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Environmental Impact of Uranium Mining: Assessment of the Remediation Project at Stráž pod Ralskem

A Master's Thesis submitted for the degree of
"Master of Science"

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Vienna, 10.10.2012

Affidavit

I, **KAROLINA ZÁZVORKOVÁ**, hereby declare

1. that I am the sole author of the present Master's Thesis, "ENVIRONMENTAL IMPACT OF URANIUM MINING: ASSESSMENT OF THE REMEDIATION PROJECT AT STRÁŽ POD RALSKEM", 71 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
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Abstract

Uranium exploitation burdens the environment, ranging from moderate disturbances of the local environment to substantial release of radioactive and toxic mining waste. The severity of this uranium mining legacy highly depends on the mining method, the environmental protection used during mine operation and on the post-closure remediation in particular.

Uranium mine remediation is a complex and cost intensive undertaking, requiring a development of a comprehensive and efficient plan. This thesis analyses an example of such a remediation programme. The examined case is a former in situ leaching mine at Stráž pod Ralskem in the Czech Republic where an inadequate mining practice has caused an extensive environmental damage. The remediation of the mine remains currently the most challenging and most expensive remediation project in the Czech Republic which is expected to last for another three decades.

Firstly, the thesis evaluated the project by the means of a comparison with international best practice guidelines in order to identify the components vital for its successful implementation. As a part of this evaluation, a proposal for a long-term stewardship programme was developed.

Secondly, a financial analysis was conducted which identified the environmental damage caused by the uranium exploitation as a negative externality. In order to stress the economic impact of the environmental burden, the remediation costs were internalised in the price of nuclear energy generation in the Czech Republic. The calculations revealed that the remediation costs highly exceed the revenues from the sale of uranium produced in the examined time period and that if the costs were internalised, the nuclear energy price would increase by 14 %. In consequence, since the costs are covered by the Czech state, the funding of the remediation constitutes a subsidy to the nuclear power industry in the Czech Republic.

The overall assessment of the remediation plan showed that its technological and scientific level was adequate. The failure to implement a long-term, legally established financial security was identified in this thesis as the main constraint which led to further environmental damage, efficiency losses and considerable cost increase. To prevent such negative developments in the future, remediation design procedures including a concrete financial scheme should be ideally standardised by law.

On the whole, the findings illustrate from both environmental and economic point of view the high significance of possible environmental impact of uranium mining within the entire nuclear fuel cycle.

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A. Introduction

In public conscience, the environmental problematics of nuclear power are connected almost exclusively to the back end of the nuclear fuel cycle (NFC). The contentious topics relate to the final storage for spent nuclear fuel or most recently to the impacts of nuclear accidents. Concerning the front end of the cycle, the attention of the media and public focuses on the uranium enrichment because of its close relation to possible development of nuclear weapons. These all are pressing issues that overshadow the role of uranium mining in the overall evaluation of nuclear power and its impact on the environment.

The consequences of uranium exploitation for the environment can be, however substantial, especially if protection measures are neglected. The amount of waste which has to be appropriately treated is thousand times larger than the amount of spent nuclear fuel. For instance, only in the European Union (EU), there are approximately 314 million m^3 of uranium mining tailings, 90 % of which originates from chemical processing.[1] Even though the radiation risk arising from uranium mining waste is relatively low, it contains radioactive and highly toxic compounds that require an appropriate remediation and long-term after-care.

The research topic of this thesis is uranium mining site remediation. The focus lies on the one hand on the development of the remediation project as whole and on the determination of the components vital for its successful implementation. On the other hand, a financial analysis is conducted where the remediation costs are internalised in the price of nuclear power generation in order to highlight the possible economic consequences of environmental damage caused by uranium exploitation.

The analysis was carried out on the basis of a case study. As the research subject, the remediation of an in situ leaching (ISL) mining site in the Czech Republic was chosen. An attempt has been made to evaluate this remediation project by the means of a comparison with internationally acknowledged best practice as well as to estimate on an exemplary basis which percentage of the price for nuclear power in the Czech Republic would be necessary to cover the costs arising from the inadequate mining practice at the chosen mining site.

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[1] Vrijen, J. et al. (2006): Situation Concerning Uranium Mine and Mill Tailings in an Enlarged EU - Report to the European Commission, TREN/04/NUCL/S07.39881, Chemnitz/Aachen.

Regarding the best practice in uranium mining and its environmental management, numerous guidelines by leading institutions such as International Atomic Energy Agency (IAEA) or Nuclear Energy Agency (NEA) with the Organisation for Economic Cooperation and Development (OECD) were issued, based on extensive theoretical and practical scientific research on uranium mining, its environmental impact and possible remediation methods. The remediation technologies were for example discussed in detail in the IAEA report *Technologies for remediation of radioactively contaminated sites*.[2] Other relevant guidelines are for instance the *Environmental Remediation of Uranium Production Facilities*[3] published by the IAEA/NEA in 2002 or most recently the IAEA report on *Best Practice in Environmental Management of Uranium Mining*[4] from 2010. Several scientific case studies on environmental status in different uranium mining countries were also conducted.

For this thesis, a study issued by the European Commission *Situation Concerning Uranium Mine and Milling Tailings in the European Union*[5] which gives an overview of current uranium mining legacies in the EU, and the post-communist countries in particular, is especially relevant. Also other reports contain brief information on the environmental status of the mining sites in the Czech Republic. Mostly, the information for these reports was collected by the means of questionnaires which were filled in by the companies conducting the remediation. Furthermore, several papers on the remediation technology at the former ISL mining site in the Czech Republic that focus mostly on the technological aspect of the problem were published.[6]

To the knowledge of the author, there is currently no detailed presentation of the remediation project at the ISL mine in the Czech Republic available that would examine the programme as whole, including the internalisation of the remediation costs into the nuclear power price in the Czech Republic. This thesis makes the

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[2] IAEA (1999): Technologies for remediation of radioactively contaminated sites, IAEA-TECDOC-1086, Vienna.

[3] NEA, IAEA (2002): Environmental Remediation of Uranium Production Facilities, Paris.

[4] IAEA (2010): Best Practice in Environmental Management of Uranium Mining, IAEA Nuclear Energy Series No. NF-T-12, Vienna.

[5] European Commission, Report TREN/04/NUCL/S07.39881, Situation Concerning Uranium Mine and Mill Tailings in an Enlarged EU, 2006.

[6] For instance: Beneš, V. (2011): Acid ISL of Uranium in Czech Republic, in: The Uranium Mining Remediation Exchange Group (UMREG) Selected Papers 1995-2007, Vienna, pp. 238-246.

attempt to provide a first incentive for further research in this area, the negative externalities arising from uranium mining especially.

Since the research was conducted on an exemplary basis, no claim to the completeness is asserted. In particular, the legal aspects of the issue were addressed only tangentially.

Methodology

The subject of interest is analysed by the means of a case study using international guidelines and relevant theory as a basis for the final evaluation of the remediation project. The case of the Czech Republic has been chosen for several reasons: Firstly, the uranium production in the Czech Republic before the fall of the communism was quite intensive, leaving behind a large environmental burden. The volume of uranium mining tailings in the Czech Republic is the second largest after Germany, amounting to about 15 % of all tailings in the EU.[7] Furthermore, the scope of the remediation project is uniquely large and complex, requiring extraordinary long time for its completion as well as considerable financial means. Therefore, the case offers a strong illustration of the possible impacts of uranium mining, both from environmental and economic point of view.

The data sources are mainly reports, internal documentation and information provided by the employees of the company responsible for the remediation project.

As a reference for the evaluation, guidelines and best practice reports issued by the IAEA, NEA and the European Commission were chosen. Furthermore, for the theoretical parts, relevant scientific literature was consulted.

Structure of the Thesis

This thesis consists of three parts. In the first chapter, the general issues and problems related to uranium mining, generated waste and the remediation of the mines, with the emphasis on the ISL method, are outlined. Furthermore, the recommendations of international experts for the development of remediation projects are presented. This chapter is followed by the case study - the remediation of the ISL mine in the Czech Republic. The case study itself is divided into two sections. First, a detailed overview of the environmental remediation project and the

[7] Vrijen (2006).

technologies used is provided. Based on this examination, the plan is compared with the expert recommendations in order to identify strengths and weaknesses of the project. Furthermore, a proposal for a future after-care of the mining site is given. The second part of the case study is dedicated to the financial aspects of the plan. This part contains a brief introduction into the theory of nuclear power price assessment. Subsequently, the characteristics of the Czech nuclear power market are presented, followed by the determination of the overall costs of the remediation of the ISL mine at Stráž. These figures are then used as input data for calculations which attempt to internalise expenses of the remediation into the price for nuclear power in the Czech Republic.

Lastly, the findings from both parts of the case study are linked together and an overall analysis of the examined remediation project in the Czech Republic is conducted.

B. Uranium Mining and Processing

In general, there are three widely used uranium extraction technologies: open pit mining, underground mining and in situ leaching. All methods produce mining waste which requires storage appropriate for substances with ionizing characteristics. The type and the amount of waste are strongly dependent on the extraction method and thus are the precautions which are necessary for protection of the environment and human health from adverse effects originating from the waste.

This thesis focuses on the ISL mining, the waste generated by this technology and the possible remediation methods. Before the specific characteristics of ISL will be described, few general remarks on uranium mining waste and its impacts are provided.

1. General Characteristics of Uranium Mining Waste

Uranium mining and milling waste are residues with content of naturally radioactive substances. They can be characterised as follows: 1) waste from mining operations and 2) waste from industrial processes related to uranium mining and processing including for instance equipment contaminated with radionuclides.[8]

The volume of mining residues, waste rock in particular, is typically large. Hence, the area required for mining and the waste generated is considerable, resulting in limited options for containment. In consequence, contact of waste with the surrounding environment cannot be fully prevented.[9] Therefore, effective preventive measures and after-care have to be put in place.

According to the IAEA, tailings are responsible for 85 % of the radioactivity resulting from ore processing and uranium recovery, especially radon formation. Moreover, they hold heavy metals and other chemical contaminants.[10]

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[8] H. Monken Fernandes et al. (2008b): Critical analysis of the waste management performance of two uranium production units in Brazil-part II: Caetite production centre, in: Journal of Environmental Management 88, pp. 914-925.

[9] European Commission (2011): Situation Concerning Uranium Mine and Milling Tailings in the European Union, Commission Staff Working Paper, available at http://ec.europa.eu/energy/nuclear/waste_management/doc/sec-2011_340_final1_v2_en.pdf, last access 2 May 2012.

