Journal of Radiological Protection

Official journal of the Society for Radiological Protection

PAPER • OPEN ACCESS

Remediation of the uranium industry in the Czech Republic: regulation aspects and main technologies

To cite this article: Miroslav Jurda and Miloslav Němec 2022 *J. Radiol. Prot.* **42** 010504

IOP Publishing J. Radiol. Prot. 42 (2022) 010504 https://doi.org/10.1088/1361-6498/ac0d40

Journal of Radiological Protection

CrossMark

OPEN ACCESS

RECEIVED
29 January 2021

REVISED
30 May 2021

ACCEPTED FOR PUBLICATION
21 June 2021

PUBLISHED
17 January 2022

PAPER

Remediation of the uranium industry in the Czech Republic: regulation aspects and main technologies

Miroslav Jurda and Miloslav Němec*

State Office for Nuclear Safety, Prague, Czech Republic

* Author to whom any correspondence should be addressed.

E-mail: miloslav.nemec@sujb.cz

Keywords: remediations, regulations, uranium industry, Czech Republic

Abstract

There is a long history of uranium mining and milling in what is now the Czech Republic, with the main exploitation beginning in the second half of the 19th century. The greatest expansion was during the Cold War, which was then reduced after political changes in eastern Europe in the 1990s. Thereafter, almost all uranium work was stopped, the mines and mills were closed, and plans for decommissioning and remediation of sites and facilities were initiated. The paper describes the application of the regulatory framework for the decommissioning and remediation of the uranium waste sites and facilities in the Czech Republic, illustrated by examples of deep and surface mining, *in-situ* leaching sites, and ore processing facilities. It builds on information provided as a case study for the Nuclear Energy Agency's Expert Group on Legacy Management. Some practical experience and lessons learned are presented. The sharing of the lessons and experience is noted as an important mechanism for avoiding the creation of future legacies.

1. History of uranium mining and milling in the Czech Republic

The Czech Republic has a long history of uranium mining and milling, with the main period of exploitation beginning in the second half of the 19th century. Wide-scale uranium mining started in the 1890s on an industrial scale in and near the town of Jachymov, especially to produce the colours requested by glass and porcelain manufacturers. In the early 1900s, Marie Curie discovered radium within the uranium at the Jachymov mines, and until World War I this was the only known source of radium production in the world. Pre–Cold-War uranium production was estimated to be around 1000 tons, but starting from 1947, the Czech Republic produced uranium for the Soviet Union.

The greatest expansion was during the Cold War, first to small deposits in western Bohemia (Jáchymov, Slavkov, Chodov). This was followed by a large deposit in the western part of Pribram and large deposits in Moravia Rozna and Olsi-Drahonin. A large-capacity Mydlovary treatment plant was built for these deposits with the intention of being a central treatment plant, but with a further increase in the mined volume, an ore treatment plant was also built directly at the Rozna and Príbram mining plants. In the 1970s, mining began to develop rapidly in the North Bohemian region of Straz pod Ralskem, both by conventional deep mining and *in situ* leaching. After the social changes in 1989, it was decided that the uranium industry was slowing down very quickly. By 1995, mining was terminated in all areas except the Rozna plant.

This paper briefly outlines Czech uranium mining and ore processing history and then describes the regulation of remediation and decommissioning of facilities at the underground mine Rozna, in the Dolní Rozinka deposit, the surface compound uranium mine Hamr I, the chemical mill in Straz pod Ralskem, and the *in-situ* leaching (ISL) deposit in Straz pod Ralskem. It builds on information provided as a case study for the Nuclear Energy Agency's Expert Group on Legacy Management reported in NEA (2019).

Including the early mining sites such as Jachymov, Horní Slavkov, and Pribram, the Czech Republic produced 110 000 tons of uranium from 64 uranium deposits. The main former mining sites are shown in figure 1 and the uranium production in individual areas is shown in figure 2. The total uranium production in the Czech Republic by year is shown in figure 3.

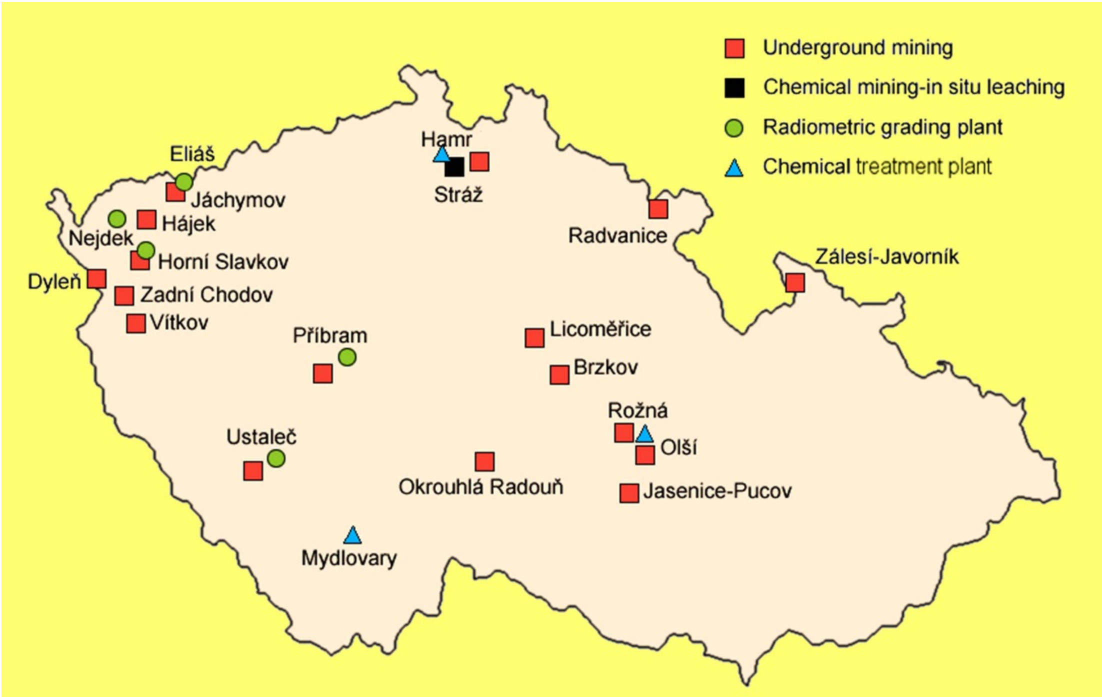


Figure 1. Sites of uranium extraction and working.

