMAÏR's water consumption increased from 2.7 million m³/year in 2005 to 4.6 million m³/year in 2010. This is mainly due to increased uranium production (from 1,315 tonnes in 2005 to 2,650 tonnes in 2010). More than 60% of this water is used for industrial activities (aspersion of the mining area to limit the amount of dust, manufacturing of sulphuric acid, and processing of the ore). SOMAÏR withdraws 1.7 million litres of water for each ton of uranium produced (Somaïr, 2010). Some of the wells drilled in the Tarat aquifer cannot be used afterward due to lack of water and contamination (Chareyron 2010b).

In Namibia, the problem of water supply is so intense that mining companies are building costly water desalination plants. AREVA inaugurated one in April 2010, with a planned capacity of 20 million m³/year. This plant was built to feed the new uranium mine under construction at Trekkopje, 40 kilometres from the mine. AREVA announced however in October 2012 that the development of this mine would be suspended due to low uranium prices.

3.2.7.3 Use of fossil fuels and production of greenhouse gases

Uranium mining and milling require a great deal of energy from fossil fuels. Fossil fuels are used for supplying vehicles used in the mine, for the transportation of necessary equipment and chemicals, for transporting yellow cake (trucks, trains, boats), for drying yellow cake, and for the general running of the mines including electricity generation.

Energy production

In the case of SOMAÏR and COMINAK mines in **Niger** for example, the electricity used for the mines and mills is produced by a charcoal thermal plant located about 180 km from the uranium mines.

Sonichar is the name of the company extracting the charcoal locally from an open pit 40m deep. It also operates two 18.8 MW thermal plants. Sonichar's operations

Uranium mining and milling require huge amounts of water. This is a big concern especially in places where this resource is scarce

require the pumping of underground water from another non-renewable aquifer located 30 km from the mine.

In 2006, to produce 167,503 MWh (electricity), Sonichar used 160,748 tonnes of charcoal and 1.29 million m³ of water. About 3,500 m³ of water evaporated daily for the cooling of the plant. About 85% of the electricity produced by Sonichar was bought by the uranium mining companies (SOMAIR and COMINAK). These activities have a high environmental impact on the air, soil and water of the area (Chareyron, 2009b).



Figs. 53-54

Sonichar charcoal mine and thermal plant, Niger

Source: CRIIRAD, April 2009

Consumption of fossil fuel and CO₂ equivalent emissions

In 2009, to produce 1,435 tonnes of uranium, COMINAK used 78,037 MWh of electricity from fossil fuel, and 8,435 m³ of diesel and heavy oil, for a global energy consumption of 17.84 tonnes of oil equivalent per ton of produced uranium (COMINAK, 2009).

In 2010, to produce 2,650 tonnes of uranium, SOMAIR used 54,222 MWh of electricity from fossil fuel and 30,486 m³ of diesel and heavy oil (Somaïr, 2010).

In 2012, to produce 2,699 tonnes of uranium oxide, Rössing emitted 211,600 tonnes of CO₂ equivalent. This is equivalent to 78.41 tonnes of CO₂ equivalent emissions per tonne of uranium oxide produced (Rössing, 2014).

In Malawi, at the Kayalekera mine, electricity is generated using a local diesel-fuelled power plant. For the period 2011/2012, the annual consumption of diesel was 12,835 m³ for power generation and 5,031 m³ for vehicles. Greenhouse gas emissions were estimated to be 48,597 tonnes of CO₂ equivalent (Paladin, 2012).

Uranium mining and milling require huge amounts of energy from fossil fuels

4

Human health impacts

Previous chapters of this report described the radioactivity of various materials during uranium mining and milling processes, and their impacts on the environment. The workers of uranium mines and local population are also exposed to low doses of radiation and to various chemicals which have an impact on their health.

4.1 Health impacts of ionizing radiation

4.1.1 Increase of cancer incidence

Exposure to low doses of radiation increases cancer risk. The type of cancer depends on the body organs that receive the dose. For example, exposure to radon gas and radioactive dust will increase the risk of lung cancer, while exposure to uranium or polonium will increase the risk of leukaemia because these metals can accumulate at the surface of bone tissues.

Cancer may occur from a few years to decades after exposure to radiation. It is extremely difficult to prove, for a given individual, if a cancer case is due to exposure to ionizing radiation. Large scale epidemiological studies are necessary in order to establish a statistical link between specific pathologies and exposure to a given hazardous substance. However, these are very difficult to perform and are not conclusive for individual cases.

According to official epidemiological studies carried out for French uranium miners, the cancer death rate is about 40% above normal for lung cancer and 90% for kidney cancer (Vacquier, 2005).

4.1.2 Other effects

Exposure to low doses of radiation can increase the risk of genetic abnormalities for the offspring. It can also have an effect on all body functions (not only in terms of cancer), leading for example to the malfunction of the cardio-vascular system, the digestive system, and cerebral functions.

Examples of health effects induced by contamination with uranium include:

- Pulmonary problems including cancer of the lungs
- Cancer of the digestive system

According to official epidemiological studies carried out for French uranium miners, the cancer death rate is about 40% above normal for lung cancer and 90 % for kidney cancer



Even at low doses, the risk of cancer and other pathologies increases with the dose accumulation. Recent epidemiological studies found no threshold, no safe limit below which there is no risk

- Cancer of the kidney and kidney malfunction
- Liver malfunction
- Leukaemia and bone cancer (a fraction of the uranium is trapped in the bones for decades)
- Lymphoma
- Multiple myeloma
- Mental disorders, anorexia, neurological problems
- Genetic anomalies
- Impaired reproductive functions

4.2 Radioprotection principles

There is probably no 'safe limit' for ionizing radiation. Even at low doses (i.e. doses equivalent to natural background radiation), the risk of cancer and other pathologies increases with the accumulation of the dose.

In the case of exposure to radon gas through inhalation, recent epidemiological studies found no threshold, no safe limit below which there is no risk. The more radon is inhaled, the higher the probability of dying of lung cancer (Lubin, 2004; Krewski, 2005; Darby, 2005).

The system of radiological protection recommended by the International Commission on Radiological Protection (ICRP) is based upon the assumption that at doses below approximately 100 mSv, a given increment in dose will produce a directly proportionate increment in the probability of incurring cancer or heritable effects attributable to radiation. This assumption is generally known as the 'linear non-threshold' (LNT) hypothesis and forms the basis of the LNT dose-response model. According to ICRP, this model remains²¹ a prudent basis for radiation protection at low doses and low dose rates. In this model, a single radiation track through a cell may be sufficient to initiate injury.

Therefore, for giving some degree of protection to the people against harmful effects of ionizing radiation, ICRP²² recommends three principles:

1. Justification.

"Any decision that alters the radiation exposure situation should do more good than harm".

2. Optimisation of protection or ALARA principle ("As Low As reasonably Achievable").

²¹ For many independent scientists this model may not be relevant and may underestimate the risks especially at low doses, see for example ECRR (2010).

²² See for example: Annals of the ICRP, ICRP Publication 104 / "Scope of Radiological Protection Control Measures", Volume 37 N° 5, 2007.



“The likelihood of incurring exposure, the number of people exposed, and the magnitude of their individual doses should all be kept as low as reasonably achievable, taking into account economic and societal factors”.

These economic and societal factors include how much (and where) a mining company is willing to pay to lower these levels.

3. Annual dose limit

The ICRP has set annual dose limits for individual exposure. The limits have been lowered several times over the years. Under these limits, there is still a risk of dying of cancer but it is considered as socially acceptable. Current annual dose limits are:

1 milliSievert per year for members of the public, i.e, 1,000 microSieverts per year.

20 milliSieverts per year for workers, i.e, 20,000 microSieverts per year.

It is important to understand that:

- A) According to the LNT model, the dose limits are not limits under which the risk is nil, but limits above which the risk is **socially unacceptable**.

For example, according to the ICRP LNT model (evaluation published²³ in 1990), a dose of 1 milliSievert is associated with a risk of 5 deaths by cancer among 100,000 exposed people.

With the improvement of knowledge about the adverse effects of ionizing radiation, the annual dose limit has been continuously lowered as illustrated by **Table 21** below.

Years	Maximal annual dose limit for the workers (mSv/annum) recommended by ICRP
1934 to 1950	460
1950	150
1956	50
1990	20

Table 21

Lowering of the maximum annual dose limit for workers as recommended by the ICRP

Source: ICRP compiled by CRIIRAD

Table 22 below also shows that other official international expert institutions recommend higher values of the risk factor.

²³ In recommendations published in 2007, the ICRP proposed a new evaluation of the risk factors but the differences were not strong enough to justify a revision of the annual dose limit of 1 milliSievert per year.

Reference	Year	Evaluation of the number of people dying of radiation induced cancer among 1 million people exposed to 10 mSv
ICRP 26	1977	125
UNSCEAR	1977	75 to 175
BEIR III	1980	158 to 501
MSK	1980	6,000
RERF	1987	1,740
UNSCEAR	1988	400 to 1 100
ICRP 60	1990	500
BEIR V	1990	800
NRPB	1992	1,000

Table 22

Evaluation of risk of dying of radiation induced cancer by various international expert institutions

Source: BEIR, ICRP, MSK, NRPB, RERF, UNSCEAR compiled by CRIIRAD

- B) The dose limit **does not take into consideration** exposure to **natural background radiation** and radiation received by patients in connection with **medical activities**. It is a concept used for the monitoring of industrial activities like the operation of a nuclear reactor or the impact of uranium mining activities.
- C) In the case of the impact of a nuclear plant, most of the radioactive substances discharged into the environment are artificial. The impact of the plant can be more easily evaluated than that of a uranium mine.

As with uranium mines, radioactive substances have a natural origin. In order to evaluate the actual contribution of mining activities, one has to isolate the impact of natural radiation called background radiation. This is feasible when a detailed survey is conducted before the opening of the mine. However, if such a reference study is not available, it is usually very difficult to evaluate the contribution of the mining activities alone. Mining companies have on some occasions (like the Rössing - Rio Tinto mines in Namibia or AREVA in France) used this reasoning to state that the exposure of the public to radiation, or the impact on the environment is due to high levels of background radiation, rather than the consequence of mining operations.

D) The annual dose received by the population and workers should be evaluated by summing the contributions of all radiation sources (except for natural background and medical sources) and all exposure pathways. These include:

- External irradiation by gamma radiation
- Doses from inhalation of radon gas
- Doses from inhalation of radioactive dust
- Doses from ingestion of contaminated food and water, etc..

4.3 Impacts on workers

4.3.3 Difficulties of protecting workers

Some mining companies do not give the detailed results of the evaluation of the doses received by the workers

In a nuclear plant, workers are usually kept away from the sources of radiation. The dose rate of a rod of spent fuel taken out of a nuclear reactor is so intense that a human being spending a few moments close to such material would receive a deadly dose and die within days. This is what happened to some of the rescue members that used shovels to carry pieces of spent fuel across the roof of the damaged Chernobyl reactor in 1986. In a nuclear reactor, the highly radioactive spent fuel is kept under water in the reactor vessel or in deactivation pools. Some workers are particularly exposed during maintenance operations.

With uranium mining, the doses are relatively low (typically a few mSv per year), but workers are more or less permanently exposed. It is not technically possible to effectively protect mine workers against the powerful gamma rays emitted by some uranium daughter products, especially lead-214 and bismuth-214. For example, with some of the gamma rays emitted by bismuth-214, about one centimetre of lead shielding would be necessary to reduce the gamma dose rate by 50%. At the Cigar Lake mine in Canada, the uranium concentration of the ore and the subsequent gamma radiation rates are so high that mining is performed with automated methods.

It is also extremely difficult to totally control the risk of inhalation of radioactive dust and radon gas in a mine or mill. Workers usually cannot wear a protective mask permanently. Therefore, uranium miners are among the most exposed workers of the nuclear fuel cycle.

4.3.4 Lack of transparency

Some mining companies do not provide detailed results of evaluations of doses received by workers.

In Paladin's 2012 sustainability report, the word 'dose' is never mentioned and no figures are available on accumulated dose. The chapter about 'health and safety' gives figures for injuries but contains no evaluation of long-term cancer risk for workers in the Langer Heinrich (Namibia) and Kayelekera (Malawi) mines (Paladin, 2012).

In Brazil, the workers of the INB-URA mine interviewed by CRIIRAD said that they could not get access to the records of the doses they received (Porto, 2014a).