[10] IAEA (2010).

The main contamination pathways of radionuclides and other contaminants related to uranium mining into the environment include natural erosion processes (water, wind and geological activity), direct radiation or human activities such as spillage during handling of waste, controlled release of contaminated water, or inappropriate use of mining waste for constructions.[11]

For humans, the health risk arises especially by inhalation of radioactive progeny of ^{222}Rn, inhalation of airborne dust, intake of radionuclides from water, soil and via food chain, and direct irradiation (β and γ rays). The relevance of these pathways relates to the type of ore processing and varies over the lifetime of a mine. For instance, the main concern during operation of a mine is the release of contaminated water and its effect on aquatic ecosystem, whereas after the mine closure, the terrestrial contamination is of greater importance.[12]

Residues with increased uranium concentrations can cause higher levels of outdoor or indoor radon, respectively, if uranium contaminated material is used as construction material.[13]

Moreover, the ^{226}Ra activity in the residues is relatively significant. Together with the typically large volumes of mining waste, the uranium mining tailings can be seen as an important radiation exposure source to the public. In the long-term view, the radiation originating from uranium mining is likely to be the most dominant source of radioactivity in regard to public exposure compared to other radioactive waste.[14]

Furthermore, the element uranium is highly toxic. This is environmentally more relevant property since its radioactivity is rather low. Moreover, especially in the case of the ISL, pollution with other toxic elements and chemicals used in ore processing is of great concern.[15]

[11] IAEA (2002): Monitoring and Surveillance of Residues from the Mining and Milling of Uranium and Thorium (Safety Reports Series No. 27), Vienna.
[12] van Dam, R.A. et al. (2002): Mining in the Alligator Rivers Region, northern Australia: Assessing potential and actual effects on ecosystem and human health, in: Toxicology 181-182, pp. 505-515.
[13] European Commission (2011): Commission Staff Working Paper, Situation Concerning Uranium Mine and Mill Tailings in the European Union, Brussels.
[14] European Commission (2006).
[15] European Commission (2011).

2. Remediation Methods, Best Practice and Management

In general, the main remediation approaches applied are the following: i) removal of the source (bulk removal, surface scrapping, turf cutting); ii) containment (capping, subsurface barriers); iii) immobilization (cement-based solidification and chemical immobilization – both ex and in situ); iv) separation (soil washing, flotation, chemical/solvent extraction).[16]

To choose between these methods, the site specifics have to be considered as well as possible risks to human health and the cost-benefit dimension.[17]

Fernandes et al. summarise the advantages and disadvantages of the above mentioned approaches as follows: Removal and separation strategies are suitable for reduction of waterborne radionuclide intrusion and radon emissions. Immobilisation and containment (excluding capping) also reduce the risk of groundwater contamination but have no significant effect on radon emissions. Finally, cappings – proportional to their thickness – help to reduce radon emissions and water contamination.[18]

In 2002, the NEA and IAEA issued a report on *Environmental Remediation of Uranium Production Facilities*[19] stating the most important principles for ensuring an effective remediation. According to their recommendations, the decision-makers should consider in their remediation projects especially the following issues:

- Remediation should be conducted after proper planning and site assessment including risk assessment.
- Remediation follows the as 'low as can be reasonably achieved' (ALARA) principle that aims to limit the impact on the environment, including economic and societal factors.
- Adequate storage and monitoring of the contaminants (especially radon and radioactive dust) has to be assured taking into account the final land use.
- All potential pollution recipient pathways, water in particular, should be protected to appropriate levels.

[16] H. Monken Fernandes et al. (2008a): Critical analysis of the waste management performance of two uranium production units in Brazil-part I: Poços de Caldas production centre, in: Journal of Environmental Management 87, pp. 59-72.
[17] Monken Fernandes (2008a).
[18] Monken Fernandes (2008a).
[19] NEA, IAEA (2002).

- The site remediation is carried out in such manner that the after-care is reduced to the extent practicable.

The report focuses on the following areas which are crucial steps in the remediation process: site characterisation; decontamination, dismantling and decommissioning; waste management; water remediation; long-term stewardship and monitoring; legislation; and economic issues.[20]

Regarding the site characterisation, the report emphasizes the importance of baseline data collection on the basic of biogeochemical (including radiological characteristics) as well as socio-economic and legal conditions that are essential for the development of a remediation programme. The risk assessment should analyse the following issues: damage to the environment; environmental and occupational human health risks; financial and economic risks; and technical risks. According to the report, the stages of an optimal risk assessment are typically a) scoping – qualitative evaluation of contaminant release, migration and fate; b) exposure assessment; c) ecological and human effects assessment. Regarding the remediation programmes, the crucial stages are i) determination of remedial objectives and goals; ii) analysis of remedial alternatives; iii) public consultations; iv) monitoring site operation and maintenance.[21]

In regard to the second area - decontamination, dismantling and decommissioning, one of the most important issues is to choose an adequate waste disposal site prior to the dismantling of a facility. Thus, the volume of generated contaminated waste should be estimated as accurately as possible. Moreover, if material or equipments are designed for further use, an appropriate decontamination has to be carried out. [22]

The waste management depends strongly on the extraction method used. For the ISL, the optimal waste management measures are discussed later in this paper.

For the remediation of tailings impoundments, two approaches are used depending on the climate: dry cover or permanent water cover.[23]

Since the paper focuses on ISL, the following section describes the ISL method, its specific environmental impact and the best suitable remediation strategy.

[20] NEA, IAEA (2002).
[21] NEA, IAEA (2002).
[22] Ibid.
[23] Ibid.

2.1 ISL – Process and Best Practice

Open pit and underground mining typically produce a large volume of solid waste such as waste rocks and mill tailings which require appropriate storage. In contrast, the solid waste generated in case of ISL is very low; the tailings - mainly in form of by-products of chemical leaching reactions - remain mostly in the underground deposit zone. This is the result of the specific ISL technology that enables recovery of uranium from the deposit without transport of the ore to the surface. The ISL at the present state of the art is considered as the most cost efficient and environmentally friendly mining method. Currently, 45 % of uranium produced worldwide originates from the ISL.[24]

The type of uranium suitable for ISL typically develops over time periods of thousands to millions years by precipitation of the uranium from the carrier fluid. The transport and deposition zones are often confined by low permeability zones above and below the deposit. In order to extract the uranium from the ore, a leaching solution containing either sodium (bi)carbonate or sulphuric acid together with an oxidant has to be injected into the deposit zone. The uranium then oxidizes from the insoluble U^{4+} to the soluble U^{6+} and dissolves in the leaching solution as either a uranyl tricarbonate or a uranyl sulphate complex. The enriched solution is then recovered via pipelines and transported to a facility where the uranium is extracted by ion exchange or solvent extraction methods. The spent leaching solution is regenerated and re-injected into the ground.[25]

The ISL method, when properly applied, causes smaller release of radiation and other contaminants in comparison to conventional mining since no extraction or breaking of the ore on the surface is necessary and hence no waste rock or mill tailings are produced. Even though the airborne radiological release cannot be entirely excluded since during the ISL process also solid waste such as debris, process solids, contaminated soil or used equipment are generated, the threat of airborne contamination is still minimal.[26]

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[24] World Nuclear Association; In Situ Leach (ISL) Mining of Uranium, available at http://www.world-nuclear.org/info/inf27.html, last access 23 September 2012.

[25] SENES Consultants Limited (2008): Environmental Impacts of Different Uranium Mining Processes, Ottawa.

[26] Ibid.

The most relevant contamination pathway for ISL is waterborne. In the underground ores, the chemical reactions taking place during the leaching process can mobilize heavy metals; progenies of the uranium decay chain such as thorium, radium and radon; as well as elements such as arsenic, zinc or vanadium which can pollute the underground environment. A surface contamination is also possible in case of spillage or failure of (near-)surface piping.[27]

In order for ISL to be successful and environmentally safe, the leaching agent has to be contained in the application zone. This depends on the permeability of the subsurface environment and on the possibility to establish a negative hydraulic gradient in the zone. This under-balance can be ensured if the enriched leaching solution is pumped out of the wells faster than the regenerated fluids are re-injected. Furthermore, continuous removal of leaching products and prevention of injections of redundant substances (e.g., NH_3) is advisable. The excess solution can be removed by chemical treatment, evaporation, reverse osmosis or deep injection into suitable geological formations.[28] Regarding the leaching agent of choice, experience in the US showed that the ISL mines where sulphuric and nitric acid as leaching agents were used, were very difficult to remediate to acceptable levels.[29] Thus, where possible, other leaching agents should be chosen.

Moreover, a proper isolation of the technological fluids during the injection, uranium extraction and neutralization of the barren solution has to be assured. Besides maintaining secure well and pipe casings, an important pollution prevention measure is the installation of monitoring wells outside the main well-field, at a distance that would allow detection of any leakage. Furthermore, to prevent potential radon release, radon can be captured by pressurized and sealed process equipment.[30]

The waste generated by ISL include mostly solids and slurries from neutralisation facilities; spent exchange resins; salt residues and used filters from reverse osmosis plants; scales from pipes, pumps and others; residues from evaporation ponds and excess leachate. The possible treatment measures are re-injection into aquifer if no aquifer contamination occurred or discharge after treatment with bulk precipitation,

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[27] SENES (2008).
[28] Beneš (2011); DIAMO s.p. website, http://www.diamo.cz/en/tuu, last access 17 April 2012; Vrijen (2006), SENES (2008).
[29] NEA, IAEA (2002).
[30] SENES (2008).

reverse osmosis or ion exchange. For the residues of these processes as well as other solid waste generated, a proper containment has to be determined.[31]

2.2 ISL – Remediation and After-Care

In order to detect a contamination and to set restoration targets for the remediation, an extensive set of baseline data on environmental status has to be collected before construction of every uranium mine. For ISL, especially the data on water quality as well as detailed assessment of chemical composition of the ore body are essential. For mines where pre-operational data are not available, information from unaffected background areas and data on the current contamination can be used for the assessment of pre-existing environmental conditions.[32] Furthermore, the types of waste generated from the used technology have to be identified and quantified.[33]

The rehabilitation of the water courses after the closure of an ISL mine involves removal of immobile substances which were contained in the technological fluids and of products that were mobilized during the leaching processes in the underground environment. Two basic chemical treatment options have been applied for the water restoration: groundwater sweep where the underground water is removed via the injection wells and transferred to an evaporation pond; reverse osmosis or eventually an aquifer water recirculation.[34]

The trace metals and other polluting anions can be diminished by using chemical reductants. Moreover, bioremediation can help restoring the original environment, for instance via growth stimulation of micro-organism that can reduce the pollutant levels by natural biochemical processes.[35]

A deep well injection as a disposal option for technological fluids has higher efficiency and smaller area requirements in comparison to evaporation ponds. However, the geological condition of the injection zone has to be suitable to prevent vertical migration of contaminants. The wells used for such injections are usually

[31] NEA, IAEA (2002).
[32] NEA, IAEA (2002b): Monitoring and Surveillance of Residues from the Mining and Milling of Uranium and Thorium (Safety Reports Series No. 27), Vienna.
[33] IAEA (2004): The Long Term Stabilization of Uranium Mill Tailings, IAEA-TECDOC-1043, Vienna.
[34] NEA, IAEA (2002b); SENES (2008).
[35] SENES (2008).