Mining area	Exploitation duration	% of total CR production
Pribram	1949 - 1992	36,5
West Moravia - Rozna,Olsi-Drahonin	1957 - 2017	19,2
North Bohemia - Straz pod Ralskem, Hamr	mines 1974 - 1993	10,3
	ISL 1969 – 1996 since 1996 uranium acquired by ISL in frame of remediation	15,1
West Bohemia	1954 - 1992	9,0
Jachymov	1945 - 1962	6,2
Horni Slavkov	1949 - 1963	2,2
Geological survey sites	1955 - 1990	1,5

CR means Czechoslovakia until 1992 and since 1993 the Czech Republic

Figure 2. Uranium production by area.

2. Regulatory framework

The regulatory authority in the area of peaceful utilisation of nuclear energy and ionizing radiation is the State Office for Nuclear Safety (SÚJB), established on 1st January 1993 as a direct successor of the Czechoslovak Atomic Energy Commission. The regulatory framework for radiation protection and nuclear

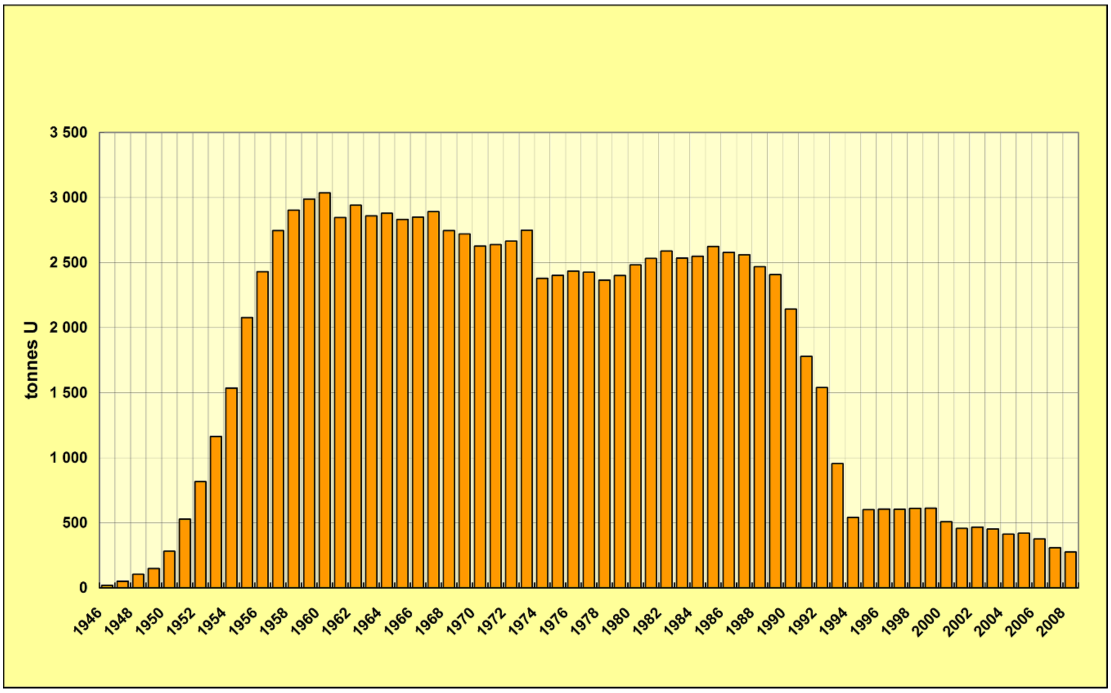


Figure 3. Uranium production by year (production U for years 2010–2017 was 1000 t and from 2018, approximately 15 tons of remediation technologies per year).

safety in the Czech Republic is built on international standards, recommendations, and guidance, notably the international Basic Safety Standards (IAEA 2011). The updated nuclear law of the Czech Republic entered into force on 1st January 2017 (Parliament of the Czech Republic 2016), implementing Decrees, e.g.:

- No. 422/2016 Coll. on radiation protection and security of a radioactive source,
- No. 377/2016 Coll. on the requirements for the safe management of radioactive waste and on the decommissioning of nuclear installations of category III or IV workplaces, and
- No. 360/2016 Coll. on radiation situation monitoring.

Activity involving radiation means an activity in which a natural radionuclide is used in the context of planned exposure situations for its radioactive, fissile, or fertile properties, including activity related to acquiring of radioactive minerals.

Activities related to acquiring of radioactive minerals are taken to include:

(a) exploration of deposits of radioactive minerals at the stage of detailed and mining exploration,
(b) mining of radioactive minerals,
(c) carriage of radioactive minerals,
(d) treatment and processing of radioactive minerals,
(e) management of uranium concentrate,
(f) accumulation of extractive waste in tips and sludge lagoons that were created by mining activities during acquiring of radioactive minerals,
(g) operation of decontamination stations of mining works in operation,
(h) treatment of industrial waste water from workplaces that are part of facilities for the treatment of radioactive minerals,
(i) mining of radioactive material by chemical leaching,
(j) processing of leaching solutions used for mining of radioactive mineral,
(k) treatment of mine water from closed radioactive mineral deposits, and
(l) remediation work.