In Namibia, Rössing's performance data table gives only the "*number of personal annual radiation exposures above 20 mSv/annum*". Given that this number is equal to zero (between 2008 and 2011) the actual exposure is not given (Rössing, 2014). A questionnaire carried out with workers and ex-workers of Rössing confirmed that workers don't have access to their medical records and in several occasion have died without knowing their real pathologies (Kohrs and Kafuka, 2014)

4.3.5 Non-negligible doses

In Niger, COMINAK indicates that the maximal individual annual dose was 16.15 mSv in 2009. The breakdown of the doses is plotted in **Table 23** below (COMINAK, 2009). The maximum annual dose limit in Niger is 20 mSv per annum and COMINAK decided to apply a lower limit of 18 mSv per annum.

Worker category	Number of workers	Number of workers exposed to a dose of				Mean annual dose (mSv)	Max. annual dose (mSv)
		0 to 6 mSv	6 to 12 mSv	12 to 18 mSv	18 to 20 mSv		
Member of Cominak staff	1,122	687	340	95	0	5.63	15.8
Subcontractors	755	625	108	22	0	3.28	16.15

Table 23 Individual annual dose of COMINAK mine workers (year 2009)

Source: COMINAK, compiled by CRIIRAD

SOMAÏR indicates that the maximum individual annual dose was²⁴ 9.54 mSv in 2009 while the objective was to stay below 9.5 mSv. The mean individual dose was 3.3 mSv. The breakdown of the doses is plotted in **Table 24** (Somaïr 2010).

Worker category	Number of workers	Number of workers exposed to a dose of							Collective dose (man.mSv)
		0 to 2 mSv	2 to 4 mSv	4 to 6 mSv	6 to 8 mSv	8 to 10 mSv	10 to 12 mSv	12 to 14 mSv	
Member of Somaïr staff	603	241	281	422	114	36	10	0	1.244
Subcontractors	501	39	104	361	89	9	1	0	874
Total	1,104	280	385	783	203	45	11	0	2.118

Table 24 Individual annual dose of Somaïr mine workers (year 2009)

Source: SOMAÏR, compiled by CRIIRAD

SOMAÏR also provides the collective dose, which is the sum of the individual doses received in a given time period by a specific population from exposure to a specified source of radiation (see **Table 25** below).

Worker category	Number of workers	Collective dose (man.mSv)			% Internal / total
		Internal dose	External dose	Total dose	
Member of Somaïr staff	603	940	304	1.244	76%
Subcontractors	501	739	135	874	85%
Total	1,104	1.679	439	2.118	79%

Table 25

Collective annual dose of Somaïr mine workers (year 2009)

Source: SOMAÏR, compiled by CRIIRAD

According to this data, about 80% of the collective dose comes from internal exposure and 20% from external exposure to gamma radiation. However, the method of estimating the doses is not given in the report.

²⁴ The original tables show some inconsistencies. For example the 9.54 mSv maximal individual annual dose is reported with the same value for Somaïr staff and subcontractors and is not coherent with the fact that in both categories some workers are in the column "dose between 10 and 12 mSv".

These results illustrate the difficulty in limiting the inhalation of contaminated dust and radon in the air. Workers state they cannot permanently use respiratory tract protective masks. With regard to protection against radon, they would have to use special filters containing charcoal as radon gas is not trapped by current paper filters.

4.3.6 Evaluation of risk

The fact that the individual doses are below the annual limit of 20 mSv, does not mean that the workers will not die of radiation induced pathologies in the long term

The results of the individual dosimetry of workers from COMINAK and Somaïr mines show values below the limit of 20 mSv per year. Such results would suggest that they are 'safe'.

But the following points should be borne in mind:

The fact that individual doses are below the annual limit of 20 mSv, does not mean that workers will not die of radiation induced pathologies in the long term. As explained in section 4.2 above, the annual dose limit is not a frontier between safe and dangerous, but between acceptable and socially unacceptable risks of dying.

Using the results of individual or collective doses published by COMINAK and SOMAÏR for the year 2009 and the risk factor of 0.04 cancer death per Sv (recommended by the ICRP), one can grossly estimate that after 20 years of operation, about 9 workers will die of radiation induced cancer (see Table 26 below). A more precise evaluation would require detailed knowledge of the affected organs, age of the workers, detailed internal contamination evaluations, etc.

Company	Number of workers (year 2009)	Collective dose (man.mSv) (year 2009) *	Number of workers dying of cancer (ICRP risk factor of 0.04 per Sv)		
			After 1 year of work	After 20 years of work	After 40 years of work
Cominak (workers and subcontractors)	1,877	8,793	0.35	7.0	14.1
Somaïr (workers and subcontractors)	1,104	2,118	0.08	1.7	3.4
Total (Cominak + Somaïr)	2,981	10,911	0.4	8.7	17.5

Table 26 Preliminary evaluation of the number of COMINAK and Somaïr workers that may be dying of cancer using ICRP risk factor of 0.04 per Sv

* Cominak does not give a collective dose. We estimate it using the mean annual dose for subcontractors and regular staff

Source: CRIIRAD using SOMAÏR and COMINAK raw data

The evaluation of radiation induced fatalities as suggested above underestimates the actual risks for different reasons in connection with the underestimation of dose and risk factors:

- The evaluation of the risk of dying of radiation-induced cancer used here is the official value recommended by the ICRP. Many independent scientists across the world believe the ICRP model underestimates the actual risk (ECRR 2010).
- This calculation does not consider the cancers that can be effectively treated and will not result in fatalities. According to ICRP data, the risk factor for



cancer incidence is 0.11 per Sv, while it is 0.04 per Sv for cancer fatalities. However, in many countries due to a lack of resources, the treatment offered to workers may be insufficient. In some cases, workers do not receive treatment at all. Therefore actual cancer fatalities will increase.

- The risk of dying of other radiation induced pathologies besides cancer is not taken into consideration
- The synergetic effect of ionizing radiation and other hazards is not considered (chemicals, non-ionizing radiation, general working conditions, etc.)
- The doses are usually monitored by companies or laboratories subcontracted by the companies. Based on CRIIRAD's experience, failures of environmental radiation monitoring evaluations performed by the companies are common. One can doubt the reliability of these dosimetric evaluations, especially for workers exposed in the seventies and eighties.
- These figures do not include the exposure of workers when they return home. Several examples detailed above (about radiation in homes in Gabon, Niger or France) show that workers may be exposed at home as well.

For all these reasons, the number of workers actually dying of cancer and other pathologies induced by their exposure to ionizing radiation in uranium mines and mills may be much higher than the figures given above.

4.3.7 Evaluation of the actual health impact

A solution for the evaluation of impacts on the health of workers would be to use epidemiological studies to actually monitor the health status of the workers. Epidemiological studies have been carried out, among others on the Navajo population in the US, and on former workers of the Wismut mine that operated until 1990 in Germany. Studies have shown links between exposure and diseases such as bronchial and lung cancer (see among others, Gilliland et al., 2000 for the US and Kreuzer et al., 2010 for Germany).

Such studies are however extremely difficult to conduct. First, most of the health problems will be clinically discovered only years, and even decades after exposure to ionizing radiation and other hazards. Workers would have to be followed even after they leave the company. Such long term follow-up is extremely difficult to perform, especially with subcontractors, and in countries that do not have appropriate institutions for organizing such studies.

Another problem is the fact that much useful data about the health status of workers is kept by the medical structures of the companies themselves. These departments do not always want to share this information, as has been the case with Rössing in Namibia (Kohrs and Kafuka, 2014).

Different studies performed by independent institutions or NGOs around the world have shown that the health status of the workers of uranium mines and mills is extremely poor. Such studies have been conducted by the French NGOs SHERPA, Médecins du Monde and CRIIRAD in Gabon (Daoud et al., 2007), and more recently by Earthlife Namibia and LaRRI in Namibia (Kohrs and Kafuka,

The population living near uranium mines and mills are submitted to ionizing radiation both by external irradiation and internal contamination through ingestion of contaminated food and water and inhalation of radioactive dust and radon gas



2014). They show a lack of appropriate protection of workers, especially in the early years of uranium mining.

One of the answers to this methodological problem is to develop Popular Epidemiology studies. This strategy is discussed in another EJOLT report (Porto 2014b).

4.4 Impacts on the population

4.4.1 Exposure pathways

The population living in the surroundings of uranium mines and mills are submitted to ionizing radiation both by external irradiation and internal contamination. This occurs through ingestion of contaminated food and water and inhalation of radioactive dust and radon gas. Examples of such exposure pathways have been given in the above chapters, they include:

- External irradiation outside dwellings in connection with the re-use of waste rock, the transportation of radioactive material, the re-use of contaminated equipment.
- External irradiation inside their dwellings when radioactive material has been used for construction, or when contaminated equipment is re-used (such as scrap metal and filters).
- Inhalation of radioactive dust connected to mining, crushing and milling activities.
- Inhalation of radon in the open air coming from waste rock and tailings dams, ore piles, and underground mine vents.
- Inhalation of radon inside dwellings when radioactive material has been used for construction, or when contaminated equipment is re-used (such as scrap metal and filters).
- Ingestion of contaminated surface or underground water.
- Ingestion of food that has come into contact with contaminated water, the deposition of radioactive dust on soil and crops, and the deposition of long- life radon daughter products on soil and crops.

This exposure begins with prospecting activities and lasts long after mine closure if waste (waste rock, scrap, tailings) is not managed properly and if remediation measures are insufficient, which is the case in most if not all mines.

4.4.2 Evaluation of doses

As for workers, a way to evaluate the health risk of the local population is to estimate their doses. This task is very difficult for workers and even more complex in the case of local populations. To do so, companies usually use the term 'critical group', referring to those people whose living conditions mean they receive the most exposure. Companies use a network of monitoring posts and environmental samples to evaluate these doses. Several problems however present themselves with this system of monitoring:



Unreliability of official figures

In the course of radiological studies performed in areas surrounding uranium mines in France, Niger, Gabon, Bulgaria, Brazil and Namibia, the CRIIRAD laboratory discovered that official evaluations were not reliable. Some examples of typical underestimations are summarised below:

- Exposure to external irradiation is evaluated using monitoring posts which are not located at the contaminated places where the people actually live.
- The assessment of the contamination of water used for human consumption does not take into account all chemicals and radionuclides (for example dissolved radon-222).
- Exposure to radon gas is usually evaluated without considering the amount of radon inside dwellings affected by the re-use of radioactive rock or contaminated equipment.
- The evaluation of the contamination of edible food does not take into consideration all the radionuclides (excluding polonium-210, for example).
- The actual amount of time spent by people in contaminated places is underestimated.
- The evaluation of the dose is performed for an adult and does not take into consideration the doses to young children and babies, etc.
- The accuracy of risk factors used to calculate doses and convert them into a health risk is questionable, as discussed above for workers.

Non-negligible doses in excess of annual dose limits

Even without considering the points mentioned above, the official doses calculated by mining companies are usually non-negligible and sometimes exceed the maximum annual dose limit for the public (1 milliSievert per year).

For example, in the case of the COMINAK mine in Niger, according to AREVA, the annual added dose for citizens of the city of Akokan who live close to the mine was 1.36 milliSievert or 1,360 microSievert in 2008 (Chareyron, 2010b).

It is useful to compare this figure with the official²⁵ evaluation of the doses received by the population living near an operating nuclear reactor in France. In the case of the Golfech nuclear reactor (two 1,300 MW reactors) this dose was estimated at 2.6 μ Sv/year by the operator (ASN, 2007).

The dose received by inhabitants of Akokan in Niger who live near the mine is more than **500 times higher** than the one received by the people living close to a nuclear reactor.

As discussed above, when taking into consideration the dose received in dwellings constructed with radioactive materials, some inhabitants of Mounana (Gabon) receive annual doses in excess of 10 milliSievert per year.

²⁵ CRIIRAD does not agree with this evaluation which is underestimated. This official figure is given here only as an example.

Example of evaluation of the risks for the population (Niger)

The Arlit community (including Akokan) has a population of 112,432 inhabitants (INS, 2011).

We do not know the breakdown of the individual doses that mining activities cause for each inhabitant. Some of them are exposed to doses of several milliSieverts per year (and even tens of mSv) when they live in contaminated dwellings. Others receive lower doses depending on their living habits.

Using different hypotheses for individual doses, we get different evaluations of the number of people that may die of radiation-induced cancer (see **Table 27** below which uses the ICRP risk factor of 0.05 cancer death per Sv for the general public).

After 20 years spent in the Arlit area, a few tens or hundreds of people may die of radiation-induced cancer. Again it may be much more when considering the uncertainties of dose evaluation and risk factors discussed above in the case of workers.