900 to 3,000 m deep and have to be bound by confining layers in order to prevent contact with overlying water sources.[36]

In sum, a successful closure of an ISL mine should involve decommissioning and decontamination of facilities, neutralisation and stabilisation of the underground extraction zones and plugging of the wells.[37] Afterwards, a long-term stewardship of the closed mine is necessary. The principles of such stewardship are outlined below.

2.3 General Considerations for Long-term Stewardship

Due to long-lived radionuclides contained in the waste, the mining sites require such a remediation project that would assure its stability over long time periods. Thus, even after technical completion of the remediation, long-term institutional monitoring and maintenance of the site will be necessary. Such remediation approach is referred to as a long-term stewardship.[38]

The remediation plans should consider long-term stewardship issues already from the initial stage on. For sites where remediation is likely to take place for a long time period, a risk-based approach and prioritisation is necessary.[39]

Regarding the time span for a stewardship programme, the IAEA came to the conclusion that developing a programme lasting beyond three generations is not suitable due to very high uncertainties like economic and political situation, technological development and other societal factors. Since a stewardship will always be a subject to these uncertainties, a static programme is not reasonable. The design has to have the capacity to adapt and respond to the circumstances. Thus, regular revisions of the programme are crucial.[40]

A successful stewardship should be site-specific and designed according to the following considerations:

- Realistic timeframes;
- Involvement of stakeholders;
- Flexible economics;

[36] SENES (2008).
[37] SENES (2008).
[38] Flack, Eberhard W. (2008): The Long-Term Safety of Uranium Mine and Mill Tailing Legacies in an Enlarged EU, Petten.
[39] European Commission (2011).
[40] Flack (2008).

- Accordance with the surrounding environment in order to achieve a biogeochemical stability;
- Preservation of records and feedback based on this monitoring.

The continuity of institutional control and maintenance is one of the most problematic aspects of the long-term stewardship since the ability of the institutions to proceed with the monitoring are subject to high uncertainties, especially funding. Thus, the final objective should be to achieve a remediation status that would minimise the need of active controls.[41]

To ensure that the stewardship would remain in place even in case of political or economic crises in the respective country, an additional surveillance by an international organisation such as IAEA or European Commission can be considered. On the EU level, the European Nuclear Safety Regulators Group (ENSREG), created in 2007, aims for developing a common understanding among nuclear safety authorities from the Member States, including development of common approach to stewardship programmes.[42]

The stewardship programme should ideally determine the following factors: the frequency of monitoring; the parameters to be measured; the equipment needed; the measurements that will trigger a response action; and the authority responsible for the monitoring and maintenance. The above mentioned indicators have to be identified on the basis of a site characterisation. The monitoring itself can then be carried out by the means of site inspections; geotechnical monitoring; ground- and surface water monitoring; ambient air monitoring; and ecological monitoring.[43]

2.4 Factors Influencing Remediation Costs

The expected costs for a successful and environmentally sound closure of a mining site are very important issue to consider prior to uranium exploitation as they could reach considerable amounts. Thus, certain site characteristics have to be identified which can significantly influence the remediation costs. These are especially the deposit size; ore grade; the mining method; climate; surrounding population density; remediation goals; technological development and funding source.

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[41] NEA, IAEA (2002).
[42] Flack (2008); ENSREG website, http://www.ensreg.eu/, last access 26 June 2012.
[43] NEA, IAEA (2002).

Typically, the remediation costs increase with the amount of waste rock and tailings. Thus, the larger deposit and the lower ore grade are mostly associated with higher costs. In case of ISL, no waste rock or ore is generated. The waste produced is limited mainly to products of neutralisation. However, the ISL requires restoration of the hydrological environment. The costs for the water remediation are highly dependent on the utilisation of the respective aquifers and the leaching agent used. In general, the costs for remediation of ISL mines are lower than for other mining methods.[44]

Other ISL relevant issue is the risk of drainage in areas with high precipitation rate which requires more sophisticated cover and capping designs and thus results in higher remediation costs. Moreover, the costs increase with the stringency of requirements on the remediation results, affected inter alia by the population density which typically leads to more stringent pollution limits, claims for more valuable future land use, and to the need for longer and more extensive monitoring. On the other hand, the costs could decrease if a positive resale balance in densely populated regions can be achieved.[45] Technological development has usually a cost reducing effect since it offers more effective mining and remediation methods.[46]

[44] NEA, IAEA, (2002).
[45] Ibid.
[46] Ibid.

C. Case Study Part I: Environmental Remediation of the ISL Mining Site Stráž pod Ralskem

1. Uranium Mining in the Czech Republic

On the territory of the Czech Republic, uranium mining is conducted since 1945, with a peak production in the late 50s. After 1989, a gradual contraction of uranium mining has been planned due to economic feasibility uncertainties connected with the global decline in uranium prices. In the period 1945-2007, more than 110 thousand tons of uranium were produced.[47]

Currently, the only operating uranium mine in the Czech Republic and practically in the entire EU is the deposit Rožná. According to the decision of the Czech government in 2007, the uranium mining will continue without time constraints until the mining is economically feasible. An entitlement to financial support from the state budget is not provided.[48]

Uranium mining in the Czech Republic is conducted by the state-owned enterprise DIAMO s.p. The company and its subsidiaries are also responsible for the remediation of the mining sites.

Until 1990, the uranium produced in Czechoslovakia was exported exclusively to the Soviet Union. Since early 90s, almost all uranium is sold to ČEZ a.s., the owner of the two Czech nuclear power plants. The conversion of Czech uranium into nuclear fuel takes place in conversion facilities abroad (e.g. in France, Canada, or Russia).[49]

In 2008, the Joint Research Centre of the European Commission conducted a study on uranium mines and mining waste in the enlarged EU. The report stated that the 47 million m^3 tailings in total area of 630 ha that are situated in the Czech Republic are currently sufficiently secured and do not cause unacceptable environmental

[47] DIAMO s,p. website, http://www.diamo.cz/en/straz-pod-ralskem, last access 17 April 2012.
[48] Ministerstvo průmyslu a obchodu: Zpráva o aktualizaci Státní energetické koncepce [Ministry of Industry and Trade: Report about the update of the State Energy Concept], available at http://www.komora.cz/pomahame-vasemu-podnikani/pripominkovani-legislativy-2/nove-materialy-k-pripominkam-1/nove-materialy-k-pripominkam/59-11-zprava-o-aktualizaci-statni-energeticke-koncepce-t-21-3-2011.aspx, last access 15 April 2012.
[49] DIAMO Newspaper, Volume XI (XXVIII), No. 9, September 2005.

damage.[50] However, in order to maintain the stabilised situation, considerable remediation works have to be carried out. In the following chapter, the situation at the mining site with the largest, most severe and most expensive environmental legacy in the Czech Republic is described and analysed – the ISL mining site at Stráž pod Ralskem.

2. The ISL Mining Site Stráž pod Ralskem

The Stráž mining site lies in Northern Bohemia, in the Liberec region. At the Stráž deposit, two uranium mining methods were used in parallel: underground mining at the Hamr mine and the ISL. In this paper, the focus shall lie on the environmental remediation of the latter.

The exploration works preceding the ISL application were conducted in the years 1966-1971.[51] The ISL mining method was then applied from 1971 until 1996, when the mine was closed by the decision of the Czech government due to increasing concerns regarding the impacts on water resources.[52]

In the mine area, which is displayed in the map below, thirty-five leaching fields of total surface of 628 ha were put in place. The site encompasses 24.1 km^2; 7,684 mining wells and 2,210 exploration bore holes were drilled into the ground and the mining depth reached approximately 220 m.[53] Size of the leaching fields varied from 1 to 3.5 ha. The flow capacity of the two processing plants was 60,000 m^3 and the production capacity 800 t uranium per year. The total volume of enriched solution extracted until the mine closure in 1996 amounts to 400 million m^3 from which 15,800 tons of uranium were produced.[54] At present, uranium is still generated as a by-product of the environmental remediation. From 1996 until 2011, 1960.2 tons of uranium were produced during the decontamination, starting with 300 t in 1996 and gradually decreasing to current 13 t per year.[55]

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[50] Vrijen (2006).
[51] DIAMO s.p., o.z TÚU, internal material from 31 August 2012.
[52] DIAMO s.p. website, http://www.diamo.cz/en/straz-pod-ralskem, last access 17 April 2012; Tomáš, Josef (2000): Environmental Remediation Program of In-situ Leaching Uranium sites in the Czech Republic, in: WM’00 Conference, February 27 – March 2, 2000, Tuscon.
[53] During the remediation, the number of bore holes steadily increased due to drilling of remediation wells. Currently, there are around 15,000 wells at the site.
[54] DIAMO s.p. website, http://www.diamo.cz/en/straz-pod-ralskem, last access 17 April 2012; Tomáš, (2000); Beneš (2011).
[55] DIAMO s.p., o.z TÚU, internal material from 31 August 2012.