Concerning the decommissioning and remediation of old radiation sites and facilities, radiation liabilities are exposure situations existing as a result of other circumstances, e.g., mining a milling site where operations finished before 1997, the year that the first 'Atomic Law' in the Czech Republic came into force. According to this:

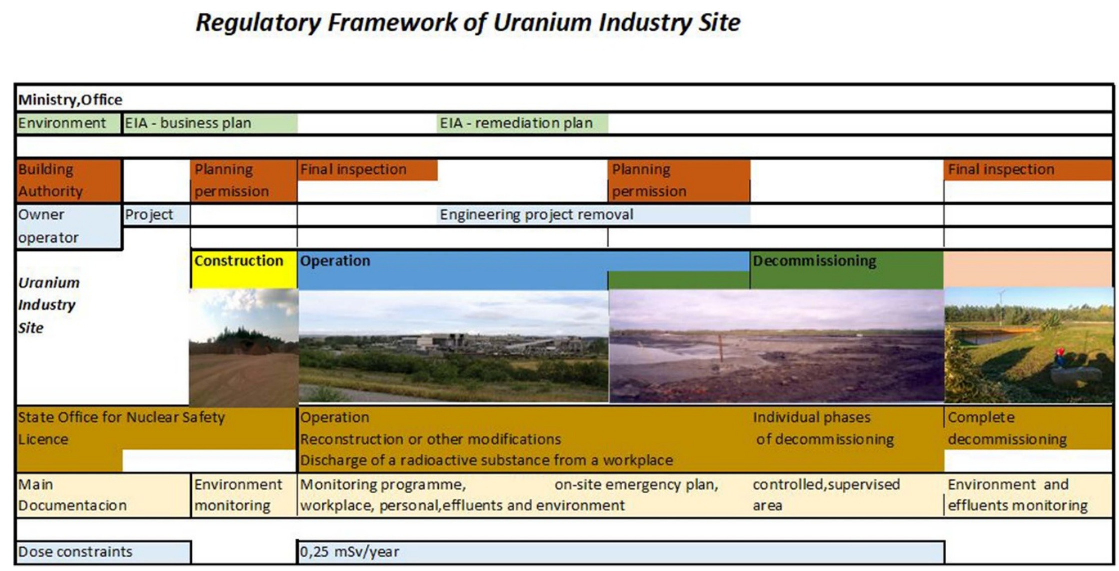


Figure 4. Regulatory framework of uranium industry site.

(a) The SUJB may, by means of a general measure, take measures to regulate exposure in existing exposure situations resulting from or a discontinued activity in a planned exposure situation (hereinafter 'lasting exposure'), where a significant increase in health detriment to members of the public following exposure could occur unless an intervention is made.

(b) Lasting exposure shall be regulated by the SUJB in accordance with paragraph 1 by fixing reference levels for the average effective dose to the representative person per calendar year within the range of 1–20 mSv. Radioactive contamination of foodstuffs, animal feedstuffs, or water shall also be regulated by the SUJB by fixing maximum permissible levels of radioactive contamination for the relevant existing exposure situation.

Figure 4 describes which ministry or government agency issues which permits before and during the life cycle of an on-site uranium industry facility, and which permits are required from the SUJB at each stage.

- The ministry of the environment assesses the business plan within the EIA before the start of construction and then before the start of remediation.
- The building authority issues building permits and final inspection for construction and remediation.
- The owner is responsible for the elaboration of a construction project and engineering project of removal.
- The state office for nuclear safety issues permits for individual phases of decommissioning and complete decommissioning.

The dose constraint is the same for all phases.

> First, the organisation must develop an engineering project of removal, which must go through EIA management. Followed by a request for a building permit for the construction and official request for authorisation at individual phases of decommissioning to SUJB. Upon completion of remediation is issued a certificate of occupancy building authority and decision about complete decommissioning to SÚJB.

EIA Process:

- within the EIA procedures are applied the comments of the various responsible authorities.

Issues of permits:

- within the construction management are applied the comments of the various responsible authorities.

State Enterprise DIAMO, located in Straz pod Ralskem, is the organisation dealing with elimination of consequences of uranium ore mining activities. The attenuation and remediation programme complies with

Figure 5. View of the Hamr I mine.

the state policy for progressive improvement of the quality of environment and elimination of old environmental burdens with state funding.

The remediation programme consists of implementation of an attenuation programme for the uranium industry with elimination of consequences of survey, mining, treatment, and processing of uranium from uranium deposits. This programme commenced in 1989.

The concept of the performed liquidation and remediation works is based on individual resolutions of the Government of the Czech Republic; for individual sites, the concept is described in the discussion of Engineering Projects of Disposal and Remediation. Removal of consequences of survey, mining, and processing of the above-mentioned raw materials is performed in compliance with strict requirements for environmental protection and development.

3. Uranium site description and progress with decommissioning and remediation

3.1. Underground mine Hamr I and central decontamination station—surface compound decommissioning

Underground mine Hamr I was in operation from 1978–2001. During operation, 9557 million t ore were mined and uranium production was 11 740 t. Decommissioning took place in the years 2014–2015. The central decontamination station was in operation 1987–2001. Decommissioning and remediation work at the Hamr I mine (figure 5) was undertaken by the stock company ENERGIE, which had experience with non-uranium mining activities. The whole programme was under licensing and supervision of SÚJB.

The following results and conclusions are the most important.

Two thousand people worked in this surface compound (figure 6) when it was in operation and only 178 workers (168 radiation workers) participated in decommissioning procedures, which were completed relatively quickly, in 16 months. Costs were 25 million euros.

Work resulted in 166 000 t of material with radioactive contamination, 2400 t of material with combined radioactive and oil substance contamination, and 109 000 t of material without any contamination. The latter can be used for tailings pond reclamation and remediation.

Activity concentration in materials with radioactive contamination (parts of technology, buildings, contaminated soil, technologic liquid residues, etc.) reached ones mg l^{-1} or mg kg^{-1} of uranium and hundreds kBq kg^{-1} of Ra^{226}.

External gamma doses were estimated from personal thermoluminescent dosemeters (TLDs) for category A radiation workers. Internal doses from radon and its progeny, and from long-lived alpha emitters,

Figure 6. Mine Hamr I surface compound decommissioning.

were estimated from workplace monitoring. Radiation workers' collective dose was 21.28 mSv, average 0.13 mSv and maximum 0.49 mSv, during the whole action. Doses during decommissioning were approximately 1/10 of doses during operation in the same workplace controlled areas. Relations between the main exposure contributors (external gamma radiation, short-lived radon daughters, and long-lived alpha emitters) were almost the same as during site operations. On this basis, radiation control was possible based on only one criterion—gamma dose rate to be lower than 0.3 μSv h^{-1}. The value 0.3 μSv h^{-1} results from risk analysis (Neznal 2010). Possible exposure pathways were analysed in this risk analysis. The terrain surface was covered with clean soil after the end of decommissioning, and external gamma radiation is the only significant exposure pathway. This target parameter was reached and use of this area in the future is without any restriction.