Place	Number of people (year 2011)	Individual added annual dose (hypothesis), mSv	Collective dose (man.mSv) (year 2009)*	Number of people dying of cancer (ICRP risk factor of 0.05 per Sv)		
				After 1 year spent in the city	After 20 years	After 40 years
Arlit city (including Akokan)	112,432	0.1	11,243	0.6	11.2	22.5
Arlit city (including Akokan)	112,432	0.5	56,216	2.8	56.2	112.4
Arlit city (including Akokan)	112,432	1	112,432	5.6	112.4	224.9
Arlit city (including Akokan)	112,432	2	224,864	11.2	224.9	449.7

Table 27 Evaluation of the number of citizens of Arlit-Akokan cities (Niger) that may be dying of cancer using ICRP risk factor of 0.05 per Sv

Source: CRIIRAD

Global evaluation suggested by the UNSCEAR

Uranium mining and milling is one of the most polluting activities of the nuclear fuel cycle (without considering nuclear accidents like Chernobyl or Fukushima).

This is illustrated by the evaluation of the normalized collective effective dose to members of the public from radionuclides released in effluents from the nuclear fuel cycle (UNSCEAR 1993). UNSCEAR evaluations are plotted in **Table 28** below.

These evaluations do not take into consideration all exposure pathways for populations living near uranium mines and mills.

However, uranium mining and milling is the highest contributor:

- to the local and regional component of the normalized collective effective dose (48%), while reactor operation is contributing to 45%,
- to the dose associated with the solid waste disposal and the global component (75%).

Uranium mining and milling is one of the most polluting activity of the nuclear fuel cycle (without considering nuclear accidents like Chernobyl or Fukushima)

Source	Normalized collective effective dose (man.Sv (GWa) ⁻¹)	Contribution of mining and milling activities (%)
Local and regional component		
Mining	1.1	
Milling	0.05	
Mine and mill tailings (releases over 5 years)	0.3	
Fuel fabrication	0.003	
Reactor operation / atmospheric	1.3	
Reactor operation / aquatic	0.04	
Reprocessing / atmospheric	0.05	
Reprocessing / aquatic	0.2	
Transportation	0.1	
Total (rounded)	3	48%
Solid waste disposal and global component		
Mine and mill tailings (releases of radon over 10,000 years)	150	
Reactor operation / Low level waste disposal	0.00005	
Reactor operation / Intermediate-level waste disposal	0.5	
Reprocessing solid waste disposal	0.05	
Globally dispersed radionuclides (truncated to 10,000 years)	50	
Total (rounded)	200	75%

Table 28 Normalized collective effective dose to members of the public from radionuclides released in effluents from the nuclear fuel cycle

Source: UNSCEAR, 1993

4.4.3 Evaluation of the actual health impact

No epidemiological studies have been performed to adequately evaluate the actual health impacts of mining activities on populations living near uranium mines in Niger, Gabon, Namibia or France. However, this is not a reason for not promoting the implementation of such studies and of popular epidemiology studies.

Populations living near operational or dismantled uranium mines and the local NGOs complain about health deterioration. This is the case in Brazil, Namibia, Niger, Gabon, and France. However, no scientific studies are available to support these complaints.

Taking into consideration knowledge about the health impacts of ionizing radiation, and the evaluation of the doses received by the workers and population affected by uranium mining activities, it should not be necessary to wait further before taking action to learn more about the impacts and reduce exposure.

5

Recommendations

This chapter brings together recommendations stemming from the findings of the previous chapters and already suggested such as baseline studies and monitoring. This chapter also includes considerations on cost evaluation, training and legislation.

5.1 Baseline studies

Without proper baseline studies, it is not possible to properly evaluate the impact of uranium mining activities. This is particularly important as uranium is naturally present in the environment. When high levels of uranium or uranium daughter products are detected in the soil, air, water or the food chain, mining companies claim that this it is not due to contamination, but a result of natural radiation that was present before the commencement of mining activities.

Baseline studies should be performed before the beginning of the most intense prospecting activities (drilling, implementation of prospecting trenches). More detailed studies should be made if a company actually intends to extract uranium. These studies should be carefully supervised by local and national authorities and independent experts. They should include the following elements:

5.1.1 Gamma radiation

An airborne gamma radiation mapping of the area should be carried out. It should include a detailed mapping of gamma radiation dose rates 1 metre above ground, and at the soil surface on the areas that will be directly affected by the mining operations. This includes the banks of the rivers potentially impacted by the water discharge of the mine. The detailed mapping should be done with a grid of less than 5 metres. This is now possible using portable scintillometers connected to a GPS unit.

5.1.2 Air

Recommended measures include:

- Monitoring of the radiological characteristics of dust (detailed activity of uranium-238, uranium-234, thorium-230, radium-226, lead-210, polonium-210) and the amount of dust in the air ($\mu\text{g}/\text{m}^3$), over the course of at least one year, on a monthly basis.
- Monitoring of the radiological characteristics of bioindicators (lichens, terrestrial mosses).

- Monitoring of radon-222 and radon-220 potential alpha energy in the air, over the course of at least one year, on a monthly basis, in order to consider seasonal variations and the impact of meteorological conditions.

For dust and radon monitoring, monitoring posts should be numerous enough to account for variability of the geology, soil structure, and topography of the area.

5.1.3 Soil samples

Sampling of top soil and natural rock should be carried out to monitor uranium-238, uranium-234, thorium-230, radium-226, lead-210, polonium-210, the main daughter products of the uranium-235 and thorium-232 decay chain, and potassium-40. A detailed chemical characterisation of the soil surface and rock is also recommended.

5.1.4 Water samples

Sampling of all available surface waters and underground water resources (drills, wells, springs), at least two times in different seasons.

For each sample, the following analysis should be performed:

- a detailed radiological characterization including: gross alpha and gross beta activity, dissolved radon-222 activity, specific activity of uranium-238, uranium-234, thorium-230, radium-226, lead-210, polonium-210, uranium-235, thorium-232;
- a detailed chemical characterization including : pH, conductivity, Eh, main anions and cations, main metals, main organic pollutants;
- monitoring of the radiological characteristics of aquatic bioindicators (aquatic mosses, aquatic fauna).

5.1.5 Foodchain

Priority should be given to crops, fruits and vegetables with the greatest potential for being affected by the future aerial and liquid discharge of the mine, taking into consideration the main wind currents, topography and hydrological conditions. The parameters to be analysed should be the same as for soil samples but with sufficiently sensitive analytical methodologies.

If there is not enough technical or financial capacity the minimum recommendation is to monitor uranium-238, radium-226 and lead-210.

5.2 Environmental impact studies

The Environmental impact studies (EIA), once prepared by companies and their subcontractors, should be reviewed in a comprehensive way by competent national and local authorities, and by an independent group comprised of representatives of the affected communities, local NGOs and independent scientists.

In order to organise this independent review in an efficient manner, companies should provide paper and digital copies of impact studies, ensuring that the language used is suited to the practices of the local population.

The review process should be planned at least 6 months in advance in order to enable exchanges of questions and answers in writing. It should also comprise at least two technical meetings between all stakeholders. The expenses of this process should be paid by the mining company.

5.3 Cost evaluation

Before deciding to open a new mine, particular attention should be given to various costs that are usually not properly assessed or taken into consideration, for example:

- The long term environmental monitoring of the mining area (air, water, foodchain).
- The long term maintenance of water treatment facilities in order to collect and decontaminate the surface and underground water impacted by the mine, waste rock dumps, tailings dams and, radioactive waste storage facilities.
- The long term maintenance of the waste rock dumps and tailings dams (maintenance of a sufficient layer of soil or other material on top of the areas in order to limit radon exhalation, gamma dose rates and water percolation).
- Adverse impact of the mine on existing economic resources (for example, natural parks, tourism, and agriculture).
- The fact that the mine will require a lot of fresh water that will sometimes be withdrawn from non-renewable aquifers. Solutions should be anticipated for supplying water to the local communities after mine closure, especially if there is the likelihood that local resources could be exhausted and/or contaminated.
- The maintenance of hospitals and social welfare systems in order to take care of workers and local communities whose health is affected in the long term by the impact of the mining operations.

5.4 Training

It is extremely important to train workers, local communities, local authorities and national authorities about the short and long term adverse impacts of uranium mining activities on health and the environment. Special emphasis should be placed on radioactivity and the impact of ionizing radiation, the problem of water consumption and contamination, the difficulty of waste management, and on the very long term and the associated costs.

In the course of the EJOLT project we observed that workers involved in mining operations for as long as 10 years lacked critical information about radiation and the impacts of ionizing radiation. Some companies are accustomed to tell workers and communities that uranium is not a dangerous substance, because it is natural, has low activity, and that uranium mining actually diminishes the radiation of the area because the uranium is exported.

When workers and communities are given sound scientific information about the actual radiotoxicity of uranium, about the concepts of external irradiation and internal contamination, they can at least avoid making mistakes like bringing home contaminated equipment or re-using radioactive waste rocks. They would also be able to make an informed decision of whether they want to work in such an environment.

Training activities will contribute to lowering workers' exposure to ionizing radiation. First because they will understand what should or should not be done at an individual level, and second this will give them more confidence and strength as a collective group (through unions or NGOs) in order to negotiate the improvement of uranium mining practices with the companies and competent authorities.

These training programs and the organization of information exchange between affected communities of different countries should be developed by institutions independent of mining companies.

5.5 Legislation

With all the known impacts that uranium mining has on the environment and people, it would be expected that a strong legal framework for uranium mining exists that allows for adequate control and regulation. However, this is not the case, at least not in many places where uranium is mined.

Africa has the most relaxed uranium mining rules. According to the South African Institute of International Affairs Governance of Africa, Africa produces 18% of the world's uranium, yet many countries there lack the capacity to implement regulations that would guarantee safer uranium mining (McKenzie, 2012). A similar concern over the lack of national binding legislation is voiced in a forthcoming review of Namibia's nuclear legislation (Renkhoff, forthcoming). The review points out that it would be naïve to hope that industry will comply with regulations voluntarily, especially bearing in mind that international companies prefer Africa because of its low environmental standards.

The reasons for the low regulatory standards in some countries are multifaceted. In first place, laws and regulations to control the adverse impacts of uranium mining are largely not in place, or, when they are, they tend to be of voluntary nature or riddled with legal loopholes (Renkhoff, forthcoming; Dasnois, 2012). However, even if the rules were firmly set out, institutions would not have the capacity to ensure adequate implementation by mining companies (Dasnois, 2012). The key problem is that the uranium mining industry is far more powerful than governments or civil society, which makes compliance with rules a matter of the goodwill of companies (Dasnois, 2012).

Because Namibia has a longer history of uranium mining, it has had time to develop at least a rough regulatory framework, but African countries that have only recently started to extract uranium (e.g., Malawi, in 2009) or are only now entering the uranium rush (Tanzania, Botswana, Guinea, Mali and Zambia) have

practically no legislation in the field. This is a situation that companies are likely to take advantage of (McKenzie, 2012). As much as it is urgent that all of those countries develop their national regulatory frameworks, a transitional solution is needed. This is where international agreements can play a role.

Unfortunately, most of the agreements are promoted by the WNA and the IAEA, which are pro-nuclear institutions for which environmental protection is not the foremost priority.

There are several international agreements that aim at regulating uranium mining and its impacts: 11 principles of 'sustainable' uranium mining of the World Nuclear Association, ranging from health and safety to mine decommissioning and site rehabilitation (WNA, 2008), Extractive Industries Transparency Initiative (Extractive Industries Transparency Initiative, 2012) and the general recommendations for 'sustainable' uranium mining of the International Atomic Energy Agency (IAEA, 2014). International agreements that deal with public participation processes (e.g., Rio Declaration on Environment and Development or Aarhus convention) and rights to compensation of indigenous communities affected by mining projects (e.g. United Nations Declaration on the Rights of Indigenous Peoples, ILO convention No. 169 - Indigenous and Tribal Peoples Convention, and the so called native title or indigenous title to land) are also relevant (Renkhoff, 2011). Reporting on the fulfilment of the listed standards and agreements must be demanded by the international community, as this would provide an insight for governments, civil society, the media and citizens into the quality of the operations of the uranium mines (Dasnois, 2012). IAEA members should push their organisation to ensure that African governments take an appropriate level of action in regards to the positive and negative impacts of uranium mining (Dasnois, 2012).

Respect of international agreements is an important step, but it cannot fully replace the lack of national level legislation. To develop its own regulatory framework, it might be interesting to observe the regulatory frameworks of countries that have had a long experience in uranium mining, such as Australia and Canada, which have developed best practices to limit negative effects. Although far from perfect, the mentioned countries have relatively well developed regulatory frameworks. They have authorities that are capable of seeing through the implementation of regulations and have a vocal and active civil society, capable of monitoring implementation (Dasnois, 2012).

Authorities, which are capable of enforcing uranium mining regulations and vocal civil society are of key importance, as it can be observed from the case of China. In 1984, China established a nuclear safety regulatory body, but as China expanded its nuclear power sector in the past decades, the regulatory body remained under-funded and understaffed, and hence unable to perform its functions satisfactorily (Hibbs and Patton Schell, 2014).