At the Stráž site, there is one tailings pond consisting of two stages (I. and II.) separated by a dam, covering an area of 935,000 m^2 each. Originally, it served for disposal of waste generated during uranium processing from deep mining at Hamr. Nowadays, the impoundment contains waste from both deep and ISL mining sites. At stage I., residues from the deep mine and decommissioning waste are stored. The products from neutralisation stations are disposed of at II. stage.[56]

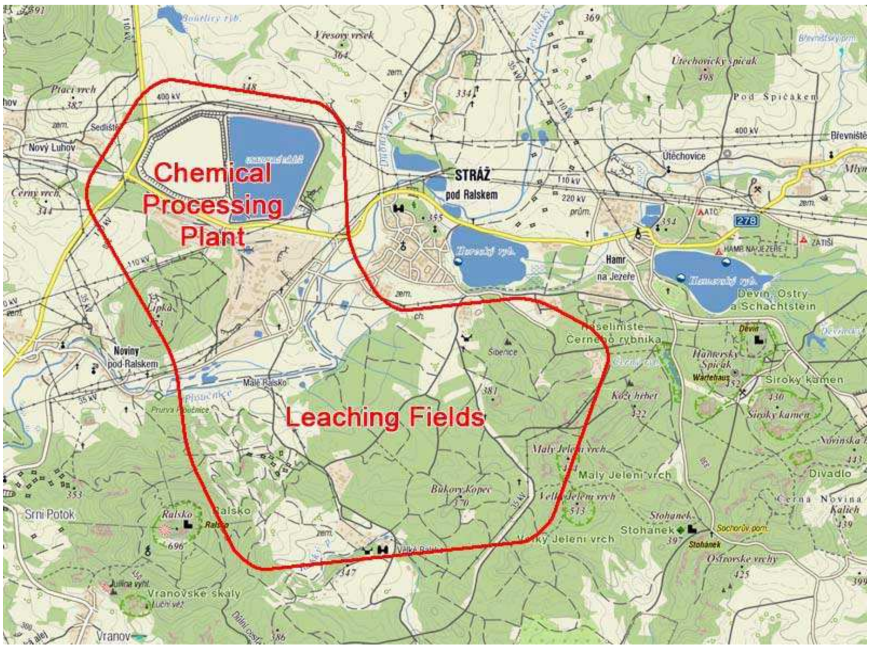

Figure 1. Map of the ISL Site at Stráž pod Ralskem.
Source: DIAMO s. p. website, http://www.diamo.cz/en/locations-tuu/straz-pod-ralskem.

The main environmental problem at Stráž is the contamination of the aquifers where the uranium deposit is situated. In the following, the specification of this contamination is described.

2.1 Contamination of the Aquifers

Uranium reserves at Stráž lie in sedimentary rocks of the North Bohemian Cretaceous basin which is an important drinking water source. The deposit is of a stratiform and sandstone type and lies in the lower Cenomanian sedimentary complex. [57]

Concerning the water reservoirs, there are two separate groundwater levels with porous or porous-fractured permeability. The upper Turonian aquifer is one of the

[56] NEA, IAEA (2002).
[57] Beneš (2011).

most important sources of drinking water in the Czech Republic. It has a free water table and its recharge comes from precipitation, whereas the Cenomanian groundwater is of artisan nature. The Cenomanian aquifer was never used as a drinking water reservoir since the water naturally contains high amounts of ^{226}Ra. The levels are about 100 times higher than the safety limits. The lower Turonian (siltstones) forms the upper confining layer of the Cenomanian, separating the two aquifers.[58]

The geological characteristics at Stráž are not favourable for ISL. One part of the minerals is leachable only under diffusion conditions and the other is difficult to leach because the reactions are very slow and must be accelerated with higher concentration of the agent. Due to these circumstances, only acid leaching could be successful for the uranium exploitation. As the leaching agent, sulphuric acid was used and nitric acid as oxidant. The sulphuric acid had concentration of about 5 %.[59]
To overcome the low chemical reactivity of the minerals and the diffusion processes, the density of the well network had to be gradually increased. The ISL was applied for the period of 15-25 years, with decreasing use of leaching agent and accordingly decreasing concentrations of uranium exploited.[60]
The leaching solution underwent a series of reactions with the ores: the sulphuric acid reacted with carbonates, iron metals and alum silicates. The reaction results were metallic sulphates which finally lead to surge of SO_4^{2-} and polyvalent metal cations. HNO_3 oxidised with uranium, sulphides and organic matter. The overall composition of the reactions is not entirely known. Nitrous and other nitrogen oxides as well as nitrogen are likely to be a part of the solution. NH_3 was not consumed in any reaction. For the clean-up of the wells, hydrofluoric acid was used which most likely reacted with gangue minerals. The following tables illustrate the chemical contents of the recovered solutions.[61]

[58] Beneš (2011).
[59] Beneš (2011).
[60] Ibid.
[61] Ibid.

Table 1. Chemical Composition of the Recovered Solution, part I

Main Compounds	in g/l	Minor Compounds	in ppm
SO_4^{2-}	40 - 65	Si	100 - 200
H_2SO_4	15 - 30	P	50 - 150
Al	4 - 6	K	40 - 70
NH_4^+	1 - 1.5	Zn	30 - 50
Fe	0.5 - 1.5	Mg	20 - 30
NO_3^-	0.3 - 0.8	Ni	20 - 30
Ca	0.2 - 0.3	V	10 - 15
F	0.1 - 0.3	Cr	5 - 15

Source: Beneš (2011).

Table 2. Chemical Composition of the Recovered Solution, part II

Parameters	Turonian Aquifer – water contents	Cenomanian Aquifer – concentrated solutions
pH	3 – 5.7	1 – 2.8
U	0.05-0.2 g/m^{-3}	≤ 0.1 g/m^{-3}
^{226}Ra	50-800 Bq/m^{-3}*	50,000-90,000 Bq/m^{-3}
Total dissolved solids (TDS)	2 – 5 kg/m^{-3}	64-100 kg/m^{-3}

Note: values as reported in 2002. *Source: NEA, IAEA (2002).*

* Maximal allowed limit for public water supply in the Czech Republic: 300 Bq/l; target value: 50 Bq/l.

For the uranium separation, ion exchange resin method was applied. At the end of the process, the uranium concentration varied from 30 to 100 ppm; the highest concentration recovered was approximately 500 ppm during the initial years of the ISL exploitation. In the wells with the most favourable geological conditions, about 80 % of the present uranium reserves could be extracted. At the end of the uranium processing - after neutralization with ammonium and subsequent filtration, washing and drying - the final product was ammonium diuranate.[62]

The negative environmental impact of the circulating chemical solutions originates firstly from the geological conditions that did not allow keeping the technological fluids strictly within the leaching fields. The exploration and research phase before the ISL was insufficient, leading to wrong assumption about the geological environment and thus to inadequate mining technology. The primary ISL did not take into consideration the different ore characteristics throughout the deposit. In consequence, the chemical solutions dispersed both horizontally and vertically into both aquifers. Moreover, damaged and qualitatively inferior well casings allowed chemicals from the Cenomanian aquifer to enter the Turonian water. Even though with time, the well safety and the mining methodology gradually improved, contaminations could not be entirely avoided since those improvements were made during mine operation. No remediation of the occurred environmental damage was conducted.[63]

Secondly, a significant complication was the vicinity of the deep mine Hamr that influences the hydrogeology at the whole Stráž deposit. Since the deep mining method required pumping out of water from the deposit, the water from the ISL fields migrated into the water depression region, contaminating further area.

Historical reports indicate that the mutual negative influence of the two mining methods, the resulting pollution and its environmental impact on drinking water sources were known already in 1973. Only in 1983, a hydraulic barrier was built to stop the negative impacts of the acidic fluids on the deposit at Hamr. The barrier is a system of drill holes and pipes in which treated water is injected to maintain the necessary pressure. However, no measures that would prevent further contamination of the aquifers were undertaken until 1990.[64]

Moreover, there was a permanent over-balance of the solutions due to addition of other substances and waste water. This overbalance amounted to 3-5 % of the

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[62] Beneš (2011).
[63] Ibid.
[64] Tomek, Prokop: Československý uran 1945-1989. Těžba a prodej československého uranu v éře komunismu [Czechoslovak uranium 1945-1989. Mining and sale of Czechoslovak uranium in the Communist era], available at http://www.ceskatelevize.cz/ct24/exkluzivne-na-ct24/osobnosti-na-ct24/111730-drahy-uran/, last access 15 August 2012.

leaching solution used. In the 25 years, the chemical solutions increased to 10 million m^3 which constitutes more than 10 % of the original volume of the water source.[65]

In consequence, a considerable amount of contaminating fluids has been collected in the Cenomanian aquifer as the following figures show.

The volume of chemicals injected into the ground amounts to 4.1 million t of sulphuric acid. Eighty percent of the acid reacted with the ore, leaving 820,000 tons of H_2SO_4 in the ground. Furthermore, 313,000 t of nitric acid; 111,000 t of NH_4^+; and 26,000 t of hydrogen fluoride for well cleaning were injected into the deposit. In total, 266 million m^3 of residual technological fluids remained underground -186 million m^3 in Cenomanian and 80 million m^3 in the Turonian aquifer. These technological fluids left around 6.07 million tons of TDS in the aquifers. The main pollutants are SO_4^{2-}(3.6 million t), Al (542,000 t), Fe (136,000 t), and NH_4^+ (83,000 t). Other health and environmentally relevant elements are Cr (1,140 t), Co (724 t), As (532 t), Tl (127 t) and Be (71 t).[66]

The total water volume influenced by the chemicals (concentration of sulphates higher than 80 mg/l) is in the Cenomanian aquifer approximately 383 million m^3, covering an area of about 27 km^2. This constitutes 99.5% of the overall water contamination. In the Turonian aquifer, there are 26.7 m^3 polluted water in the area of 7.6 km^2 with the total volume of TDS of 17,000 t (7,886 t SO_4^{2-} and 748 t NH_4^+).[67]

The extent of current contamination is shown in the following picture.

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[65] Beneš (2011).

[66] DIAMO s.p. website, http://www.diamo.cz/straz-pod-ralskem, last access 17 April 2012; Tomáš (2000); DIAMO Newspaper, Volume XI (XXVIII), No. 9, September 2005.

[67] Czech Chamber of Commerce, 186_Zpráva o výsledcích aktualizace analýzy rizik a jejích dopadů do celkových nákladů a výdajů spojených s řešením důsledků po chemické těžbě uranu a souvisejících činností v oblasti Stráže pod Ralskem a způsob jejich financování pro období let 2012 až 2042 [Report about the results of the actualization of risk assessment and its impact on the total costs connected to dealing with the impacts of chemical uranium mining and related activities at Stráž pod Ralskem and its financing for the time period 2012 – 2042]], available at http://www.komora.cz/pomahame-vasemu-podnikani/pripominkovani-legislativy-2/nove-materialy-k-pripominkam-1/nove-materialy-k-pripominkam/186-11-analyza-dusledku-po-chemicke-tezbe-uranu-v-oblasti-straze-pod-ralskem-t-24-8-2011.aspx, last access 10 August 2012; DIAMO s.p. website, http://www.diamo.cz/straz-pod-ralskem, last access 17 April 2012; Tomáš (2000); DIAMO Newspaper, Volume XI (XXVIII), No. 9, September 2005.