3.2. Chemical mill compound Stráž pod Ralskem

This chemical mill was in operation in the years 1975–2009, and processed 9.46 mil. t of uranium ore. Decommissioning took place in the years 2014–2015. Decommissioning and remediation work was undertaken by SYNER Ltd, the first experience with the uranium industry for this company. The whole programme was under licensing and supervision of SÚJB.

A total of 200 people worked in the chemical mill during operation and 50 workers (19 radiation workers A category) participated in decommissioning procedures. Decommissioning activities were completed over the same period as the surface compound of the Hamr I underground mine decommissioning. Costs were 20 million euros.

Decommissioning material contamination was similar to that at the Hamr from the surface compound. One additional contamination type was Polychlorinated biphenyls (PCBs). In total, the work resulted in 303 000 t of material with radioactive contamination, 260 t of material with combined radioactive and oil substance contamination, 10.5 t of material with combined radioactive and PCB contamination, and 72 000 t of material without any contamination. All material was used for tailings pond reclamation and remediation except for waste with PCB contamination; these materials were disposed in a special waste dump.

The most hazardous operation was demolition of the uranium concentrate dryer building, because the technology inside the tower was contaminated with yellow cake. Special anti-dust measures were necessary, see figures 7 and 8. Radiation workers inside the building wore special protection clothes and respirators.

The second greatest challenge was liquid yellow cake underground storage tank removal. The liquid yellow cake was only present in this tank. The disposal of the yellow cake storage tank took only one month and was carried out by only two workers. Work was carried out in special protective clothing and respiratory masks. Exposure was only from external gamma radiation. The effective dose during this operation was less than 0.2 mSv.

Personal doses were estimated from personal TLDs for category A radiation workers. Personal doses from radon and its progeny, and long-lived alpha emitters, were estimated from workplace monitoring. Category A radiation workers worked on decommissioning in year 2015 only, and maximum effective dose was 0.47 mSv.

Figure 7. Uranium concentrate dryer building.

Figure 8. Uranium concentrate dryer—inside the building.

Doses during decommissioning are approximately 1/10 doses in the operation in the same workplace, the controlled area 'uranium concentrate dryer building.' Proportions of the main exposure contributors (external gamma radiation, radon, and alpha emitters) were almost the same as during site operation.

It was estimated the only one criterion, gamma dose rate on the site after end of decommissioning, must be lessthen 0.3 μSv h^{-1}. The value 0.3 μSv h^{-1} results from risk analysis (Neznal 2010). This target parameter was reached, and use of this area in the future is without any restriction.

Frequency of visits by SUJB was approximately one visit monthly except during the more hazardous activities in the dryer building and underground storage tank, when from one to two visits weekly were made.

3.3. Underground mine and mill site Rozna

The Rozna facility figure 9 is located 55 km northwest of Brno, in the Vysocina Region. Uranium mining began in 1958 and a chemical processing plant and two tailings ponds began operation in 1968. There are 11 shafts and approximately 580 km of mine tunnels dug over an area of 8.76 km^2. Mining was conducted to a depth of between 950 and 1100 m underground.

Annual uranium extraction at Rozna was around 200 tons between 2000 and 2016, with around 18 370 tons of extracted material over the site exploitation. Work activities at Rozna have consisted of gradual wall slicing under a manmade ceiling, with backfill, the selective method for multi-level tunnels. There also exists

Figure 9. View of the Rozna site.

Table 1. Annual effective dose.

Working place	Year	Number of workers	Annual efective dose (mSv)		
			Average	Maximum	Collective
Mine	2020	184	0.3	1.7	58
	2019	193	0.2	1.6	45
	2000	381	9.78	34.31	3727
	1999	402	9.89	38.84	3976
Mill and tailng ponds	2020	51	0.8	1.2	41
	2019	55	0.9	2.0	51
	2000	98	4.0	10.8	391
	1999	101	4.5	9.4	460

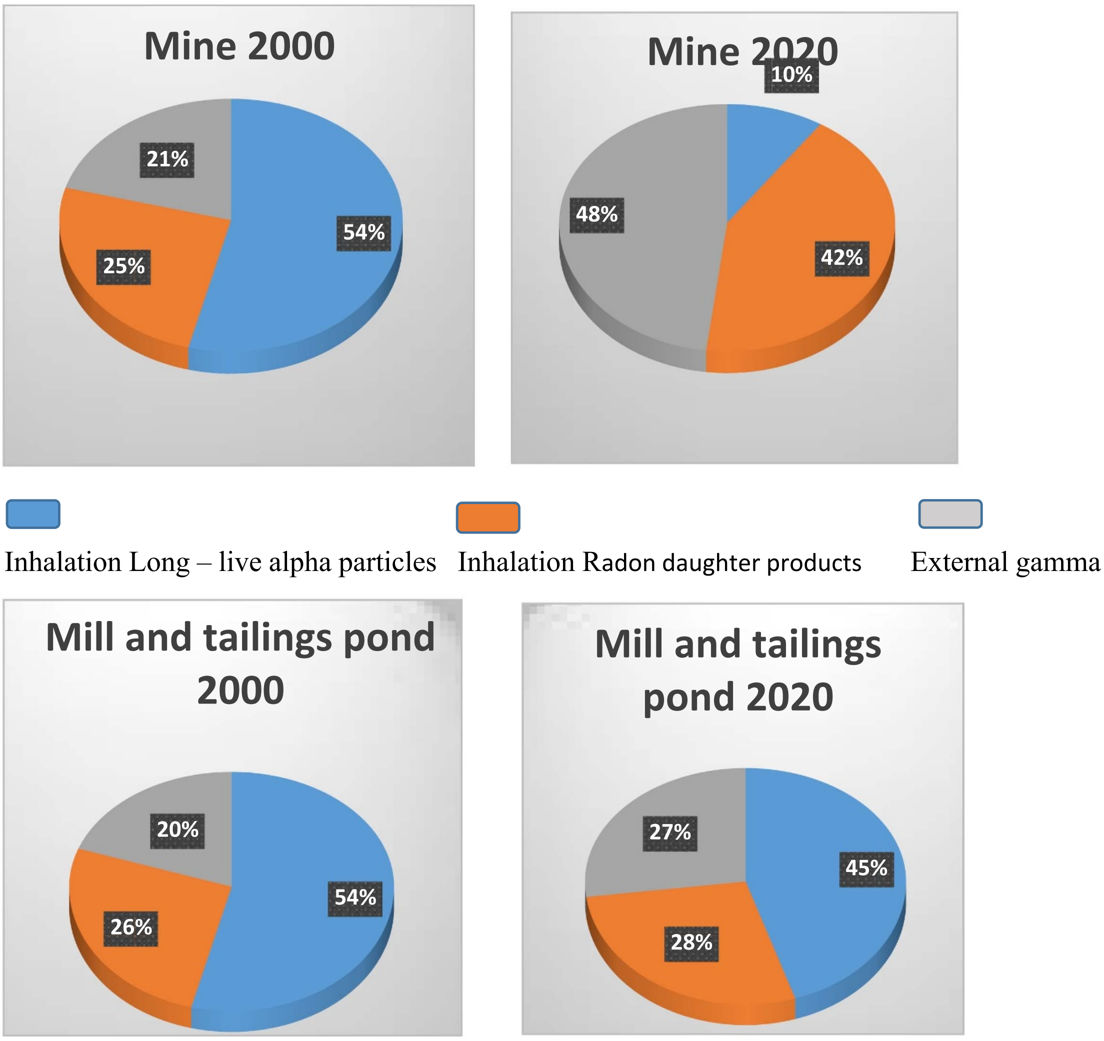
a chemical uranium ore processing plant (alkaline leaching) and storage of sludge at the tailings impoundments. The extraction of uranium ore was stopped in April 2017.