International, national or local legislation or regulation should be improved when necessary, in order to guarantee the following points:

- The rights of the communities to have access to detailed information about the mining project and all the steps of the mine development including the prospecting activities. Documentation should be reviewed by independent experts and written in a language that is directly accessible to the communities.
- The right of the community to have Free, Prior and Informed Consent (FPIC) to the mining project. This should include informative sessions by independent actors as well as the mining company.
- The right of the community to participate actively in all decisions regarding the mining project. This should include the organisation of regular meetings with the company, local and national authorities.
- The quality of environmental monitoring programs (air, soil, water, food chain, flora and fauna)
- The quality of the standards applied to:
 - the treatment of liquid effluents from the mine, mill and waste disposal facilities;
 - the discharge of radioactive dust and radon to the atmosphere;
 - the decontamination of all potentially contaminated equipment used in the mine and mill before clearance;
 - the annual dose limit to the impacted population. The reference should be a dose constraint of 0.3 mSv, and possibly lower, taking into consideration the fact that the contamination will last for very long periods of time;
 - the annual dose limit to the workers.
- The objectives of residual exposure to the general public after reclamation of the mine.
- The design and maintenance of waste rock dumps and tailings dams.
- The amount of financial resources that the company should keep in order to pay the reclamation costs and take care of the long term expenses necessary for environmental monitoring and maintenance of fences, pumps, water treatment facilities.

5.6 Environmental monitoring

Environmental monitoring programs developed by uranium mining companies usually don't carry out a fair evaluation of the impacts. Several examples of such failures have been noted in this report. These failures have to do with the following problems:

- Monitoring is not performed at the right place. For example, ambient gamma radiation is monitored at a post located a few tens of metres from the contaminated place. Sediments of affected rivers are not sampled at the place where the transfer from water to sediments is high but at a place where the water flow is high and the deposition low. Monitoring of radon-222 activity in the open air is not performed downwind of tailings dumps.
- Monitoring is not performed at the right moment in time. For example, annual monitoring consists of taking only one sample of rainfall, or underground water or soil at a time when the probability of transfer from the mine is low with respect to local hydro geological or meteorological conditions.
- Samples are not representative of impacts. For example, only water is sampled from rivers, excluding aquatic mosses or other specimen of biota that have a high probability of accumulating radioactive heavy metals.
- The fraction of the sample submitted to analysis may be questionable. For example, only the flesh of a contaminated fish is analysed when the local community may be accustomed to eating the bones as well. Bones accumulate much more radium-226 and lead-210 than flesh does.
- The methodology used to calculate doses does not include all pertinent parameters, or parameters are monitored with methods that are not sufficiently sensitive to detect actually the impact. For example, dissolved radon-222 is not monitored in underground water samples, lead-210 is not monitored in top soil or crops that may be impacted by the aerial discharge of radon-222, and chemicals associated with mining and milling processes are not monitored in the air or water.

In order to improve this situation, the specifications of the environmental monitoring program should be reviewed by independent scientists and by representatives of affected communities.

Communities have a deep knowledge of their environment and can provide valuable information about the type of crops, fauna and flora specimen, meteorological conditions, and customs that will influence the quality of the monitoring programme.

Community representatives should be trained to take samples and take part in the monitoring activities, and to the interpretation of the results. Communities should also be allocated dedicated resources for submitting samples for independent analysis.

5.7 Monitoring of health impacts

The methodologies developed to analyse the health impact of uranium mining activities on the workers and affected populations suffer from many weaknesses. Some of these are outlined below.

5.7.1 Evaluation of doses

The doses received by the population are usually evaluated without taking into consideration all radioactive substances or chemicals (for example radon-222 in the water), all pathways (for example the re-use in the dwellings of contaminated scrap or radioactive rocks for building), or all age groups (higher sensitivity of the young children and babies to exposure of ionizing radiation).

The methods for estimating worker doses do not give a comprehensive view of the risks. For example, monitoring does not include doses received at home. The actual internal contamination of the workers is not checked properly as the control period of urine samples is too short.

Even if the doses were evaluated properly, the question of risk connected to the dose would remain questionable. Many independent scientists point out the fact that the risk factors recommended by the ICRP are mainly based on the follow-up of Hiroshima and Nagasaki survivors and are not fit to evaluate the risk associated with mines. With Hiroshima, people were exposed to instant high doses, mainly by external irradiation. Miners and the local population living near uranium mines are exposed to external and internal contamination at low doses, but more or less permanently over very long periods of time. The synergy of exposure to radioactive heavy metals and non-radioactive chemicals is also not accounted for.

The way doses are evaluated should be reviewed by independent scientists in cooperation with workers and affected communities. This process should include independent monitoring activities that could comprise monitoring of uranium and uranium daughter-products in samples of urine or hair.

Workers should moreover have access to the data of their individual monitoring, and the global non-nominative results of the dose evaluation of the workforce should be made available to the public.

5.7.2 Epidemiological studies

Epidemiological studies should be developed both on the health status of the workers and the affected communities living nearby. These studies should not concentrate on cancer mortality only, but should include global morbidity and all pathologies and health indicators including mental diseases and birth defects. The studies should also include follow-up periods of several decades. Popular epidemiology studies should be promoted in parallel to classical epidemiology studies.

6

Conclusions

Taking examples from Europe (France and Bulgaria), Africa (Gabon, Malawi, Mali, Namibia, Niger) and Brazil, this report demonstrated clearly that uranium mining and milling is one of the most polluting activities of the whole nuclear fuel cycle.

Uranium extraction implies a long term contamination of the environment (water, soil, fauna and flora) with very radiotoxic substances and various chemicals. It also implies a non-negligible exposure of workers and local populations to ionizing radiation and other chemicals. Workers of uranium mines and mills are among the most exposed to radiation in the whole nuclear process. Furthermore, uranium mining involves the intensive use of water and fossil fuels.

The official monitoring programs performed by mining companies do not properly reflect these impacts. Independent monitoring performed in the environment of operating or decommissioned uranium mines and mills show environmental contamination and a lack of proper protection of workers and local inhabitants.

This is due to a lack of proper regulations, poor awareness of the radiological hazards associated with uranium and its daughter-products, insufficient monitoring practices and a lack of control from local and national administrative bodies.

Uranium mining creates enormous amounts of radioactive waste and neither the companies nor the state know how to manage it in the long term. When mines are shut down, radioactive waste remains, and the costs for managing this radioactive legacy including the maintenance of water treatment systems, are passed on to society instead of being taken care of by mining companies. Nor are these costs integrated into the calculation of the overall cost of nuclear electricity.

In order to improve this situation, it is important to promote independent and collaborative work that synergises the contributions of local communities and independent scientists. If local citizens are provided with information and tools they are in a better position to make their own assessments and radiological checks. Communities will also gain confidence in their ability to understand what radiation is, how to monitor it and how to limit its impacts.

The present report is the fruit of such collaboration between affected communities, NGOs and independent scientists. Many of the collaborations developed here have been made possible using the dynamics of the EJOLT project.



Acknowledgments

This work has been made possible thanks to the dynamics and resources of the EJOLT Project, which facilitated independent on-site radiological surveys near uranium mines in Brazil, Bulgaria, Namibia and Malawi. The EJOLT project also enabled training activities with affected communities.

Special thanks to Marta Conde for making initial contact with CRIIRAD in 2010, the initiative of involving CRIIRAD into EJOLT work and the continuous support to all the aspects of the project. Thanks also to UAB, especially Joan Martinez Alier and Beatriz Rodríguez-Labajos for supporting this initiative.

Thanks to the members of the EJOLT WP3 team: Lidjia Živčič and Tomislav Tkalec (FOCUS, Slovenia), Todor Slavov (Za Zemiata, Bulgaria), Bertchen Kohrs (Earthlife Namibia), Reinford Mwangonde and William Nyirenda (CFJ, Malawi) and to colleagues from Brazil (Marcelo Firpo and Renan Finamore from FIOCRUZ). Thanks also to Nathalie Renkoff for providing materials to prepare parts of this report related with the legal framework.

Thanks to the CRIIRAD team - Christian Courbon for his participation in the sampling activities, Jocelyne Ribouet for preparing the samples and Stephane Patrigeon for the laboratory analysis. Thanks to Corinne Castanier (CRIIRAD) and Marta Conde (ICTA) for reviewing the draft report, to Lidjia Živčič and Beatriz Rodríguez-Labajos for the layout and editing work and to Hali Healy for English proofreading.

Some of the material used for the present report has been gathered by CRIIRAD over a period of more than 20 years while studying the impact of uranium mines in France and Africa. Special thanks to all the citizens, workers, and NGOs which have been involved in attempts to gain independent information about the impact of uranium mines, and to improve the availability of information and protection for people against ionizing radiation. It is not possible to mention all of them here, but a special mention should be given to AGHIRIN'MAN and its President, M. Almoustapha ALHACEN for the work performed in Arlit (Niger) since 2002.

References

AGHIRIN'MAN (2011) Rapport d'activité 2011 et plan d'action 2012.

AQUATERRA (2011) RPS Aquaterra: Rössing – Prediction of groundwater seepage movement, October 2011.

ASN (2007) Revue contrôle N°177, «Les rejets radioactifs en France», novembre 2007.

Chareyron, B., Castanier, C. (1994) CRIIRAD, Etudes radioécologiques sur la division minière de la Crouzille, Février 1994.

Chareyron, B. (1998), Division minière de la Crouzille, Mesures de terrain et analyses réalisées par le laboratoire de la CRIIRAD du 9 au 11 septembre 1998.

Chareyron, B. (2002a) Compte rendu de mesures effectuées par le laboratoire de la CRIIRAD sur un bloc de minerai d'uranium présent chez un particulier de la commune de Saint-Priest-La-Prugne (Loire).

Chareyron, B. (2002b) Rapport CRIIRAD N°03-38, Bilan radioécologique du Site Bois Noirs, octobre 2002.

Chareyron, B. (2003a) Note CRIIRAD N°03-40. Compte rendu de mission à Arlit (Niger) du 3 au 11 décembre 2003. Décembre 2003.

Chareyron, B. (2003b), L'impact radiologique des anciennes mines d'uranium de COGEMA en Limousin, un scandale persistant, Doc. BC031125 V0.

Chareyron, B. (2004) Rapport CRIIRAD N°04-05. Contrôles radiologiques préliminaires dans l'environnement de la mine d'uranium de Saint-Pierre (Cantal). Mars 2004.

Chareyron, B. (2005a) Note CRIIRAD N°05-02. Analyse de sédiments lors de la vidange du lac de Saint-Pierre (Cantal). Mars-avril 2005.

Chareyron, B. (2005b) Note CRIIRAD N°05-17. Impact de l'exploitation de l'uranium par les filiales de COGEMA-AREVA au Niger. Avril 2005.

Chareyron B (2006a) Note CRIIRAD N°06-41. Remarques sur le projet COGEMA-AREVA de stockage de boues et sédiments contaminés sur le site de Bellezane (Haute-Vienne). Juin 2006.

Chareyron, B. (2006b) Rapport CRIIRAD N°06-88. Impact radiologique de l'usine COMURHEX (Groupe AREVA) de Malvesi (Aude), Novembre 2006.

Chareyron, B., Constantin-Blanc, T. (2007a) Rapport CRIIRAD N°07-68 Expertise 2006 Phase 2 Tome 1 Milieu aquatique. Situation radiologique de la mine d'uranium de Saint-Pierre (Cantal) et de son environnement. Octobre 2007.

Chareyron, B., Constantin-Blanc, T. (2007c) Rapport CRIIRAD N°07-68 Expertise 2006 Phase 2 Tome 3 Radon. Situation radiologique de la mine d'uranium de Saint-Pierre



(Cantal) et de son environnement. Octobre 2007.

Chareyron, B. (2008a) Note CRIIRAD N°08-02 AREVA: du discours à la réalité – L'exemple des mines d'uranium du Niger. Janvier 2008.

Chareyron, B. (2008b) Note de synthèse CRIIRAD N°08-50 Ancien site d'extraction d'uranium AREVA des Bois Noirs / Suivi CRIIRAD-Collectif des Bois Noirs 2006-2007. Avril 2008.

Chareyron, B. (2008c). Radiological hazards from uranium mining. In: Merkel, B. J.; Hasche-Berger, A. Uranium, Mining and Hydrogeology. Berlin: Springer, 2008.

Chareyron, B. (2009a), Note CRIIRAD N°09-118, Contamination radiologique relevée en 2009 sur l'ancien site minier uranifère de COMUF-AREVA à Mounana (Gabon), décembre 2009.