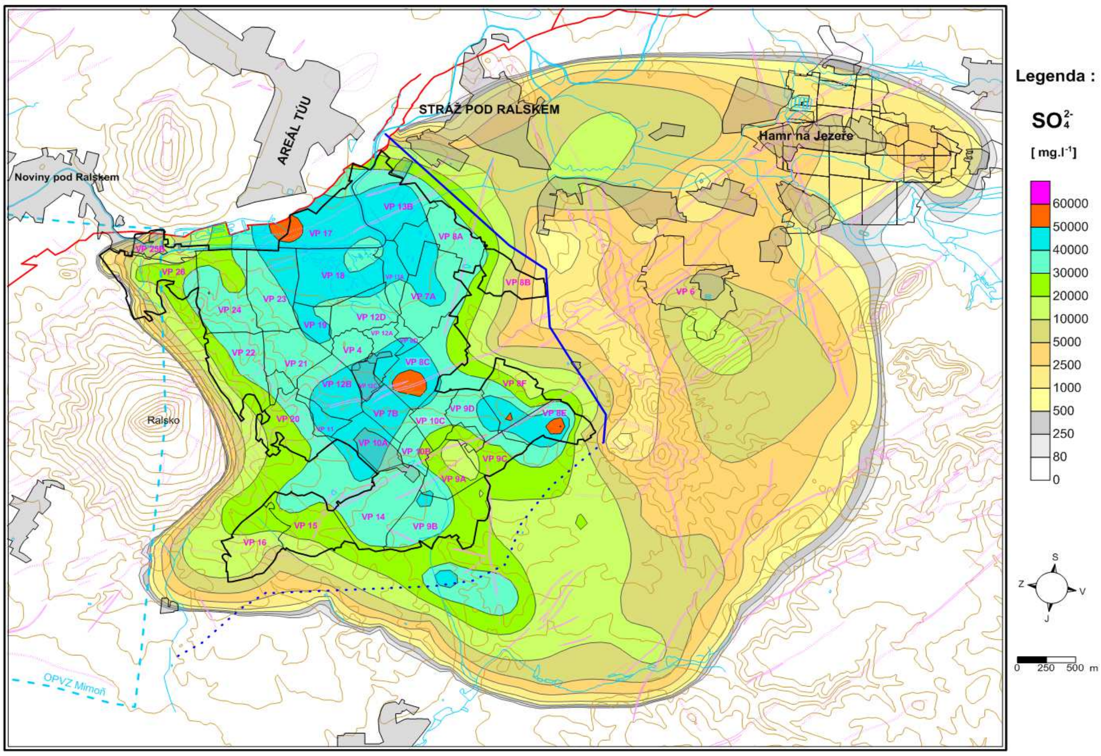

Figure 2. Current Extent of Contamination.
Source: DIAMO s.p., o.z. TÚU, internal material from 31 August 2012.

2.2 Remediation Process

The entire rehabilitation of both Stráž mining sites (ISL and deep mine) is the responsibility of o.z. TÚU, a subsidiary of the state-owned company DIAMO. The projects are approved by Territorial Mining Boards, in which the State Office for Nuclear Safety (SÚJB), the involved Ministries and regional authorities take part. The finances of the projects are determined and overseen by the Ministry of Industry and Trade; the exposure and contamination levels by SÚJB, the Ministry of Environment and local authorities.[68] The funding aspects of the site remediation are analysed later in this thesis.

The main objectives of the remediation can be summarized as follows:

- restoring of the (hydro)geological environment to ensure continuous drinking quality of Turonian water;
- decommissioning of the ISL related installations (extraction wells and above ground facilities);

[68] Vrijen (2006).

- integrating the affected surface area into the surrounding environment, with consideration of the future land use.[69]

2.2.1 Remediation Plan Development: Mine Closure

In 1991, the former Czechoslovak government decided not to expand the ISL fields any further until the assessment of the environmental status and the plans for mining termination and remediation are developed. The subsequently conducted analyses showed intolerable impacts on water reservoirs and thus the need for closure of the ISL mine. There were not any known pre-existing protective measures which could serve as a basis for the upcoming remediation even though historical protocols show that the negative impacts on drinking water sources were known already in 1973.[70] For the time period 1992-1994, a special mining regime was established involving limitations of the exploitation only to central fields, where the contamination was high, and a gradual decrease of leaching solutions injections. Simultaneously, assessment of tectonics, hydrogeological and biogeochemical conditions was conducted. The analysis aimed to examine the possibility of water contact between the Cenomanian and Turonian aquifers after the site remediation. On the basis of the results, concrete remediation steps were developed.[71]

According to the government decision no. 170/1996 about termination of ISL mining at Stráž, the injection of leaching agent into the deposit stopped in 1996. Furthermore, it was agreed that a determination of target pollutant concentration limits by December 1997 was necessary.[72]

[69] Ekert, Vladimír; Mužák, Jiří (2010): Mining and Remediation at the Stráž pod Ralskem Uranium deposit, in: GeoScience Engineering 3 - Special Issue, pp. 1-6.
[70] Tomek, Prokop: Československý uran 1945-1989. Těžba a prodej československého uranu v éře komunismu [Czechoslovakian uranium 1945-1989. Mining and sale of Czechoslovakian uranium in the Communist era], available at http://www.ceskatelevize.cz/ct24/exkluzivne-na-ct24/osobnosti-na-ct24/111730-drahy-uran/, last access 15 August 2012.
[71] Czech Chamber of Commerce (2011); DIAMO Newspaper, Volume XIII (XXX), No. 3, March 2007.
[72] Czech Chamber of Commerce (2011).

At the beginning of remediation works, DIAMO developed a remediation program consisting roughly of the following steps:

1. Stop the intrusion of leaching acids into the geological environment.
2. Start with the decontamination of the aquifers.
3. Assess the surface contamination in the region, the littoral zone of Ploučnice river in particular.
4. Develop a mathematic model of pollutants pathways for both aquifers.
5. Establish monitoring of the Stráž mining site and yearly evaluations of the remediation progress.[73]

In the following section, the remediation steps are examined in more detail.

2.2.2 Remediation Plan Development: Pre-remediation measures 1996-2001

In the case of the ISL mine, the determination of the target limits and thus of the optimal remediation method depends on the level of contamination (in mobile state of pollutants) which can be left in the Cenomanian aquifer without risking a contamination of the Turonian aquifer above allowed levels.[74]

The risk assessment based on this research was developed 1996-1997 as a conceptual methodological model so that actualizations any time in the future can be conducted. Based on the results, the target limits for the TDS concentration in Cenomanian aquifer were set to 8 g/l for the next 10 years. In addition, it was decided to conduct a study on the possibility of an in situ immobilization as another remediation method. The respective research was carried out in the years 1995-2000. An experimental operation was planned for the next remediation stage. Moreover, the assessment of an optimal solution for the treatment of technological fluids and the resulting waste was still under development. The aim was to achieve a maximal possible further usability of the resulting products.[75]

In practice, the preparation for remediation focused in the beginning on the horizontal and vertical stabilization of the residual technological fluids in the aquifers. For this purpose, the Station for Liquidation of Acid Solutions (SLKR I)

[73] Tomáš (2000).
[74] DIAMO Newspaper, Volume XIII (XXX), No. 3, March 2007.
[75] Czech Chamber of Commerce (2011); Tomáš, Josef (2001): Sanace území po těžbě a úpravě uranu v České Republice a posuzovaní vlivů těchto činností na ŽP [Remediation of uranium mining sites in the Czech Republic and the impact assessment of these activities on the environment], available at http://slon.diamo.cz/hpvt/2001/sekce/sanace/01/S01.htm, last access 10 August 2012.

was build and commenced its operation in 1996. The technical details of the processes taking place in the decontamination facilities are given in the following section.

In 1997, first remediation wells were drilled into the Cenomanian aquifer. Moreover, further decontamination technologies were researched and lead to the construction of SLKR II which commenced its operation in 2001.[76]

In regard to monitoring, the TÚU has been obligated to provide annual or semi-annual monitoring reports on impacts on pre-determined environmental parameters, on hydrogeological status and on status of contaminated mine water. Moreover, the radioactivity and pollution by radionuclides have to be included in the monitoring scheme. An important aspect of the remediation concept is also the coordination of the closures of the ISL and the deep mining site at Hamr including decommissioning of chemical processing plant and tailings pond in the whole Stráž area.[77]

The preparing stage of the remediation was finalized in 2001 with the beginning of a systematic withdrawing of the contaminated water, subsequent alum production and its reprocessing to aluminium sulphate.[78]

2.2.3 Remediation Plan Development: Remediation Activities 2002-2011

As of 2001, the following technologies were used for water decontamination: Chemical Station where the uranium was separated; SLKR I and II. In 2003, the neutralisation station NDS 6 was integrated into the decontamination process which was initially used only for the treatment of mine water from deep mine Hamr I.

After a risk assessment actualisation in 2005, development of new remediation methods and plans focused on neutralisation technologies. Subsequently, the construction of NDS ML (Neutralisation Station for Mother Liquor) and NDS 10; remediation wells – II. Stage; the project “Final Solution of the tailings pond at Stráž pod Ralskem” as well as enlargement of the SLKR II were approved.[79]

In the years 1998-2009, the assessment of the environmental status at the ISL site continued. The hydraulic model was revised under consideration of new data and new technological possibilities. The research involved analysis of water exchange

[76] Tomáš (2001).
[77] Tomáš (2001).
[78] Czech Chamber of Commerce (2011).
[79] Czech Chamber of Commerce (2011).

rate between the two aquifers and contamination levels of fucoid sandstone in the upper part of the Cenomanian collector which contains 46% of total aquifer contamination. Furthermore, research of new monitoring, drill and sampling methods as well as regular updates of the risk assessment were conducted.[80] The assessment of the status at the ISL site in the period 1998-2009 lead to the following conclusions: the current concentration of the residual technological fluids in the Cenomanian aquifer poses a real, extremely high and unacceptable exposure risk to water sources for surrounding resident areas as well as to water and water related ecosystems of the river Ploučnice. Without an adequate remediation, there is a risk of unacceptable negative impacts on the Turonian aquifer. The concerned water area reaches 160 km^2. As the most relevant contaminants were identified Al, Fe, NH_4^+, Cr, Be, Tl, As, Co and sulphates.[81]

On the basis of this re-assessment, new remediation target limits were determined as shown in Table 3. Their fulfilment is according to the report realistic by 2037 at the earliest.[82]

Table 3. Target Values of Chosen Parameters

Parameter	**Concentration [mg/l]**		
	New target values		**Original limits from risk assessment 1997**
	Median	**Maximal acceptable limit (for limited areas)**	
Al	800	2 400	-
Fe	150	600	-
Ammonium ions	80	210	160
Sulphates	6 000	18 000	6 900
TDS	7 000	21 000	8 000

Source: DIAMO Newspaper, Volume XVI (XXXIII), No. 11, November 2011.