Table 1 compares the annual effective dose of mine and plant workers during mining (1999, 2000) and after mine closure (2019, 2020). Remediation started only on the tailing ponds.

Remediation of tailing ponds and unnecessary technologies and construction on the surface of the mine has been underway since 2001. Remediation of underground facilities began in 2021. Due to the location of an underground laboratory for research into the long-term storage of spent nuclear fuel (expected to end in 2034) in the underground Rozna mine and the need to ensure mine ventilation and mine water pumping throughout its operation, the end of remediation of the Rozna area is expected in 2040.

Use will be with restriction in the future.

Site decommissioning and gradual remediation are underway (including mine tunnels, dumps, the tailings ponds, unusable structures). Based on inspections by the SUJB, entrances of deserted major mines, dismantled after the completion of prospecting and/or uranium mining, are regularly monitored by the organisation that completes site remediation. Remediation works include planting of forest treesand replacement of damaged forest trees on reclaimed dumps, as well as specific fence repairs. An important part of the decommissioning and clean-up processes is the continuous monitoring of environmental impacts,



Graph 1. Effective dose per exposure pathway during operation (2000) and remediation (2020).

Table 2. Numbers of measurements in a single year.

Water	$347 \times C_{V,U}$
	$271 \times A_{V,226Ra}$
Sediment	$15 \times A_{M,238U}$
	$15 \times A_{M,226Ra}$
Vicinity	$108 \times A_{VAL}$
	$144 \times$ EOAR
	$44 \times H_x$

conditions for which are currently under review as a part of the national radiation monitoring plan controlled by the SUJB[1].

The monitoring program of the surroundings and discharges includes monitoring of uranium concentration ($C_{V,U}$), volume activity of radium ($A_{V,226Ra}$), mass activity of radium ($A_{M,226Ra}$), mass activity of uranium ($A_{M,238U}$), equivalent volume activity of radon (EOAR), dose rate of external gamma radiation (H_x), and long-term activity of a mixture of long-term emitters of uranium-radio decay series (A_{VAL}). The number of measurements in a single year are shown in table 2.

Based on these measurements, the public dose listed in table 3 was determined.

A number of conclusions have been drawn and practical implementation carried out based on a specific investigation programme for liquidation and remediation at Rozna and approved by the SUJB. Primarily, these include the construction of new separators for inner dams and the deposition of sludge under the water

[1] For a description, see www.sujb.cz/en/radiation-situation-monitoring.

Table 3. Public dose (2015).

	E_g	E_{LE}	ALE	E
		(μSv y^{-1})		
Rozna (2015) [7]	63	149	2	214

E_g—effective dose gamma external radiation
E_{LE}—effective dose radon daughters
E_{AL}—effective dose log-live alpha
E—effective dose

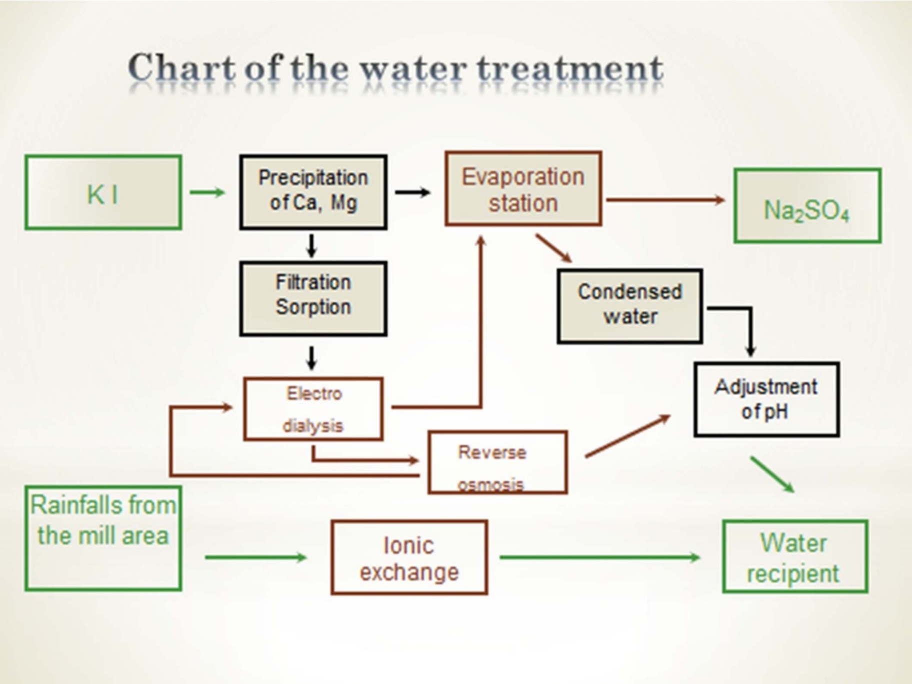


Figure 10. Improvements to tailings pond at Rozna.

level reaching the centre of the tailings pond. As a preliminary step towards technical restoration, it was recommended that methods should be considered for covering the finest tailings that have been deposited in the centre of the tailings pond, e.g., with non-sorted fresh tailings.