Chareyron, B. (2009b), Note CRIIRAD N°09-25 / Mine de charbon et centrale thermique de production d'électricité SONICHAR à Tchirozérine (Niger), Analyse chimique des eaux d'exhaure, Juin 2009.

Chareyron, B. (2009c), CRIIRAD letter to Mrs Anne Lauvergeon (AREVA), impact de l'exploitation de l'uranium par les filiales d'AREVA à ARLIT et AKOKAN, présence de matériaux irradiants dans les rues, 31 juillet 2009.

Chareyron, B. (2010a), CRIIRAD report N°10-07, Analyses of atmospheric radon 222 / canisters exposed by Greenpeace in Niger (Arlit/Akokan sector), January 2010.

Chareyron, B. (2010b), CRIIRAD report N°10-09, Remarks on the radiological situation in the vicinity of the uranium mines operated by SOMAIR and COMINAK (subsidiaries of AREVA) in northern Niger, Study conducted on behalf of Greenpeace International, February 2010.

Chareyron, B. (2011a), Rapport CRIIRAD N°11-78 / MALI / Gisements d'uranium de Falea / Relevés radiométriques et analyses d'eau, sols et sédiments (mars 2011) / Réflexions sur l'impact des travaux de prospection conduits par Rockgate, 22 décembre 2011.

Chareyron, B. (2011b), personal communication, meeting in Arandis with M. Petrus Hoaeb, former worker at Rössing uranium mine laboratory.

Chareyron, B. (2012a), CRIIRAD preliminary report N°12-32, Summary of CRIIRAD and CFJ mission to Kayelekera uranium mine, EJOLT project.

Chareyron, B. (2012b). The radiological impact of uranium extraction near Arlit and Akokan in Niger, EJOLT Factsheet.

Chareyron, B. (2012c), CRIIRAD Report No. 12-16, Preliminary results of water quality monitoring near former uranium mines in Bulgaria, EJOLT Project.

Chareyron, B. (2012d), CRIIRAD preliminary report N°12-87, Summary of CRIIRAD and FIOCRUZ mission to Caetité uranium mine (BAHIA / BRAZIL), EJOLT Project.

Chareyron, B. (2014a) Note CRIIRAD N°14-26 / Analyses radiologiques de solides prélevés sur

des sites de prospection d'uranium à Poli au Cameroun et à Teubang au Tchad, 22 avril 2014.

Chareyron, B. (2014b). Radiological Impact of Rössing Rio Tinto Uranium Mine. EJOLT & CRIIRAD Report.

Chareyron, B. (2014c). E-mail sent by CRIIRAD to the local authorities on April 19th 2014 : "Demande intervention urgente sur site Vesse / La Guillermie, secteur Bois Noirs / présence de filtres fortement contaminés issus de la SIMO".

Chareyron, B. (2014d), CRIIRAD report N°14-31, The radiological impact of INB uranium mine in Caetité (BAHIA / BRAZIL), Main findings of CRIIRAD missions to Caetité with FIOCRUZ and CPT / EJOLT Project with additional support by "Medico International".

Chareyron, B. (2014e), Lettre au sous-préfet de Roanne: «très forte contamination radiologique des plantes aquatiques dans la rivière Besbre en aval des rejets liquides de l'ancienne mine d'uranium AREVA des Bois Noirs», 17 janvier 2014.

CNPPRI (2007) CNPPRI Mounana / Scénario d'exposition aux gammas à l'intérieur des logements construits par COMUF à Mounana, décembre 2007.

COMINAK (2009) Rapport Environnemental Social et Sociétal 2009, Compagnie minière d'Akouta.

Conde, M., Kallis, G. (2012) The global uranium rush and its Africa frontier. Effects, reactions and social movements in Namibia. Global Environmental Change.

Dasnois, N. (2012). Uranium mining in Africa: A Continent at the Centre

of a Global Nuclear Renaissance. SAIIA.

Daoud, S., Getti, J-P., Chareyron, B., Brugière, M., Bouet, P., Sisco, S., Bourdon, W. (2007) AREVA au Gabon, Rapport d'enquête sur la situation des travailleurs de la COMUF, filiale gabonaise du groupe AREVA-COGEMA, 4 avril 2007. Enquête réalisée par SHERPA, en collaboration avec la CRIIRAD, Médecins du Monde, le CATRAM (anciens travailleurs au Gabon) et l'association Mounana (expatriés).

Darby S, Hill D, Auvinen A, et al. (2005) Radon in homes and risk of lung cancer: collaborative analysis of individual data from 13 European case-control studies. Br. Med. J., 330: 223-227.

Diniz, V. (2014) Japan rules no on nuclear plant restart, Uranium Investing News, May 22, 2014, available online at <http://uraniuminvestingnews.com/18366/japan-nuclear-kivalliq-uec-alpha-exploration-cameco-uranerz.html> [last accessed: 06/11/2014].

ECRR (2010) The 2010 Recommendations of the European Committee on Radiation Risk. The health effects of exposure to low doses of ionizing radiation. Regulators' Edition. Eds: Chris Busby, Alexey V Yablokov, Rosalie Bertell, Molly Scott Cato, Inge Schmitz Feuerhake, Brussels: ECRR.

Extractive Industries Transparency Initiative (2012) The EITI Principles and Criteria. <http://eiti.org/eiti/principles> (accessed on April 18 2014).

EURATOM (1996), Council Directive 96/29/EURATOM of 13 May 1996 laying down basic safety standards for the protection of the health of workers and the general public against the dangers arising from ionizing radiation.

EURATOM (2013). 2013/51. Directive 2013/51/Euratom du Conseil, du 22 octobre 2013 «fixant des exigences pour la protection de la santé de la population en ce qui concerne les substances radioactives dans les eaux destinées à la consommation humaine ».

EURATOM (2013) COUNCIL DIRECTIVE 2013/59/EURATOM of 5 December 2013 laying down basic safety standards for protection against the dangers arising from exposure to ionising radiation, and repealing Directives 89/618/Euratom, 90/641/Euratom, 96/29/Euratom, 97/43/Euratom and 2003/122/Euratom.

Gilliland, F.D., Hunt, W.C., Pardilla, M., Key, C.R. (2000) Uranium mining and lung cancer among Navajo Men in New Mexico and Arizona, 1969 to 1993. *Journal of Occupational and Environmental Medicine* 42 : 278–283.

GRIP (2001). Barrillot, B., Castanier, C., Chareyron, B., De Brouwer, C., Mampaey, L., Richard, C-M., Tavitian, N., Les armes à l'uranium appauvri, Jalons pour une interdiction. N°253, « Les livres du Grip).

Hennequin (2009) Documentary by Dominique Hennequin about the impact of uranium mining in Niger and Gabon, "Uranium, l'héritage empoisonné", 2009.

Hibbs, M. and Patton Schell, T. (2014) Governing uranium in China: Unclear legislation. Danish Institute for International Studies, Denmark.

IAEA (2014) Establishment of uranium mining and processing operations in the context of sustainable development. http://www-pub.iaea.org/MTCD/publications/PDF/Pub1401_web.pdf (accessed on April 18 2014).

IARC (1988) World Health Organization, International Agency for Research on Cancer, IARC Monographs on the Evaluation of Carcinogenic Risks to Humans, Volume 43, Man-made Mineral Fibres and Radon, 1988

ICRP 50 (1986) Lung cancer risk from indoor exposure to radon daughters.

ICRP 60 (1990) Recommendations of the International Commission on Radiological Protection.

ICRP 65 (1993) Protection against radon 222 at home and at work.

ICRP 115 (2011) Lung cancer risk from radon and progeny. *Annals of the ICRP*, volume 40, N°1-2010

ICRP (2012) Compendium of Dose Coefficients based on ICRP Publication 60. ICRP Publication 119. Ann. ICRP 41(Suppl.).

INS (2011) Institut National de la Statistique du Niger, "Le Niger en Chiffres 2011", Novembre 2011.

INB (2014) Relatório / Atendimento ao sistema de informação ao cidadão lei 12.527/2011 / RT-URA-05-14, January 21st 2014.

Kohrs et al. (2012) Uranium mining in Namibia – Is this a latent conflict?

- Özkaynak, B. et al. Mining Conflicts around the World: Common Grounds from Environmental Justice Perspective, EJOLT Report No. 7, 198 p.
- Kohrs, B., Kafuka, P. (2014) Study on low-level radiation of Rio Tinto's Rössing uranium mine workers. EJOLT and Earthlife Namibia Report.
- Kreuzer, M., Schnelzer, M., Tschense, A., Walsh, L., Grosche, B. (2010) Cohort profile: the German uranium miners cohort study (WISMUT cohort), 1946–2003. *International Journal of Epidemiology* 39, 980–987.
- Krewski, D., Lubin, J. H., Zielinski, J. M., Alavanja, M., Catalan, V. S., Field, R. W., Klotz, J. B., Letourneau, E. G., Lynch, C. F., Lyon, J. I., et al. (2005) Residential radon and risk of lung cancer: a combined analysis of 7 North American case-control studies. *Epidemiology* 16, 137-145.
- Lamireau, T. (1995) Documentary "Uranium en Limousin".
- Lubin, J. H., Wang, Z.Y., Boice Jr., J. D., Xu, Z. Y., Blot, W. J., Wang, L. D. and Kleinerman, R. A. (2004) Risk of lung cancer and residential radon in China: pooled results of two studies. *Int. J. Cancer* 109, 132-137.
- McKenzie, J. (2012) Many African countries lack capacity to regulate uranium mining – think-tank. <http://www.miningweekly.com/article/many-african-countries-lack-capacity-to-regulate-uranium-mining-think-tank-2012-07-06> (accessed on May 12 2014).
- Mudd, G. M. (2001) Critical review of acid in situ leach uranium mining: 1. USA and Australia. *Environ. Geol.*; 41:390-403.
- Paladín (2012) Paladín Energy LTD, Sustainability report, 2012.
- Porto, M. F.; Finamore, R. .; Chareyron, B. (2014a), Justiça ambiental e mineração de urânio em Caetité/BA: avaliação crítica da gestão ambiental e dos impactos à saúde da população, April 2014.
- Porto, M. F.; Finamore, R. et al. (2014b), Health as dignity: Risks, Health, and mobilizations in favour of environmental Justice, EJOLT-WP7 report, 2014.
- Raeva, D., Slavov, T., Stoyanova, D., Živčič, L., Tkalec, T., Rode, Š. (2014) Expanded nuclear power capacity in Europe, impact of uranium mining and alternatives. EJOLT Report No. 12, 129 p.
- Renkhoff, N. 2011. Public participation in the development of mining in Namibia - towards a benefit sharing relationship between occupants of communal land and the mining industry, in: Ruppel/Winter (Ed.), *Justice from within: Legal pluralism in Africa and beyond*, *Liber amicorum* Manfred O Hinz: 355-373.
- Renkhoff, N. Forthcoming. Evaluation of Nuclear Legislation – the issue of rehabilitation of uranium mine sites in Namibia.
- Rössing (2011). Social and Environmental Impact Assessment, Phase 2b: Proposed expansion of Rössing mine, November 2011.
- Rössing (2014). Rössing web site: <http://www.rossing.com/performance.htm> accessed in May 2014.
- SAIEA (2010). Strategic Environmental Assessment for the

central Namib Uranium Rush. Ministry of Mines and Energy, Windhoek, Republic of Namibia.

SOMAÏR (2010) Rapport Environnemental Social et Sociétal 2010, Société des Mines de l'Aïr.

UNSCEAR (1988) Sources and effects of ionizing radiation, United Nations Scientific Committee on the Effects of Atomic Radiation, UNSCEAR 1988 Report to the General Assembly.

UNSCEAR (1993) Sources and effects of ionizing radiation, United Nations Scientific Committee on the Effects of Atomic Radiation, UNSCEAR 1993 Report to the General Assembly.

UxC (2014) UxC Nuclear Fuel Price Indicators, available online at <http://www.uxc.com/review/UxCPrice.s.aspx>.

Vacquier, B., Laurier, D., Rogel, A., Caer, S., Quesne, B., Tirmarche, M. (2005) Updated mortality in French cohort of uranium miners: 1946-

1999. 18th International Symposium on Epidemiology in Occupational Health (EPICOH). Bergen (Norway), 11-14 May 2005.

Veit, S., Srebotnjak, T. (2010) Potential use of radioactively contaminated materials in the construction of houses from open pit uranium mines in Gabon and Niger / European Parliament, Directorate-General for external policies, Policy Department, November 2010.

WNA (2014) World Nuclear Association website (April 2014): <http://www.world-nuclear.org/info/Nuclear-Fuel-Cycle/Mining-of-Uranium/World-Uranium-Mining-Production>.