[80] DIAMO Newspaper, Volume XIII (XXX), No. 5, May 2007.
[81] Czech Chamber of Commerce (2011).
[82] Czech Chamber of Commerce (2011).

The new values are based on the presumption that after achieving the stated limits, the concentration of other pollutants concerned will also decrease to a safe level.[83] The government adopted a new remediation plan for the period 2012-2042 and assured funding to the amount of 32 billion CZK [1.28 billion EUR]. The details regarding the funding are presented in the next chapter of this thesis.

The remediation progress is to be evaluated every 5 year by the means of a risk assessment update. In order to achieve the new target limits, an optimal remediation technology has been identified. The details of the processes are given in the next section.

2.2.4 Current Decontamination Methods

Approximately 3.6 million m^3 of residual technological fluids from Cenomanian and Turonian aquifers are treated every year. During this process, the Cenomanian aquifer is kept at an under-balance: its water table is maintained in such manner so that it lies permanently below the free water table of the Turonian aquifer. Thus, a passive protection of the Turonian waters is assured and no further contamination by the residual fluids from Cenomanian aquifer is possible.[84] In order to prevent further exchange of contaminated water and other negative impacts of the vicinity of the ISL fields to the deep mining site Hamr, the hydraulic barrier separating the two deposits is used in which the treated water is pumped.[85]

In the case of the Turonian aquifer, a presence of so called ‘plums’ - spatially sharply defined areas with high degree of contamination - was found. Due to this specific characteristic, the focus of decontamination of this aquifer lies on pumping out of this water via special drill holes. This remediation measure is successful and led to a significant decrease of contamination levels in the Turonian aquifer.[86]

In general, the remediation of the aquifers follows the pump-and-treat methodology. The mine water is withdrawn and treated at a desalination, neutralization and decontamination plant. First, the uranium is separated from the solution at a chemical processing plant by using an ion exchange resin. Afterwards, the fluids are

[83] Czech Chamber of Commerce (2011).
[84] DIAMO s.p. website, http://www.diamo.cz/tuu, last access 17 April 2012.
[85] Tomáš, (2000); T. G. Masaryk Water Research Institute, Chemická těžba uranu Stráž pod Ralskem [Chemical uranium mining at Stráž pod Ralskem], website http://www.vuv.cz/index.php?id=238&L=1%27%60%28[{^~, last access 9 August 2012.
[86] DIAMO Newspaper, Volume XII (XXIX), Special Issue, March 2006.

transferred to the SLKR I facility where evaporation with the aim of thermal thickening takes place. From the concentrated solution, alum is produced by crystallisation. In the years 2005 until 2010, the alum was partly reprocessed in the station SLKR II to aluminum sulphate and ammonium sulphate for further sale. However, this economically unviable production became obsolete after a contract with a local fertilizer producer was concluded that assured purchase of all alum produced at Stráž.[87]

Other residues are transformed by calcination into insoluble products for safe storage. The treated water from these processes is released into the receiving river Ploučnice. Until 2009, the residual solutions after alum crystallisation (mother liquor) were injected back to the Cenomanian aquifer in order to reduce the amount of saline liquids in the underground.[88]

The remaining part of the residual technological fluids with lower pollutant concentrations (approximately 25 g/l) is transferred to the neutralization station (NDS 6). At the station, all contaminated waters are treated – from the Turonian and Cenomanian aquifer as well as water from the tailings pond. After the reconstruction in 2006, the station reached a processing capacity of up to 5.5 m^3 of residual fluids per minute. The treated water is discharged into the river Ploučnice.[89]

In 2009, the construction of the neutralization station for treatment of mother liquor (NDS ML) was finished. With the start of the NDS ML operation, the so called 'intensification of the remediation' begun, no re-injection of the mother liquor into the deposit is necessary anymore. Thus, the actual restoration of the deposit zone commenced.

The NDS ML increased the decontamination rate to up to 100,000 tons of TDS per year. The principle of the treatment station is neutralisation and alkalisation of the mother liquor using calcium hydroxide and subsequent liquidation of ammonia using water vapour. The capacity of NDS ML is processing of 132 m^3 residual technological fluids per hour with average concentration of dissolved solids 120 g/l. Regarding the waste generation, the NDS ML produces a maximum of 46 t of filter cake (80% calcium sulphate; 20% mostly aluminium hydroxide) per hour which is

[87] DIAMO, o.z. TÚU, personal interview, 6 September 2012.

[88] Beneš (2011); DIAMO s.p. website, http://www.diamo.cz/en/tuu, last access 17 April 2012; Vrijen (2006); Tomáš, (2000).

[89] DIAMO s.p. website, http://www.diamo.cz/en/tuu, last access 17 April 2012; DIAMO Newspaper, Volume VIII (XXX), No. 1, January 2007; Ekert (2010).

then transferred to the tailings pond. Another resulting product, ammonia hydroxide, is either stored and used for internal purposes or sold in case of excess. The annual fix costs of the station will amount to approximately 250 million CZK [10 million EUR].

After the completion of NDS ML, the re-injection of mother liquor into the deposit became obsolete. However, in order to ensure the optimal under-balance in the Cenomanian aquifer in the area of the leaching fields, injection of treated Turonian water into the barrier is necessary until the Hamr mine is completely flooded. Afterwards, the barrier could be partly used for an in situ immobilisation via injection of alkalised solutions.

For the flooding of Hamr mine, water from II. stage of the tailings pond alkalised with lime was initially used to improve hydrochemical conditions in the Hamr mine. As a positive by-effect, the pond water could be eliminated without the need for its treatment. Nowadays, the mine is flooded by the natural flow of groundwater. Additionally, residual technological solutions from the neutralisation stations NDS ML and NDS 10 with pH of about 11 are injected into the mine to increase the overall water pH.[90]

The produced solid sediments (e.g. filter cake) from all above mentioned processes are stored at the tailings pond. Additionally, any seepage water is being continuously returned to the pond.[91]

However, the present extent of decontamination is not entirely sufficient to achieve the set goals. The current installations have to be supplemented by additional facilities in order to shorten the time needed for completion of the remediation and thus significantly decrease the overall costs. These facilities are namely neutralisation station NDS 10 (second processing line); additional network of remediation wells, new pumping station and an adjustment of the II. stage of the tailings pond. These projects are foreseen for the next remediation phase. A simplified scheme of the final process flow is illustrated in the figure below.[92]

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[90] Ekert (2010); DIAMO Newspaper, Volume XIII (XXX), Special Issue, May 2008; DIAMO Newspaper, Volume XIII (XXX), No. 8, August 2008.

[91] DIAMO s.p. website, http://www.diamo.cz/en/tuu, last access 17 April 2012; DIAMO Newspaper, Volume VIII (XXX), No. 1, January 2007.

[92] Ekert (2010); DIAMO Newspaper, Volume XIII (XXX), Special Issue, May 2008.

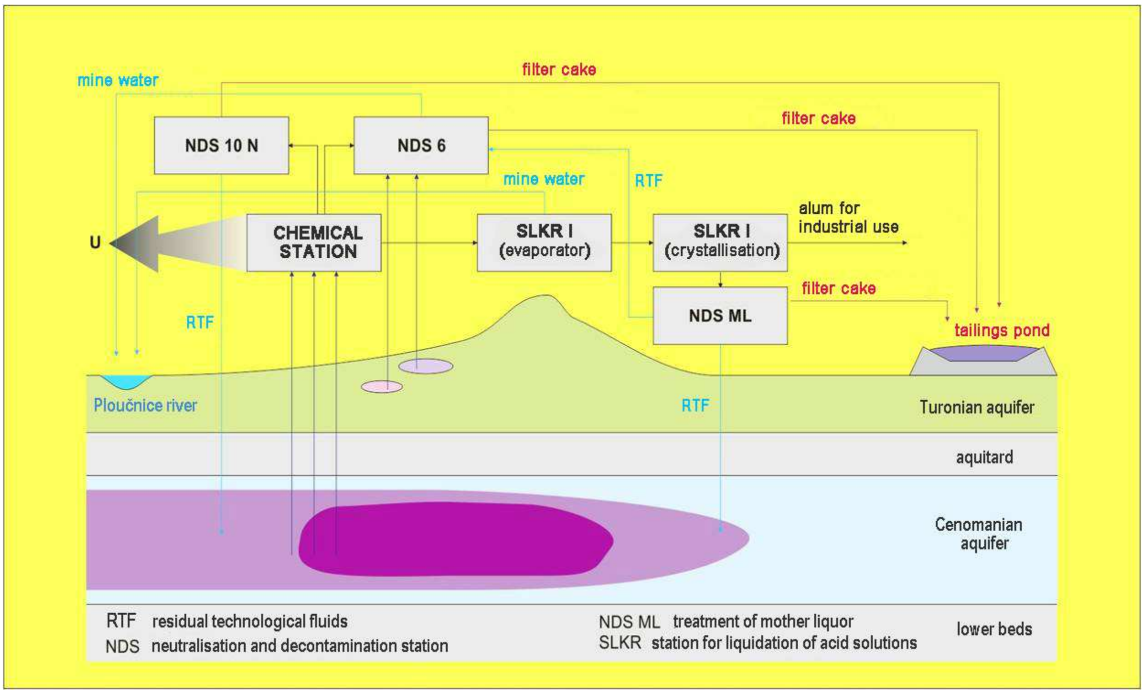

Figure 3. Final Configuration of the Remediation Process.
Source: DIAMO s.p., o.z. TÚU, internal material from 31 August 2012 [translated by the author].