Composition of the water of tailing pond in table 4.

Further needs for remediation have been determined based on mathematical modelling of the tailing ponds (Technical disposal project of site Rozna—GEAM 1998). These include a reduction of overall salinity in seepage water within 50 years; reduction of uranium concentration to one third (5 mg l^{-1}); and reduction of sulphates concentration from 16 to 4 g l^{-1}. The necessary capacity for water treatment equipment is 400 000 m^3 yr^{-1}. Additionally, the central parts of the tailings pond (which is the deepest area of the pond, where fine-grained sludge is deposited) should be filled with coarse materials for better stability and better conditions for land reclamation. Figure 10 shows improvements to tailings pond Rozna and figure 11 shows an alternative cover design for the tailing ponds.

Improvements to stability of the tailings ponds are underway.

Discussions are ongoing about the method of forming the final layer of covering.

3.4. *In-situ leaching site Stráž pod Ralskem*

ISL took place at the Straz pod Ralskem from 1967 until 1996, by which 15 562 metric tons of uranium has been extracted. The mining area covered 24.1 km^2 and reached a depth of 220 m under the ground. The area of ISL is shown in figure 12 and the schematic cross section of the area of the ISL deposit is shown in figure 13. Even though ISL has stopped, uranium is still acquired as a by-product of the remediation of this deposit. Contaminated underground water is drawing in a treatment plant, and the first step is ionic exchange uranium removal. Production is few tens of tons annually.

Table 4. Composition of the water.

pH	TDS ($g\,l^{-1}$)	U ($mg\,l^{-1}$)	SO_4^{2-} ($g\,l^{-1}$)	NH_4^+ ($mg\,l^{-1}$)	NO_2^- ($mg\,l^{-1}$)	NO_3^- ($mg\,l^{-1}$)	Na^+ ($mg\,l^{-1}$)	Ca^{2+} ($mg\,l^{-1}$)	Mg^{2+} ($mg\,l^{-1}$)	Mo ($mg\,l^{-1}$)
7.97	28.8	15.3	17.9	256	75.5	1088	7255	219	108	6.0

Figure 11. Alternative cover designs for tailing ponds.

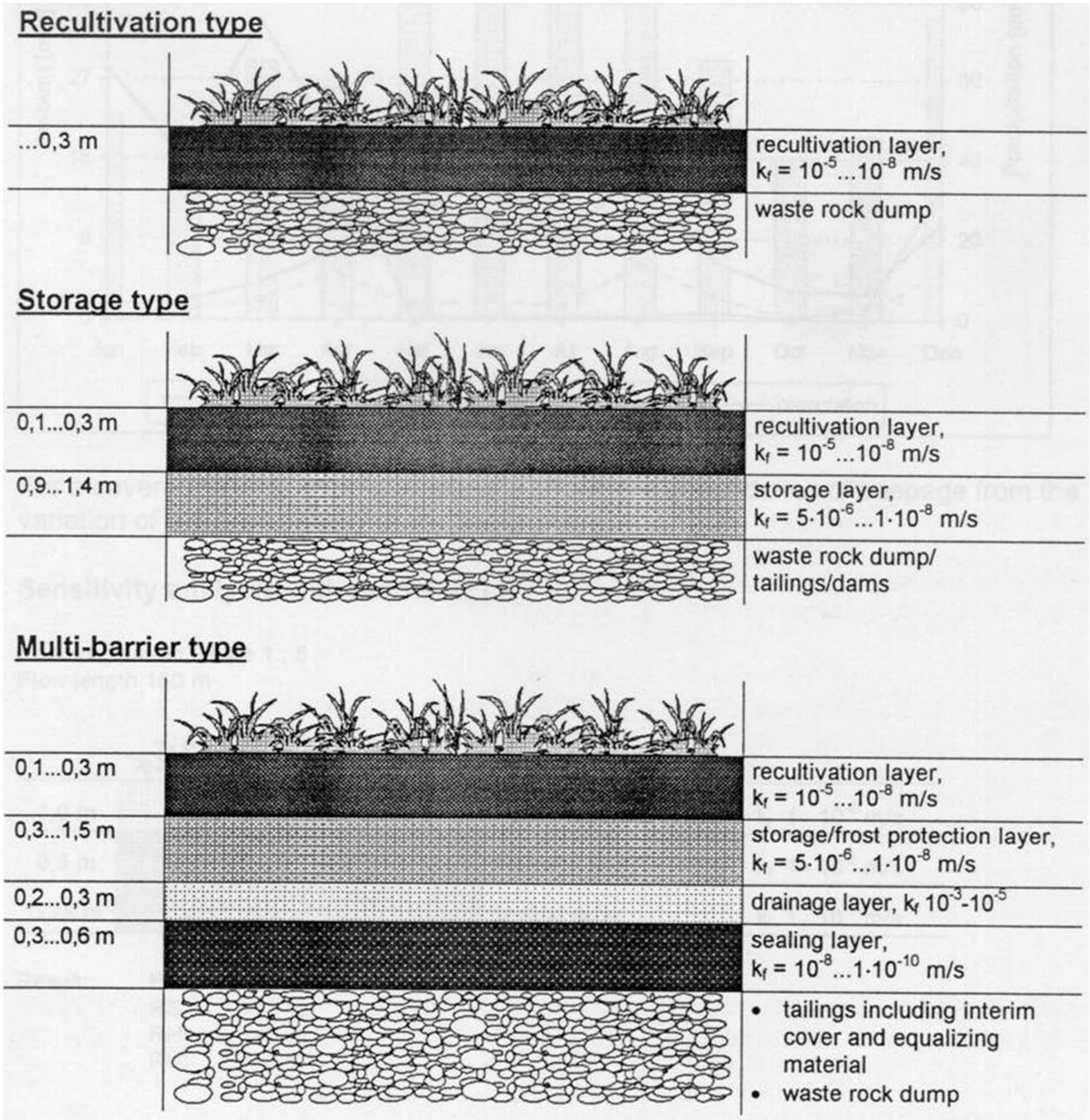


Figure 12. Alternative cover designs for tailing ponds.