World Nuclear Association (2008) Sustaining Global Best Practices in Uranium Mining and Processing: Principles for Managing Radiation, Health and Safety, Waste and the Environment. WNA, London

Appendix

Situation of uranium mining on different continents²⁶

A1.1 Europe

Uranium has been mined in various countries across the continent, however many mines were eventually shut down for economic and environmental reasons.

The **Czech Republic** is the birthplace of industrial scale uranium mining. Since 1945 uranium has been exploited on an industrial scale in a total of 23 uranium deposits. During the communist era uranium was delivered as yellow cake into the USSR. All Czech mines, with the exception of the Rožná underground mine in Dolní Rožinka, were shut down due to environmental concerns immediately following the revolution at the beginning of the 1990s. The environmental damage was enormous and the clean-up, still incomplete, has been very costly (Wallner and Stein, 2012). A similar story can be told for other Central and Eastern European countries.

Uranium mining was also carried out also on a large scale in **France** (more than 200 uranium mines) because of its extensive nuclear program. However, uranium mines or uranium processing facilities were also opened in **Bulgaria, Denmark, Estonia, Finland, Germany, Hungary, Poland, Portugal, Romania, Russia, Serbia, Slovenia, Spain, Sweden and Ukraine**²⁷.

Most of them have closed and are in the process of decommissioning. All uranium mines in **France** were shut down, with the last one closing in 2001. Since then, various NGO's including CRIIRAD have pursued to the French Radiation

²⁶ This compilation has been prepared by Tomislav Tkalec and Lidija Živčič of FOCUS, a Slovenian NGO in the EJOLT project.

²⁷ WISE Uranium Project website (Decommissioning Data – Europe), April 2014: <http://www.wise-uranium.org/uddeur.html>.



Protection Agency, asking them to take into consideration the environmental impacts of former uranium mines and implement improvements to on-going mining operations, in particular targeting those of AREVA. This report has highlighted several of the prevalent impacts of these mines.

Bulgarian uranium mines were closed down 20 years ago at the end of the Cold War. At its peak, 48 uranium mines and two enrichment plants were in operation. In the 1960s the Ranstad mine in **Sweden** produced 200 tonnes of uranium but is now closed and clean up has been completed (Wallner and Stein, 2012). In the **Czech Republic** 14 mine sites were closed until 1990s and another one in 1996. In 2000 **Spain** closed down its uranium mines and began clean-up.

The Mecsek mine (**Hungary**) produced 21,000 tonnes of uranium until it was shut down in 1997. In 1998 the clean-up of the uranium mining legacy began. This involved the: closing of underground mines, and remediation of the waste rock heaps, sediment ponds and the uranium mill. An area of 62 ha of land needed to be cleaned and 700,000 m³ of contaminated soil disposed of. The costs were enormous with some funds being made available by the EU (PHARE project), amounting in total to approximately 100 million Euro. The main remediation works were completed in 2009. However, to prevent the contamination of drinking water resources for some 200,000 people with uranium mill tailings seepage, continuous remediation efforts are necessary (Wallner and Stein, 2012: 11).

In the EU currently only two countries operate uranium mines (Wallner & Stein 2012, 5). One mine is operating in **Czech Republic**, in Rožná, the last operating underground uranium mine in the EU. In **Romania**, at the Crucea mine, the state company CNU is mining a small amount of uranium with the support of state subsidies (Wallner and Stein, 2012: 13). In Ukraine²⁸ there is also one mine (Ingul'skii) and one mill (Zheltiye Vody).

There are open issues with these on-going operations related to health, environmental impacts, and social conflicts. At the Diamo underground uranium mine in Rožná (**Czech Republic**) the average annual effective dose (8.2 mSv), the maximum annual effective dose (35.6 mSv), and the collective effective dose (3,630 mSv) showed an increase in 2013 from 2012. In 2012, 16 out of 442 underground workers were exposed to an effective dose greater than the annual dose limit of 20 mSv.

In **Romania**, in 2000, several tonnes of waste sludge contaminated with uranium poured from a mining operation into nearby streams and then the Fekete Körös River in eastern Hungary.

Several companies, mainly from Australia, Russia and Canada, are trying to obtain uranium mining licenses or are performing uranium prospecting in the Czech Republic, Slovakia, Spain, Hungary, Poland, Sweden, Finland, Belarus, Bulgaria and in many other countries (and also Greenland)²⁹. A return of uranium

²⁸ WISE Uranium Project website (Issues at Operating Uranium Mines and Mills – Other Countries), April 2014: <http://www.wise-uranium.org/umop.html#EUR>.

²⁹ WISE Uranium Project website (New Uranium Mining Projects – Europe), April 2014:



mining to Europe would entail the return of additional health and environmental impacts in addition to the damage already done by past uranium mining (Wallner and Stein, 2012: 5).

The political reason given for a return to uranium mining is energy independence. Since most states however do not have enrichment or fuel fabrication facilities in their territory, dependency on international suppliers would not be resolved. International exploration companies are rather looking for new mining options to secure available deposits. At locations where the companies find uranium resources, pressure is exerted on governments and communities (Wallner and Stein, 2012:12), yet resistance is mounting. In Slovakia, Hungary, Spain and elsewhere, where companies have presented plans for mining, citizens' initiatives are being formed and environmental organizations are campaigning against it.

European uranium reserves and mining capacities are insufficient to cover the operation of its nuclear power plants. A substantial share of uranium is imported from countries outside of Europe (Wallner and Stein, 2012: 16).

Box 1 Case study: Stráž pod Ralskem, Czech Republic (closed mine)

Probably the most damaging incident of environmental damage related to groundwater pollution in Europe occurred as a result of an In Situ leaching project in Stráž pod Ralskem, Czech Republic. Leaching fluid with sulphuric acid content was injected via 6,000 wells up to 220 m deep, with over 3,000 additional wells dug for the extraction of the uranium-bearing fluids.

From the late 1960s until the mid-1990s four million tonnes of acid were pumped into the ground. These operations, plus the activities of a neighbouring uranium mine in Hamr contaminated approximately 270 million m³ of groundwater with sulphuric acid. Several square kilometres of these regions are now severely contaminated.

The state-owned uranium mining company Diamo is working to remediate the area. Decontamination processes aim to clean the rock of the remaining acid and its deposits, and to introduce hydro barriers in order to keep the acids from leaking into the large drinking water reservoirs in this area, and the River Elbe. The remediation will take approximately 30 more years and cost an estimated total of 2.24 billion Euro. Several tonnes of uranium, ammonium sulphate and aluminium sulphate are extracted per year as by-products of this decontamination (Wallner and Stein, 2012: 11).

According to Wallner & Stein (2012: 11), the experience from Stráž pod Ralskem shows that the risk of this type of mining involves:

- heaps of radioactive mined rock and dust that becomes airborne;
- toxic sludge (tailing ponds and sedimentation ponds);
- ventilation shafts, also after the uranium mine is shut down;
- pollutants (solvents, chemicals, uranium left-overs and uranium decay products) released into the environment due to In-situ leaching;
- changes in the geological composition of the area ;
- irreversible changes in the water regime;
- damages to and destruction of the soil profile.

A1.2 Asia

In Asia a great number of countries are either mining uranium or developing new exploration projects. Kazakhstan is the leading producer in the world. It has been an important source of uranium for more than fifty years. Uranium exploration started in 1948 and deposits economically feasible for extraction were found in several parts of the country. Some 50 uranium deposits are known in six uranium provinces³⁰. Apart from Kazakhstan, Russia, Uzbekistan, China, India, and Pakistan are also large producers of uranium.

There are also more than 70 decommissioning projects being carried out.

In **Kazakhstan**, in the Caspian province, a major mining and processing complex was in operation until 1994. Past uranium mining in Kazakhstan is still causing elevated uranium concentrations in river water and elevated radiation levels near former uranium mine sites. In one location, near the Aktau uranium mines, more than one hundred thousand tonnes of hazardous waste sulphur was found. Scientists are concerned about the lack of groundwater restoration following uranium in situ leaching.

In **China**, an environmental activist was sentenced to two years of 'Re-education Through Labour' for drawing attention to problems related to a decommissioning project at the Gansu uranium mine³¹.

Tajikistan has about 54.8 million tonnes of unsecured waste from (mainly) abandoned mines. According to a UN report (UNECE, 2012), the waste is untreated, and has not been confined or secured. It has led to high uranium concentrations in water and fish and elevated radiation dose rates near the mining areas. Similar issues are also present in **Kyrgyzstan**.

In **Kazakhstan**, all except one of the operating and planned in situ leaching mines are in the central south region of the country. Mines in Steпноye have been operating since 1978, and in Tsentralnoye since 1982, both of which are in the Chu-Sarys basin which has more than half the country's known uranium resources. There are 14 mines here and an additional seven mines operating in the Western area of the Syrdarya basin, some of which has been in operation since 1985. There is one further ISL mine in the Northern province.

During the Soviet era, **Uzbekistan** provided much of the uranium to the Soviet military-industrial complex. Today the state-owned Navoi company operates more than 12 uranium mines.

In **Russia**, ARMZ (Russia's national uranium mining company) runs 19 projects in the Elkon, Streltsovskiy and Vitimskiy regions. In 2010 Russia's uranium came mainly from several large underground mines in the Streltsovskiy district of the Transbaikalian or Chita region southeast of Siberia, near the Chinese and Mongolian

³⁰ World Nuclear Association website (Uranium Mining Overview), April 2014: <http://www.world-nuclear.org/info/nuclear-fuel-cycle/mining-of-uranium/uranium-mining-overview/>.

³¹ WISE Uranium Project website (Decommissioning Projects – Asia), April 2014: <http://www.wise-uranium.org/udasi.html>.

borders. Deposits were discovered in 1967 and have been a major source of production since then. A lesser amount of production comes from operations at Khiagda in Buryatiya and Dalur in the Kurgan region.

Extensive environmental contamination has been identified near the Kranokamensk uranium mine. Researchers have shown excessive values of radium-226 and thorium-232 in soil, vegetation, groundwater and local food sampled in the vicinity of the uranium mines, significant in comparison to areas outside the zone of influence of uranium mining.

Most future production in Russia is set to come from the massive Elkon project with several mines in the Sakhta Republic (Yakutia).

In **China** there are more than 9 operating mines and a number of other processing facilities³². A report from 2012 showed that the radon and radon progeny levels in Chinese uranium mines where the 'cut and fill stoping' method is used are 3 to 5 times higher than those in foreign uranium mines³³.

In **India**³⁴, the Tummalapalle uranium mine continuously pumps out ground water, upon which farmers depend for their agricultural needs. In Jharkhand (India), reckless dumping of radioactive waste has contaminated surface and ground water, putting thousands of locals at risk of developing cancer. There are also several conflicts and protests going on in India. In one case rebels set a truck with ore on fire, pressing for jobs for displaced residents at Bagjata uranium mine. India is considering expanding its producing capabilities³⁵.

Although in **Jordan** no uranium has been mined yet, it was announced in 2008 that the Jordanian government has signed an agreement with AREVA to explore for uranium.

Apart from these countries, uranium prospecting and exploration is being performed in Armenia, Bangladesh, China, India, Indonesia, Iran, Israel, South Korea, North Korea, Kuwait, Kyrgyzstan, Mongolia, Myanmar, Nepal, Oman, Pakistan, Philippines, Russia, Saudi Arabia, Tajikistan, Turkey, Turkmenistan, Uzbekistan, Vietnam, and Yemen³⁶.

³² WISE Uranium Project website (Uranium Mine Ownership – China), April 2014: <http://www.wise-uranium.org/uocn.html>.

³³ WISE Uranium Project website (Issues at Operating Uranium Mines and Mills – Asia), April 2014: <http://www.wise-uranium.org/umopasi.html#IN>.

³⁴ WISE Uranium Project website (Uranium Mine Ownership – India), April 2014: <http://www.wise-uranium.org/uoin.html>.

³⁵ Wikipedia website (Uranium mining by country), April 2014: http://en.wikipedia.org/wiki/Uranium_mining_by_country#Australia.

³⁶ WISE Uranium Project website (New uranium Mining Projects – Asia), April 2014: <http://www.wise-uranium.org/upasi.html>.

Box 2 Case study: Koshkar-Ata mill tailing deposit, Kazakhstan – environmental damage due to uranium tailings

Uranium mining tailings pose a problem for Kazakhstan in the long term. When the surface of the tailing ponds dries out, the very fine radioactive material is dispersed by the wind over large areas. Strongly affected is the city of Aktau (156,000 inhabitants), where radioactive dust from the Koshkar-Ata tailing deposit regularly settles. Another major problem is the groundwater contamination caused by seepage from the tailing ponds and the acid which is injected directly into the ground during In-situ leaching (Wallner & Stein 2012, 12).