After completion of the whole complex of the above mentioned remediation technologies, 5.2 million m^3 of residual fluids from Cenomanian and Turonian aquifers should be treated per year, leading to the liquidation of about 120,000 t of contaminants; and generating 30,000 t of alum and 360,000 m^3 of tailings to be stored.[93]

As another step, an in situ immobilisation of contaminants is planned as soon as the water pH reaches the required levels (in this case pH 2.5 - 3). The principle of this immobilisation is to transform compounds from a mobile form (e.g. solution) into an immobile one (e.g. sediments). The process consists of injection of an alkalic immobilization agent into the ore. The agent decreases the acidity of remaining technological fluids and initiates precipitation of the contaminants (namely SO_4^{2-}, Al, Fe). In the here examined case, the alkalic solutions generated by the neutralisation stations are injected into the deep mine Hamr. The natural groundwater flow in southwest direction will then carry this solution to the area affected by the technological fluids from ISL and will ideally trigger a natural immobilization effect. The target pH value at which the natural attenuation process will be initiated

[93] DIAMO Newspaper, Volume XVII (XXXIV), No. 2, February 2012.

is about 4 - 4.5. At this pH, a sedimentation of Al occurs which bounds Be whereas at lower pH (circa 2.5), Fe precipitates and bounds As.[94]

The utilisation of this process at the ISL fields directly and its possible side effects are still being tested and evaluated on experimental level at a part of the leaching fields. Another researched remediation method is also the injection of zero valent iron into the porous underground environment.[95]

In the following sections, the remediation plan based on the most recent risk assessment actualisation is presented.

2.2.5 Remediation Plan: Activities 2012-2015

The trial operation of NDS 10 commenced in 2012. NDS 10 technology is similar to NDS ML, it utilises neutralisation and alkalisation of residual technological fluids using lime milk and subsequent elimination of ammonia using water vapour. The foreseen performance is 4.4 m^3 of fluids with concentration of maximum 25 g/l per minute. Annually, NDS 10 should dispose of 30,000 tons of contaminants. In total, the aim for this phase is to liquidate 90,000 to 120,000 t of contaminants per year. Regarding the generated waste, all the neutralisation stations (NDS 6, NDS 10 and NDS ML) will produce 240 to 335 thousand m^3 of filter cake per year. The neutralisation stations NDS 10 and NDS ML are located next to the tailings pond to ensure an effective waste management.

Moreover, in this phase, the project “Final Solution of tailings pond Stráž pod Ralskem” will be carried out. The aim is to prepare the tailings pond at Stráž for the storage of tailings resulting from the neutralisation processes. The dams of the pond will be heightened to required level. The most important part of this project is the placement of a sealing desk over the whole pond area.[96] Furthermore, mining wells will be decommissioned and plugged. At the same time, new monitoring and remediation wells will be drilled.[97]

In addition, throughout the whole remediation process, the following precaution measures were determined which should eliminate other risk factors:

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[94] DIAMO s.p., o.z. TÚU, personal communication from 17 September 2012.

[95] DIAMO Newspaper, Volume XIII (XXX), No. 2, February 2007.

[96] Ekert (2010); DIAMO Newspaper, Volume XIII (XXX), Special Issue, May 2008; DIAMO Newspaper, Volume XIII (XXX), No. 8, August 2008.

[97] DIAMO Newspaper, Volume XIII (XXX), No. 8, August 2008; DIAMO Newspaper, Volume XV (XXXII), No. 11, November 2010.

decommissioning of wells which might connect Turonian and Cenomanian aquifers; increasing pH value in the ISL fields after remediation; reducing redox reaction potential or triggering sedimentation of residual contaminants in situ. Furthermore, extending pollution monitoring by parameters Cd, Hg and Co as well as the monitoring of changes in radionuclides contamination related to the remediation progress is recommended. Simultaneously, continuous equipment renovation and necessary reconstruction works is to be carried out.[98]

The main solution flows and planned extent of the decontamination for this phase are given in the following table.

Table 4. Solution Flow and Decontamination Progress for 2012-2015

Flows	Units	2012	2013	2014	2015
Solutions to SLKR I	thousand m^3	1 682	2 102	2 102	2 102
Solutions to NDS 6	thousand m^3	1 419	1 367	1 367	1 419
Solutions to NDS ML	thousand m^3	736	841	841	841
Solutions to NDS 10	thousand m^3	420	841	946	946
Contaminants withdrawn from the Cenomanian aquifer (SO_4^{2-})	tons	82 700	103 500	101 000	95 000
Wells to be decommissioned	No.	200	200	200	200

Source: Czech Chamber of Commerce (2011): Report about the results of the actualization of risk assessment and its impact on the total costs connected to dealing with the impacts of chemical uranium mining and related activities at Stráž pod Ralskem and its financing for the time period 2012-2042.

[98] Czech Chamber of Commerce (2011).

2.2.6 Remediation Plan: Activities 2016-2020

In this period, the most important goal is to complete the remediation of the Turonian aquifer between 2016 and 2018. Furthermore, the second processing line of NDS 10 will be put into operation. The instalment of remediation well network, area-wide decommissioning of mining wells and heightening of tailings pond dam is planned to be finished.[99]

Moreover, the operation of the hydraulic barriers will end by 2019, after the complete flooding of the deep mine Hamr in 2016. The remaining wells of the barrier will be used for injection of alkalic solution in order to facilitate the natural attenuation.[100]

At the tailings pond, filter cake in the amount of 300,000 m^3 will be disposed. The decommissioning of wells and redundant surface facilities will continue. Afterwards, the cleared surface will undergo a recultivation.[101]

The main solution flows and the extent of decontamination for this phase are given in Table 5.

Table 5. Solution Flow and Decontamination Progress for 2016-2020

Flows	Units	2016-2020
Solutions to SLKR I	thousand m^3	10 249
Solutions to NDS 6	thousand m^3	4 993
Solutions to NDS ML	thousand m^3	4 205
Solutions to NDS 10	thousand m^3	7 358
Contaminants withdrawn from the Cenomanian aquifer (SO_4^{2-})	tons	456 500
Wells to be decommissioned	No.	1 389

Source: Czech Chamber of Commerce (2011).

[99] DIAMO Newspaper, Volume XVII (XXXIV), No. 2, February 2012.
[100] DIAMO Newspaper, Volume XVII (XXXIV), No. 2, February 2012.
[101] Czech Chamber of Commerce (2011).

2.2.7 Remediation Plan: Activities 2021-2030

In this time period, the operation of all remediation facilities will be adjusted to the contaminant concentration levels. Since a significant decrease in the concentration levels is expected, the function of these technologies will be gradually limited. The production of alum will cease entirely. In 2030, the decontamination station SLKR I will be closed.

The decommissioning of bore holes and facilities will continue in the same manner as in the previous stage. The filter cake storage at the tailings pond will decrease to 200,000 m^3 per year. The part of the pond where the disposal of filter cake and other mining related waste was concluded, recultivation works will start. In this regard, investments into new technologies for the tailings treatment such as its injection into former hydraulic barriers and leaching fields are planned.[102]

The volume of solution flows are shown in the table below.

Table 6. Solution Flow and Decontamination Progress for 2021-2030

Flows	Units	2016-2020
Solutions to SLKR I	thousand m^3	20 498
Solutions to NDS 6	thousand m^3	6 833
Solutions to NDS ML	thousand m^3	8 410
Solutions to NDS 10	thousand m^3	18 922
Contaminants withdrawn from the Cenomanian aquifer (SO_4^{2-})	tons	807 400
Wells to be decommissioned	No.	2 960

Source: Czech Chamber of Commerce (2011).

[102] Czech Chamber of Commerce (2011).

2.2.8 Remediation Plan: Activities 2031-2042

During the final stage, all decontamination facilities will limit their operation and by 2037, after the target values will be reached, all these facilities will be closed and decommissioned. Overall, 3.14 million tons of contaminants from the Cenomanian and 10,000 tons from the Turonian aquifer should be eliminated.

The contaminated demolition waste will be stored at the tailings pond. The disposal of filter cake at the pond will end in 2037.

From 2037 until 2040, all remediation facilities, leaching and remediation wells and other surface installation will be decommissioned. Annually, 200-300 wells will be decommissioned with the overall objective to liquidate 9,000 wells in such manner that after the completion of the water decontamination, no hydraulic communication between the two aquifers will be possible. Remaining drill holes will be kept for post-remediation monitoring purposes. The tailings pond will be decommissioned in 2 phases: in 2026, the I. stage of the pond area will be rehabilitated; the II. stage will be remediated after the completion of the decontamination. Sludge from a former lake situated near the pond will serve as remediation material. To limit the arising radiation to the lowest level possible, a 0.6 m layer of inert material will cover the remediated pond.[103] The rehabilitated tailings pond will remain as the only permanent legacy of the uranium mining at Stráž.

At last, the rehabilitation of the surface area and the river ecosystem will be finalised.[104]

The main figures for the last remediation stage are shown in Table 7.

[103] DIAMO Newspaper, Volume XVII (XXXIV), No. 2, February 2012.

[104] DIAMO Newspaper, Volume XVI (XXXIII), No. 11, November 2011; DIAMO Newspaper, Volume XVII (XXXIV), No. 2, February 2012; Czech Chamber of Commerce (2011); DIAMO s.p., o.z. TÚU (2005): Využití odkaliště Stráž pro zahlazování následků hornické činnosti [Utilisation of Tailings Pond at Stráž for Remediation of Results of Mining Activities].

Table 7. Solution Flow and Decontamination Progress for 2031-2042

Flows	Units	2031-2042
Solutions to NDS 6	thousand m^3	5 887
Solutions to NDS ML	thousand m^3	5 887
Solutions to NDS 10	thousand m^3	13 245
Contaminants withdrawn from the Cenomanian aquifer (SO_4^{2-})	tons	321 000
Wells to be decommissioned	No.	3 575

Source: Czech Chamber of Commerce (2011).

2.3 Other Sources of Pollution

Other sources of pollution at Stráž are currently only of minor importance and do not breach legal limits.