More than 2200 research bore holes and almost 7700 mining bore holes have been drilled into this deposit.

Maximal occupational dose for radiation worker A category was 2.5 mSv (2015).

Effective doses for the public are in table 5.

Figure 13. View of *in-situ* leaching site Straz pod Ralskem.

Table 5. Public dose (2015).

	E_g	E_{LE}	E_{AL}	E
	(μSv y^{-1})			
Straz pod Ralskem	36	65	14	115

E_g—effective dose gamma external radiation
E_{LE}—effective dose radon daughters
E_{AL}—effective dose log-live alpha
E—effective dose

ISL involved use of acid leaching processes including the reagent H_2SO_4 and the oxidisation material HNO_3. Thirty-five leaching fields were established, covering an area of 700 hectare.

Due to chemical processing of uranium at Straz, there is approximately 186 million m^3 of contaminated groundwater at the Cenomanian aquifer and another 80 million m^3 at the Turonian aquifer, see figure 14. There are additional challenges with the rock surrounding both aquifers. The groundwater contamination at Cenomanian and Turonian leaves residual technological fluids in the rock. During mining operations, the underground was subject to 4.1 million t of H_2SO_4 (of this, 80% reacted with the ore and 800 000 t remained as H_2SO_4), as well as 312 000 t HNO_3, 112 000 t NH_3, 26 000 t HF, and 1 500 t HCl. Groundwater in the Cenomanian aquifer is contaminated with uranium 50–390 mg l^{-1}, ^{226}Ra 1.4–6 Bq l^{-1}, and ^{234}Th 960–2980 Bq l^{-1} primarily. The most important non-radioactive contaminants are ammonium, Fe and Al ions, and sulphates.

Liquidation and remediation of the extraction fields at Straz is underway, as well as a broader remediation of the mining area with an aim to remove the uranium-enriched solutions from underground water and revitalise the local environment affected by chemical mining. The remediation activities include water abstraction and treatment at both the desalination plant and the neutralisation and decontamination plant (figure 15).

The desalination technology works by evaporation followed by crystallisation, re-crystallisation (crystal sulphate of ammonium aluminate), and the removal of salts and metals at an operational capacity of 5.5 m^3 min^{-1}, the results of which are further processed into both usable and non-usable products. The clean water is released into the Ploučnice River. Activity concentrations before treatment are uranium 50–390 mg l^{-1}, ^{226}Ra 1.4–6 Bq l^{-1}. After treatment, $U < 0.010$ mg l^{-1} and Ra^{226} < 0.027 Bq l^{-1}.

Target values for remedial parameters (so-called TVRP) were set on the basis of an original risk analysis (Vencelides 2017). The TVRP was subsequently approved by the Czech authorities (Ministry of Environment, Ministry of Industry, and SUJB), with a final goal to reach TVRP by 2037. The basic TVRP

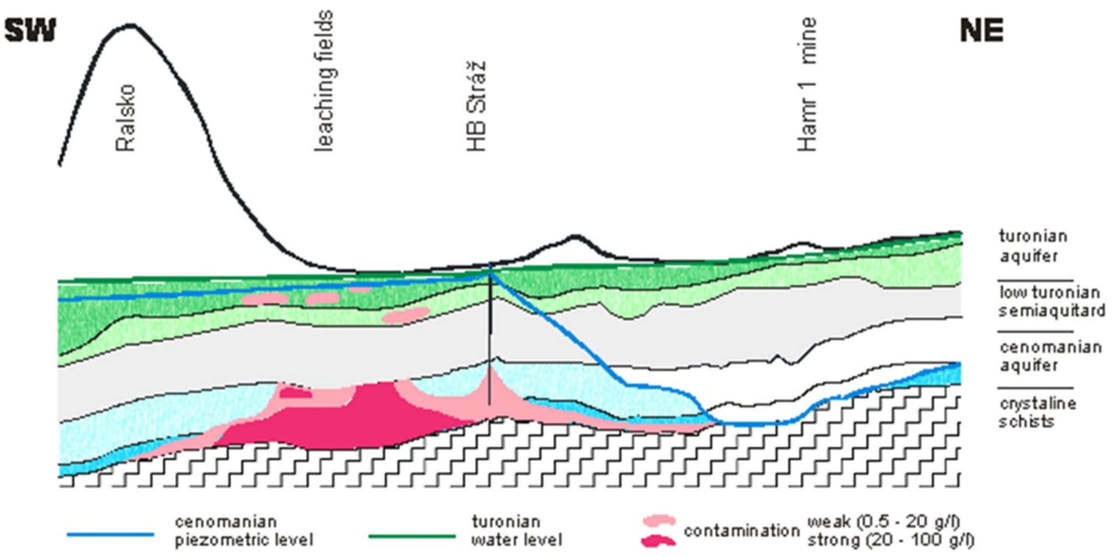


Figure 14. Station for neutralisation of acidic solutions.

Figure 15. Chart of technologies for remediation of ISL.

(in underground water and Cenomanian aquifer) is total dissolved solid 7 g l^{-1} and the others are $NH_4^+ = 80$ mg l^{-1}, Al $= 600$ mg l^{-1}, $SO_4^{2-} = 6000$ mg l^{-1}, and Fe $= 150$ mg l^{-1}.

In 2012, all necessary remedial surface technologies (neutralisation stations) were in operation and the necessary storage was secured for residual materials from technological processes. In 2014, the TVRP risk analysis was updated and the first steps of the TVRP were confirmed as completed. The Ministry of Environment then decided that this confirmation and update process will be performed every 5 years. The ultimate objective is to achieve liquidation of the ISL area and surface objects, and full landscape revitalisation by 2042. The total costs for the remediation process are expected to be on the level of 2 billion EUR.