The cleanup of old uranium mines is also a problem. Kazakhstan has no plans for cleaning up tailings from uranium mining carried out during Soviet times; nor for tailings from current or planned uranium mining. Instead state uranium mining company Kazatomprom is peddling an absurd 'scientific' claim that Kazakhstan soil possesses self-cleansing properties (Wallner and Stein, 2012: 12).

A1.3 Africa

Uranium mining has a long history in Africa. Significant quantities of the mineral have been extracted in the Democratic Republic of Congo (DRC) and Gabon. Today uranium is mined in Namibia, Niger, South Africa and Malawi, but uranium prospecting and exploration is being carried out across the continent.

The **Democratic Republic of Congo** provided much of the uranium for the Manhattan Project in the early 1940s, particularly from the Shinkolobwe mine. Uranium mining subsequently carried on until independence in 1960, when the shafts were sealed and guarded. Despite the closure, there have been cases of unauthorized mining, with artisanal miners gaining to the site by bribing guards. While the miners are after copper and cobalt, some ores also contain considerable concentrations of uranium, which can be easily extracted and sent to unknown destination countries.

In **Gabon**, the Mounana uranium deposits were discovered in 1956 and were mined from 1960 to 1999. The best known of these deposits is Oklo, discovered in 1968, which is famous for its fossil 'nuclear reactor', where natural conditions about two billion years ago created at least 17 self-sustaining 'nuclear reactors' in the wet sandstone ore body. Recently 200 homes were demolished due to excess radiation at AREVA's former uranium mine site in Mounana.

In addition, decommissioning projects have been or are still being carried out in **Madagascar, Malawi, South Africa and Zambia**³⁷.

In **South Africa**, uranium has generally been produced as a by-product of gold and copper mining. In 1951, a company was formed to exploit the uranium-rich slurries from various gold mines and from the Palabora copper mine. A study from 2012 found extreme uranium and heavy metal contamination in cattle grazing near Wonderfontein Spruit³⁸.

³⁷ WISE Uranium Project website (Decommissioning Projects – Africa), April 2014: <http://www.wise-uranium.org/udafr.html>.

³⁸ WISE Uranium Project website (Decommissioning Projects – South Africa), April 2014: <http://www.wise-uranium.org/udza.html>.

Namibia has two large uranium mines producing 10% of the world's output. Mining in Rössing started in 1976 as a large-scale open pit in very hard rock. The Langer Heinrich mine is 50 km south-southeast of Rössing, and only opened in 2007.

Niger has two significant long-running mines (from the 1970s), SOMAÏR and COMINAK, supplying 6% of the world's mined uranium.

In **Malawi**, the Kayelekera uranium mine has been temporarily closed, due to low prices of uranium. Problems there also relate to an unfavourable contract with the state and the Australian mining company Paladin. The contract was viewed as providing unfavourable working conditions for workers³⁹.

Similar issues are present in Niger, where a study found that there is a lack of protection for workers and insufficient compensation for occupational illnesses⁴⁰. As pointed in this report, contaminated materials are being sold in local markets and groundwater is radioactive and contaminated.

Uranium mines in Namibia are facing water shortages, which also affects local residents. In 2013, in Rössing, an acidic seepage from its tailings dam could be seen from space. Running streams and large pools of red and green sludge were collected alongside the mine's tailings dam. There were other issues as well, as a failure in leach tank caused a major spill of acidic ore slurry in 2013. CRIIRAD found elevated radiation levels around the mine⁴¹.

In South Africa, uranium mines are causing excessive uranium concentrations in streams and stream sediments. Also, a large number of workers have been exposed to significant radiation doses.

There are several plans for more mines in Namibia, including the Husab project on the Rössing South deposit. In the Central African Republic, AREVA began to develop the Bakouma project before recently abandoning it. In Zambia, Equinoy Minerals is developing the Lumwana project, which is primarily a copper mine with discrete uranium ore.

In Africa, foreign companies mainly from Russia, China, Australia, France and Canada, intend to start new operations. There are aspirations for the development of new projects in Algeria, Angola, Botswana, Burkina Faso, Burundi, Cameroon, Central African Republic, Chad, Congo, Egypt, Ethiopia, Gabon, Gambia, Ghana, Guinea, Libya, Madagascar, Malawi, Mali, Mauritania, Morocco, Mozambique, Namibia, Niger, Nigeria, Senegal, Sierra Leone, Somalia, South Africa, Sudan, Tanzania, Togo, Uganda, Zambia, and Zimbabwe⁴².

³⁹ WISE Uranium Project website (Issues at Operating Uranium Mines and Mills – Africa), April 2014: <http://www.wise-uranium.org/umopafr.html>.

⁴⁰ WISE Uranium Project website (Issues at Operating Uranium Mines and Mills – Niger), April 2014: <http://www.wise-uranium.org/umopne.html>.

⁴¹ CRIIRAD mission to Namibia with Earthlife Namibia. <https://www.youtube.com/watch?v=sQvNEJu7qTU>.

⁴² WISE Uranium Project website (New Uranium Mining Projects – Africa), April 2014: <http://www.wise-uranium.org/upafr.html>.



The indication is that almost all countries in Africa have the potential (in terms of geology and corporate interest) to initiate uranium mining in their territory. Large foreign uranium mining companies are interested in African countries because many of them lack strong or well developed regulations related to mining. As a result, companies are attracted to conditions that offer numerous means and opportunities to exploit local conditions in the pursuit of maximum profit.

Box 3 Case study: Rössing, Namibia – radioactive dust and lack of water

Since 1976, uranium has been mined in the Rössing mine. Surface mining requires blasting works which lead to the spread of radioactive arsenic dust in the surrounding area. The same effect is caused by sedimentation ponds (Wallner & Stein 2012, 12).

For a country as dry as Namibia however, the most urgent problem is the enormous amount of water consumed for ore processing. Water is tapping from the episodic water bodies of the Khan, Swakop and Kuiseb Rivers. This exploitation of groundwater has far-reaching impacts on local flora and fauna. Among the most affected by lower water levels of the Kuiseb river basin is the Toopnar community; as is disturbing their traditional agricultural practices.

The government of Namibia has ignored their protests and refuses to negotiate with their chiefs (Wallner and Stein, 2012). As British economic analyst Roger Murray explained at a conference on uranium mining in Namibia: "What is attractive about Namibia is next to the political stability the "relatively un-bureaucratic granting of prospecting and mining licenses" (Wallner and Stein, 2012:12).

A1.4 North America

In **Canada**, uranium ores first came to public attention in the early 1930s. Exploration for uranium began in earnest in 1942, in response to a demand for military purposes. In 1959, 23 uranium mines and 19 treatment plants were in operation. In response to the development of civil nuclear power, uranium exploration was revived in the 1970s, with the focus on northern Saskatchewan's Athabasca Basin.

For many years, Canada was the largest exporter of uranium ore in the world. It has been a major world producer since demand for uranium developed⁴³.

AREVA's Cluff Lake (Canada) mine is now closed, and is being decommissioned.

In 1947 Canada lifted the ban on private uranium mining, and the industry boomed through the 1950s. Production peaked in 1959, when 23 mines in five different districts made Canada the number-one uranium exporter. By 1963, seven mines were left in operation, a number that shrank to only three in 1972.

Canada has made a transition from second-generation uranium mines (started in 1975-83) to new high-grade ones, all in northern Saskatchewan, making its uranium mining operations among the most advanced in the world.

Cameco operates the McArthur River mine (the largest in the world), which started production at the end of 1999, and the Rabbit Lake mine. AREVA Resources operates the McClean Lake mine which commenced operation in 1999.

⁴³ Wikipedia website (Uranium mining in Canada), April 2014:
http://en.wikipedia.org/wiki/Uranium_mining_in_Canada.



In 2008 seepage from the Rabbit Lake mill was discovered when a contract worker noticed a pool of uranium-tainted ice at an outdoor worksite adjacent to the facility. After an investigation into the spill, the company found a liquid used for processing uranium was leaking through certain areas of the mill floor⁴⁴. Effluents from the Rabbit Lake mine have caused a sharp increase in uranium loads in sediments of Wollaston Lake's Hidden Bay, which have continued to increase since 2000.

A key problem related to mining in Canada is employment. Only low ranking positions are accessible to local workers, who are forced to take lower paying positions characterised by unfavourable, and even hazardous working conditions. The Cigar Lake mine for example is a 450 m deep underground mine that uses ground freezing and high-pressure water jets to excavate ore. A major flood in 2006 and another in 2008 set the project back several years and pushed costs up by 300%.

In the 1950s, the **USA** carried out a great deal of uranium mining, promoted by federal subsidies. In 1980 there were over 250 mines in operation. This number dropped to 50 in 1984 and had steadily declined until 2003, when only two small operations were running.

The late 1940s and early 1950s saw a boom in uranium mining in the western United States. The United States was the world's leading producer of uranium from 1953 until 1980.⁴⁵ Production was nationwide, with operations in New Mexico, Wyoming, Colorado, Utah, Texas, Arizona, Florida, Washington, and South Dakota. The collapse of uranium prices caused all conventional mining to cease, with the last open pit (Shirley Basin, Wyoming) shutting down in 1992.

In the US, uranium mining affected a large number of Native American nations, including the Laguna, Navajo, Zuni, Southern Ute, Ute Mountain, Hope, Acoma and other Pueblo cultures. Many of these people worked in the mines, mills and processing plants of New Mexico, Arizona, Utah and Colorado. These workers were not only poorly paid, they were seldom informed of the dangers. Nor were they given appropriate protective gear. The government, mine owners, scientific, and health communities were all aware of the hazards of working with radioactive materials at this time. These labourers were both exposed to and brought home large amounts of radiation in the form of dust on their clothing and skin. Epidemiological studies of the families of these workers have shown increased incidents of radiation-induced cancers, miscarriages, cleft palates and other birth defects. The extent of these genetic effects on indigenous populations and the extent of DNA damage is still not fully understood.

In 2003 rising uranium prices increased interest in mining again.

⁴⁴ WISE Uranium Project website (Issues at Operating Uranium Mines and Mills – Canada), April 2014: <http://www.wise-uranium.org/umopcdn.html>.

⁴⁵ Wikipedia website (Uranium mining in the United States), April 2014: http://en.wikipedia.org/wiki/Uranium_mining_in_the_United_States.



By 2008, 16 mines (10 underground and 5 ISL) operated for at least part of the year in the USA. These included the Smith Ranch-Highland mine and Christianes Ranch mine (Wyoming), the Crow Butte mine (Nebraska), the Alta Mesa mine (Texas) and mines on the Colorado Plateau and Henry Mountains in Utah.

In 2013, production came from one conventional uranium mill in Utah, and six in-situ leach operations: three in Wyoming, two in Texas, and one in Nebraska. The plants in Wyoming provided 81% of the nation's uranium production.

There were also incidents in mines and processing facilities in the United States, including leaks in pipeline, damage to a pond liner, leaking of contaminated water, excessive radon emissions, and license violations.⁴⁶

In the USA, several projects are under development, though some projects and mines have been put on standby pending market improvements.

Box 4 Case study: La Sal Mines Complex (Denison), Utah, USA

In 2011 hazardous conditions underground were discovered, similar to previously identified conditions that had resulted in partial mine closure. Among these were hazardous ground conditions related to scaling and support (the same type of conditions that caused a fatal accident in May 2010) and a lack of protection for workers exposed to high radon daughter concentrations. Despite these issues, Denison Mines Corporation began operating the La Sal mine in 2011, without an updated Plan of Operations and Environmental Assessment, and without a modified Approval Order from the Utah Division of Air Quality.

A1.5 South America

Uranium mining has been present in Central and South America, but not in such a large scale as that of North America, Europe or Asia. In **Mexico** there was uranium mine exploration in Peña Blanca, Chihuahua, but the mine is currently closed (Rojas, 1989). Currently, only two mines are operating (Argentina and Brazil), but a great number of countries are looking for new economic opportunities and see uranium mining as one of them. For this reason uranium prospecting and exploration is being performed in most countries of the continent. Uranium mining will probably start in some of them as we now explore below.

There is one operational mine in **Argentina** – the Sierra Pintada/San Rafael Uranium Mine, and one in **Brazil** – the Lagoa Real/Caetité mine, in Bahia⁴⁷.

An issue was exposed in 2012, from San Rafael in **Argentina**, where discharges from a wastewater dam with high concentrations in uranium, radium and other highly dangerous substances, including pathogens, flowed directly into the El Tigre Creek and then into the Diamante River. From 2006 onwards a number of protests was held against the reopening of the Sierra Pintada mine.