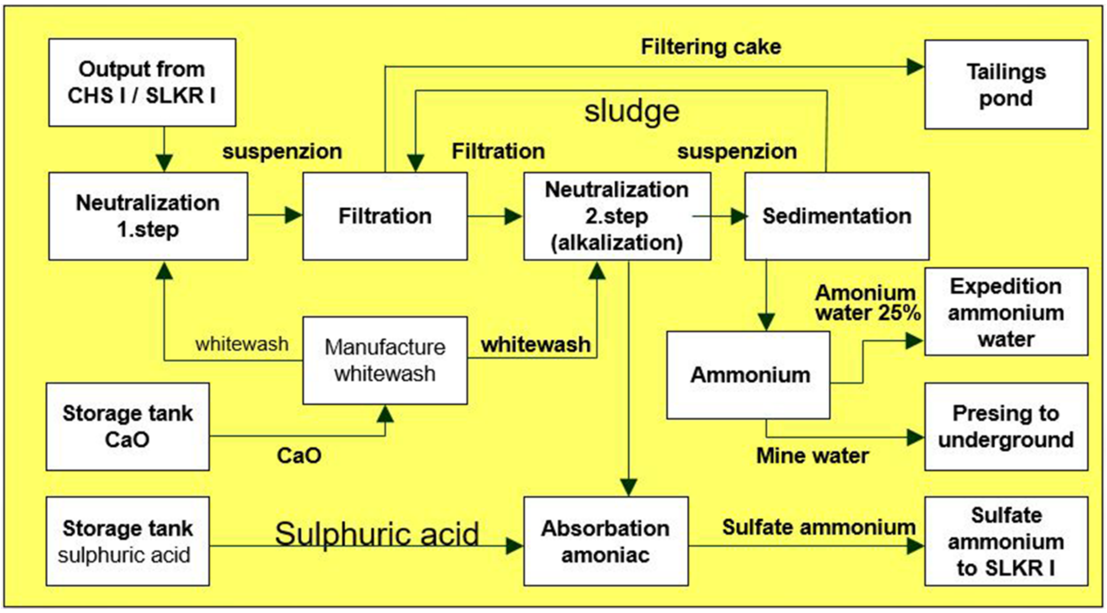


Figure 16. Chart of technologies for remediation of ISL.

Figure 17. Site and equipment for extracting and sorting aggregates.

4. Reuse of materials

An important part of the remediation programme is the reuse of aggregates from mining dumps for the construction of new containment structures. At present, it is possible to use up to 1 million tons of sorted aggregate from dumps, after uranium ore mining, per year for the construction of line structures. To control such use, SUJB issues licenses for the 'management of mining activity products originating at activities related to acquiring of radioactive mineral and deposited in dumps and tailing ponds' and for the 'discharge of a radioactive substance into the environment.' The site and equipment for extracting and sorting is shown in figures 16 and 17.

An integral part of the decommissioning proposal should be the maintenance or construction of facilities for the processing of sorted aggregates and mine and surface water treatment products.

5. Discussion and conclusions

The decommissioning of the mine and treatment plant has been completed at the Straz site in accordance with regulatory requirements that, during the process, have been subject to review and update in line with international developments. Similarly, decommissioning of the mine and treatment plant at Rozna and the chemical mining at sites of ISL are underway according to a clear programme of future work that nevertheless extends significantly into the future and therefore will be kept under continuing review. The overall objective is the return of the landscape to normal use without any restriction.

The individual stages of decommissioning are inspected and monitored every year. A report is prepared which evaluates the results of monitoring; on the basis of this report, it is assessed whether the principle of optimisation has been applied effectively. Regulatory supervision is required to be well documented and to a large extent open for review by other organisations and members of the public.

Significant practical experience has been gained during this decommissioning and remediation work. This includes insight into the number of radiation workers required for different operations, the scale of the radiological impact, and methods for control of radioactive material and radiation exposure monitoring. It is noted that there may be other hazardous chemicals present that require regulatory control. These should be taken into account in an overall optimisation process.

A thorough understanding of the site and radiation environment can help to optimise both personal and environmental monitoring, increasing protection while also reducing costs. We have also seen that significant volumes of waste materials arising in decommissioning and remediation can be reused effectively in construction of containment barriers.

It is clear that decommissioning has the same importance as the other parts of a plant's lifecycle. An important lesson is to take into account possible decommissioning problems before the start of mining or deposit exploitation. If this is not done, significant problems may result that are very costly and can take significant time to correct.

The nature and quality of approval documentation (monitoring program, emergency plan, etc.) has a great influence on the decommissioning process. Overall, it is better to plan to do the job just once and to do it correctly, even if that may require time and a staged process. Poorly designed remediation only leads to creation of new legacies, placing a continuing burden of responsibility and impact on future generations.

Additional lessons for the future include that environmental management costs should secured in advance of new mining operations, both for uranium and other minerals, based on a clear definition of environmental and human health goals during operations and at the stage of decommissioning. In particular, there is a need to ensure that mineral extraction by chemical processes such as *in-situ* leaching should not be near drinking water reservoirs or in the same areas as underground mining.

The sharing of experience through international activities such as the EGLM (NEA 2019) offers a significant opportunity to learn from these lessons to mutual benefit.

We thank the authors for permission to use data and images in the production of this article.

The authors have confirmed that any identifiable participants in this study have given their consent for publication.

ORCID iD

Miloslav Němec https://orcid.org/0000-0001-8043-7090

References

Collective of workers Annual reports of monitoring (2000, 2015, 2020), DIAMO state enterprise

Collective of workers Technical disposal project, GEAM 1998

IAEA 2011 *Radiation Protection and Safety of Radiation Sources. International Basic Safety Standards. General Safety Requirements Part 3* (Vienna: International Atomic Energy Agency)

NEA 2019 *Challenges in Nuclear and Radiological Legacy Site Management: Towards a Common Regulatory Framework. NEA No. 7419* (Paris: Nuclear Energy Agency—Organisation for Economic Co-Operation and Development)

Neznal M 2010 Risk analysis areas affected by deep uranium mining (SCES—Group Ltd)

Parliament of the Czech Republic 2016 *Act No.263/2016 Coll of 14th July 2016 Atomic Act* (available at: www.sujb.cz/fileadmin/sujb/docs/legislativa/zakony/Act_263_2016_web.pdf)

Vencelides K 2017 Cenomanian aquifer risk analysis, Straz pod Ralskem, ISL mine. DIAMO State Enterprises (Liberec: Underground Water Protection Ltd)