⁴⁶ WISE Uranium Project website (Issues at Operating Uranium Mines and Mills – USA), April 2014: <http://www.wise-uranium.org/umopusa.html>.

⁴⁷ WISE Uranium Project website (Uranium Mine Ownership – South/Central America), April 2014: <http://www.wise-uranium.org/uosam.html#SANRAF>.



In **Argentina**, 8 uranium mines have been closed, and one in **Brazil**. Decommissioning projects relate to waste rock, heap leaching waste and mill tailings⁴⁸. In 2010, a team of journalists published an exhaustive investigation on open pit mining in **Argentina**. They verified that there are at least 75 abandoned mines (not just uranium mines) across the country, which are ignored by the national government. There are no registries, or official maps nor data, but people are living at these sites⁴⁹.

In the former Pocos de Caldas uranium mine in Minas Gerais, **Brazil**, a study showed in 2012 that water treatment needs improvement due to high uranium concentrations, high manganese values and low average pH values. A number of accidents and other issues are known to have occurred at the Caetité mine in **Brazil**. These include leakages from its uranium mill, spills of uranium ore concentrate at the mill, negative impacts of the mine on groundwater, and a guard falling into a uranium pond. In **Brazil**, there are plans to open another mine in the Ceara region, but these plans face protests and opposition from Catholic organizations, notably Caritas, and the *Comissão Pastoral da Terra* (CPT)⁵⁰.

The Blue Sky Uranium Corp. of Canada, together with an Argentinean partner, in 2012 announced an exploration program in the Rio Negro and Chubut provinces of **Argentina**. In the province of Jujuy (Argentina) there have been protests and court appeals against uranium exploration at the UNESCO World Heritage site of Quebrada de Humahuaca, and also in other areas.

Uranium prospecting and exploration are also underway in **Bolivia, Chile, Colombia, Ecuador, Guatemala, Guyana, Mexico, Paraguay, Peru, Uruguay, and Venezuela**.

Box 5 Case study: Lagoa Real /Caetité mine, Bahia, Brazil

In April 2000, an estimated 5,000 cubic metres of uranium-bearing leaching liquid leaked from a collection pond at the heap leaching facility of the mine. The pond liner, consisting of an HDPE membrane based on a compacted clay layer, had leaked.

The event was made public only on July 11th, 2000, when nine plant workers informed the state attorney of Caetité. In a separate incident The Miners' Union revealed in 2013 that the mining company, Nuclear Industries of Brazil (INB) had managed to hide an accident at a large storage tank of the uranium concentrate production system in which radioactive liquid had been leaking into the soil for more than one month. After that, another leakage was detected in the final product area of the mill. In October 2012, around 100 kilograms of uranium ore concentrate spilled in the packaging area of the mill. Similar accident happened also in 2010. INB, the owner of the mine, had been fined in 2009, for not immediately reporting a spill of organic solvent containing uranium.

Hiding or not reporting about accidents in the facility happened more than once and is speaking for itself of bad practice regarding the information channelling and safety procedures.

⁴⁸ WISE Uranium Project website (Decommissioning Data – South America), April 2014: <http://www.wise-uranium.org/uddsam.html>.

⁴⁹ WISE Uranium Project website (Decommissioning Projects – South America), April 2014: <http://www.wise-uranium.org/udsam.html>.

⁵⁰ WISE Uranium Project website (New Uranium Mining Projects – South/Central America), April 2014: <http://www.wise-uranium.org/upsam.html>.

A1.6 Australia

Australia has the world's largest uranium reserves, 24% of the planet's known reserves. The majority of these are located in South Australia with other important deposits in Queensland, Western Australia and Northern Territory.

Uranium was mined at Radium Hill from 1906, but serious uranium exploration started in 1944 after requests from the United States and United Kingdom. By 1964, production had mostly ended due to depleted reserves. A second wave of exploration activity in the late 1960s occurred with the development of nuclear energy for electricity production⁵¹.

There are four closed or depleted mines: Radium Hill, the Nabarlek Uranium Mine, the Rum Jungle Mine (from 1954) and the Mary Kathleen Mine (from 1954). There are also five other sites related to uranium mining.

Mary Kathleen closed in 1982 becoming Australia's first major uranium mine site rehabilitation project. This was completed in 1985. A similar rehabilitation project at Rum Jungle also took place in the 1980s. In 2013 there were reports that the Mary Kathleen mine was leaking radioactive water from the site, 30 years after production had stopped⁵².

At the Lake Way uranium mine radiation levels more than 100 times above normal background readings were recorded, despite the fact that it had been "cleaned" a decade ago.

There are currently **four operating** uranium mines in Australia (Olympic Dam, Ranger, Beverly and Honeymoon). The Olympic Dam, the world's largest known uranium deposit, also mines copper, gold, and silver, and has reserves of global significance. The Ranger Mine is surrounded by a national park, as the mine area was not included in the original listing of the park.

The Olympic Dam mine uses 35 million litres of Great Artesian Basin water each day, making it the largest industrial user of underground water in the southern hemisphere. Water is pumped along an underground pipeline from two bore fields which are located 110 km and 200 km to the north of the mine. The salty bore water requires desalination before it is used. The high use of artesian water threatens areas of high ecological significance. In particular, the pumping of water from the bore fields has been linked to observation of reductions in flow or drying out in nearby mound springs, which are the only permanent source of water in the arid interior of South Australia⁵³.

⁵¹ Wikipedia website (Uranium mining in Australia), April 2014:
http://en.wikipedia.org/wiki/Uranium_mining_in_Australia.

⁵² WISE Uranium Project website (Decommissioning Projects – Australia), April 2014:
<http://www.wise-uranium.org/udaus.html>.

⁵³ Wikipedia website (Olympic Dam, South Australia), April 2014:
http://en.wikipedia.org/wiki/Olympic_Dam,_South_Australia.



In July 2012, more than 400 people protested against the mine expansion, arguing that the company and the government are putting short-term economic gain ahead of environmental and health concerns.

Apart from that case, Environment Australia (an agency of the Government of Australia) has documented over 200 environmental incidents since 1979 in the case of the Ranger uranium mine. They relate to radiological exposure of employees, radiological contamination of drinking water supply, and more⁵⁴.

Many new mines are being proposed. There are at least 7 known deposits for possible future mine sites. One of them has already been approved for development (Four Mile). One of the more controversial proposals is the Jabiluka mine, which is surrounded by the World Heritage listed Kakadu National Park. State governments have approved mine development in Western Australia and Queensland.

There are no nuclear power generation plants operating in Australia and therefore no domestic demand. As of 2013, uranium prices were very low and for that reason companies are placing new projects on hold until market prices rise again. Most projects would need at least five years to proceed to production.

Box 6 Case study: Ranger Mine – Australia

The Ranger Mine in Australia is located directly in the Kakadu National park. Again and again conflicts arise with the aborigines living in the neighbourhood of the mine. The local Mirrar aborigines have been protesting for years against the poor information policy of the mine operator ERA (Energy Resources of Australia) and complain about a lack of respect for them and their living space (Wallner & Stein 2012, 12). Since 1979 the Australian Ministry of the Environment (DSEWPaC) registered over 150 violations of the environmental directives. In combination with the Monsoon rainfalls and the inadequate protection measures the tailing ponds are flooded and the radioactive water contaminates the area (Wallner & Stein 2012).

In December 2009 a badly constructed dam broke and 6 million liters of contaminated water were discharged into the Gulungul Creek. The company ERA admitted the construction deficiencies and promised improvements. However, in April 2010 another incident occurred at Magela Creek in the middle of the national park, a living area of the aborigines, where radiation exposure increased (Wallner & Stein 2012).

⁵⁴ Wikipedia website (Ranger Uranium Mine), April 2014:
http://en.wikipedia.org/wiki/Ranger_Uranium_Mine.

References of Appendix

Rojas, J. A. 1989. Desarrollo nuclear de México, Universidad Nacional Autónoma de México, México D.F.

UNECE. 2012. Second Environmental Performance Review of Tajikistan highlights lack of access to clean water and sanitation and need for improved waste management.
<http://www.unece.org/index.php?id=31804>.

Wallner, A., Stein, P. 2012. Uranium mining in and for Europe.
http://www.ecology.at/files/pr801_2.pdf.

Wikipedia website (List of uranium projects), April 2014:
http://en.wikipedia.org/wiki/List_of_uranium_projects

Wikipedia website (Olympic Dam, South Australia), April 2014:
http://en.wikipedia.org/wiki/Olympic_Dam,_South_Australia

Wikipedia website (Ranger Uranium Mine), April 2014:
http://en.wikipedia.org/wiki/Ranger_Uranium_Mine

Wikipedia website (Uranium mining by country), April 2014:
http://en.wikipedia.org/wiki/Uranium_mining_by_country#Australia

Wikipedia website (Uranium mining in Australia), April 2014:
http://en.wikipedia.org/wiki/Uranium_mining_in_Australia

Wikipedia website (Uranium mining in Canada), April 2014:
http://en.wikipedia.org/wiki/Uranium_mining_in_Canada

Wikipedia website (Uranium mining in the United States), April 2014:
http://en.wikipedia.org/wiki/Uranium_mining_in_the_United_States

WISE Uranium Project website (Decommissioning Data – Africa), April 2014: <http://www.wise-uranium.org/uddafr.html>

WISE Uranium Project website (Decommissioning Data – Asia), April 2014: <http://www.wise-uranium.org/uddasi.html#MN>

WISE Uranium Project website (Decommissioning Data – Europe), April 2014: <http://www.wise-uranium.org/uddeur.html>

WISE Uranium Project website (Decommissioning Data – South America), April 2014:
<http://www.wise-uranium.org/uddsam.html>

WISE Uranium Project website (Decommissioning Projects – Africa), April 2014: <http://www.wise-uranium.org/udafr.html>

WISE Uranium Project website (Decommissioning Projects – Asia), April 2014: <http://www.wise-uranium.org/udasi.html>

WISE Uranium Project website (Decommissioning Projects – Australia), April 2014:
<http://www.wise-uranium.org/udaus.html>

WISE Uranium Project website (Decommissioning Projects – South Africa), April 2014: <http://www.wise-uranium.org/udza.html>

WISE Uranium Project website (Decommissioning Projects – South America), April 2014: <http://www.wise-uranium.org/udsam.html>

WISE Uranium Project website (Issues at Operating Uranium Mines and Mills – Africa), April 2014: <http://www.wise-uranium.org/umopafr.html>

WISE Uranium Project website (Issues at Operating Uranium Mines and Mills – Asia), April 2014: <http://www.wise-uranium.org/umopasi.html#IN>

WISE Uranium Project website (Issues at Operating Uranium Mines and Mills – Canada), April 2014: <http://www.wise-uranium.org/umopcdn.html>

WISE Uranium Project website (Issues at Operating Uranium Mines and Mills – Niger), April 2014: <http://www.wise-uranium.org/umopne.html>

WISE Uranium Project website (Issues at Operating Uranium Mines and Mills – Other Countries), April 2014: <http://www.wise-uranium.org/umop.html#EUR>

WISE Uranium Project website (Issues at Operating Uranium Mines and Mills – USA), April 2014: <http://www.wise-uranium.org/umopusa.html>

WISE Uranium Project website (Issues at Rössing Uranium Mine, Namibia), April 2014: <http://www.wise-uranium.org/umopro.html>

WISE Uranium Project website (New Uranium Mining Projects – Africa), April 2014: <http://www.wise-uranium.org/upafr.html>

WISE Uranium Project website (New Uranium Mining Projects – Asia), April 2014: <http://www.wise-uranium.org/upasi.html>

WISE Uranium Project website (New Uranium Mining Projects – Europe), April 2014: <http://www.wise-uranium.org/upeur.html>

WISE Uranium Project website (New Uranium Mining Projects – South/Central America), April 2014: <http://www.wise-uranium.org/upsam.html>

WISE Uranium Project website (Uranium Mine Ownership – Asia), April 2014: <http://www.wise-uranium.org/uoasi.html#JP>

WISE Uranium Project website (Uranium Mine Ownership – China), April 2014: <http://www.wise-uranium.org/uocn.html>

WISE Uranium Project website (Uranium Mine Ownership – India), April 2014: <http://www.wise-uranium.org/uoin.html>

WISE Uranium Project website (Uranium Mine Ownership – South/Central America), April 2014: <http://www.wise-uranium.org/uosam.html#SANRAF>

World Nuclear Association website (Uranium Mining Overview), April 2014: <http://www.world-nuclear.org/info/nuclear-fuel-cycle/mining-of-uranium/uranium-mining-overview/>

uranium
mining
nuclear fuel
radioprotection
pollution
dose
recommendations
companies
Niger
France
Namibia
impacts
Malawi
environment
Brazil
milling
workers
health
communities
Bulgaria