Regarding the air pollution, the stationary sources are mostly the remediation facilities. At Stráž, the main pollutants were generated during transformation of alum into aluminum sulphate which is not carried out anymore; during high temperature nitrogen reduction and in heat boilers. A significant mobile pollution source is the transport of generated waste to the tailings pond.[105]

The contamination of soil is caused mainly by spillage of technological fluids, originating for example from fissures in the surface pipe joints or transport accidents. If such case occurs, extraordinary measurements and monitoring is conducted, consisting inter alia of using neutralisation agents or additional gamma radiance measurements.[106]

None of the pollution generated exceeds limits stated by the legislation. In Table 8, the recent levels of most relevant pollutants are shown:

[105] DIAMO Newspaper, Volume XII (XXIX), No. 6, June 2006.
[106] DIAMO Newspaper, Volume XII (XXIX), No. 6, June 2006.

Table 8. Relevant Emissions at the Site Stráž pod Ralskem

Pollutants (tons/year)								
	PM	**NO_x**	**SO_2**	**CO**	**C_xH_y**	**NH_3**	**CH_4**	**CO_2**
2011	0.280	11.055	0.255	1.041	0.389	0.000	-	22,784
2010	0.517	16.668	10.412	7.366	0.580	0.060	-	25,859

Source: DIAMO Newspaper, Volume XVI (XXXIII), No. 5, May 2011; DIAMO Newspaper, Volume XVII (XXXIV), No. 2, February 2012.

2.4 Decontamination of the Surface Area

Simultaneously to the mine dismantling and water decontamination, the surface remediation problem is addressed. The area of the ISL mining comprises of diverse locations with varying levels of contamination and with different usability.[107]

Originally, the locality was mostly covered by forests. Fields and grasslands for agricultural use, creek meadows (especially alongside of the river Ploučnice) and wetlands were also part of the Stráž bioregion. Moreover, it was a popular and important recreational area.[108]

In order to proceed with the ISL uranium mining, an extensive deforestation was carried out. The hilly landscape underwent significant modification. At present, the terrain is pierced by wells, pipelines and dense traffic infrastructure. The water system of the wetlands has been disturbed, the soil became predominantly mudded and small ponds arose. Furthermore, the local water cycle was distorted by redirecting the water course alongside the leaching fields. After deforestation, the area was mostly left to natural plant succession. Only in a part of the area, vegetation was planted.[109]

A plan has been developed for the recultivation of the landscape after ISL. According to the remediation project, conservation as well as partial afforestation and agricultural restoration of the well fields is foreseen. The project is divided into four parts, following the land recultivation map (Figure 4).

[107] DIAMO s.p. website, http://www.diamo.cz/rekultivacni-prace/menu-id-13, last access 1 May 2012.
[108] Ibid.
[109] Ibid.

These parts are:

i) Areas influenced by potential alteration of the river Ploučnice course: This territory of about 95 ha is for the time being excluded from the rehabilitation processes until the revitalization of the river is completely finished.

ii) Areas with conservation regime: The wetlands are part of this area. For their protection, a non-intervention regime has been adopted.

iii) Built-up area on which the decontamination facilities are located. Some of the buildings as well as the road infrastructure will remain in place for future industrial or recreational use.

iv) Areas determined for revitalization and recultivation including targeted reforestation and revegetation with utilization of natural components, for further use in forestry and agriculture.[110]

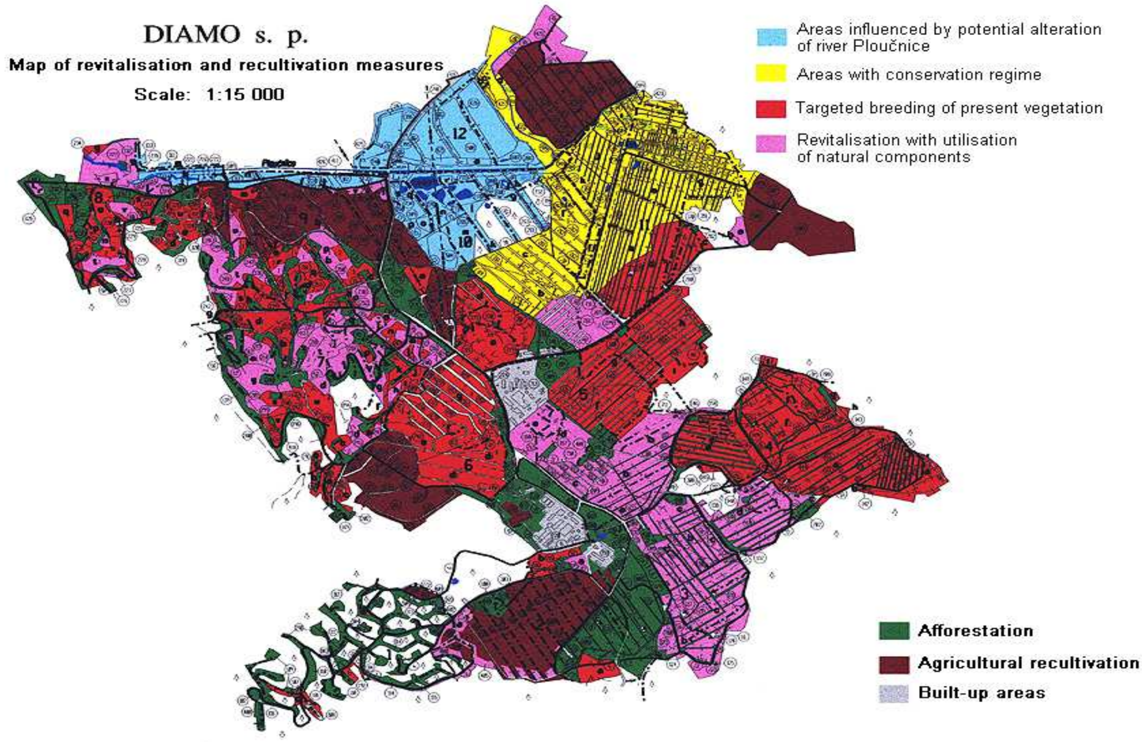

Figure 4. Map of Revitalization and Recultivation Measures at the Leaching Field Surface.
Source: DIAMO s.p., website http://www.diamo.cz/rekultivacni-prace/menu-id-13 [translated and adjusted by the author]).

[110] DIAMO s.p. website, http://www.diamo.cz/rekultivacni-prace/menu-id-13, last access 1 May 2012.

A gradual decommissioning of the redundant surface facilities is conducted. The empty facilities often attract metal thieves or are subject to illegal waste disposal. Since the buildings were built during the communist regime when the amount of material used was much larger than necessary their demolition involves a great waste generation.[111]

The decommissioning waste is currently disposed at the tailings pond, I. stage, and is immediately covered by inert material to prevent dust generation. After the complete remediation of the site, the final status of the pond should be grassland with shallow rooted vegetation and possible utilisation as a grazing field.[112]

In present, the rehabilitation of surface is progressing successfully. The afforestation is mostly left to the natural succession. The resulting vegetation is dense and offers an adequate living space for wild animals. To support the re-growth of the vegetation, measures to protect young trees have been installed such as small fences. Moreover, a part of the remediated leaching fields built on an agricultural soil is nowadays used for agricultural purposes again.[113] The surrounding forests and favourable climatic conditions are an important factor for relatively fast and successful remediation of the surface area.

2.5 Overall Monitoring of Environmental Impact

Simultaneously to the above mentioned remediation processes, the following data and parameters are annually assessed and monitored in order to determine the status of pollution and eventual impacts of remediation processes:

- volume and contamination of recovered, injected, decontaminated and released water;
- volume of affected ground- and surface water;
- emission and immisions from heating and technological sources;
- contamination of soil and other biological material;
- volume and type of generated and store mining products;
- methods and extent of recultivation;

[111] DIAMO Newspaper, Volume XIV (XXXI), No. 1, January 2009.
[112] DIAMO, o.z. TÚU, personal communication, 6 September 2012; DIAMO s.p. website, http://www.diamo.cz/rekultivacni-prace/menu-id-13, last access 1 May 2012.
[113] DIAMO Newspaper, Volume XV (XXXII), No. 6, June 2010.

- extent of contamination with radionuclides at the point of discharge and in surrounding residential area;
- level of radiation in surrounding residential area.[114]

Regarding water, the most endangered pathway, it is divided into 3 water ‘types’: mine water, surface water and groundwater (Turonian and Cenomanian). The monitored parameters differ slightly for each type, but the most important monitored pollutants are common: pH, total suspended substances (TSS), TDS, SO_4^-, F^-, Cl^-, NH_4^+, Fe, Ba, ^{226}Ra, U, Ni, Mn_{total}, Ca^{2+}, Mg^{2+}, and others. For mine water, additionally, the total alpha and beta activity as well as heavy metals such as Cd or Pb are measured.[115]

The measurements of the radiological impact on public living in the seven surrounding municipalities focus on: effective dose from external γ radiation; inhalation of radioactive substances (radon, products of radon decay chain, radionuclides from uranium-radium decay chain); ingestion of radionuclides from water and food consumption (fish and plants). The parameters for estimation of radiation exposure by ingestion are three critical radionuclides U_{nat}, ^{226}Ra and ^{210}Pb. The optimalisation limit for the public effective dose is set for the Stráž area to 50µSv per year (the general limit is 1000 µSv per year). In the period 2007-2011, the sum of yearly effective doses exceeded the optimalisation limit of 50µSv in 5 municipalities. The critical pathway for the radionuclide intake is inhalation of radon and radon products. Thus, as a possible measure, an immediate covering of all not operated parts of the tailings pond with inert material would be effective. However, the calculations showed that the high expenses connected to such measure would be higher than the gained benefit.[116]

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[114] DIAMO Newspaper, Volume XII (XXIX), Special Issue, March 2006.

[115] DIAMO s.p. (2010): Environmental Burdens under the Administration of DIAMO, s.e., Stráž pod Ralskem, Stráž pod Ralskem.

[116] DIAMO s.p., o.z. TÚU (2012): Vyhodnocení programu monitorování a dodržování ustanovení vyhlášky SÚJB č. 307/2002 Sb., o radiační ochraně, ve znění pozdějších předpisů v o.z. ´TÚU za rok 2011 [Evaluation of monitoring programme and compliance with regulation SÚJB č. 307/2002 Coll., concerning radiation protection, as subsequently amended, at o.z. TÚU for the year 2011], Stráž pod Ralskem.

Furthermore, the waste from decommissioning of surface facilities is monitored for contamination with radionuclides. Contaminated residues are disposed at tailings pond and covered with inert material to protect the nearby residential area.[117]

2.6 Other Activities of the TÚU

TÚU is continuously considering alternative options for decontamination of polluted water as well as new utilisation of final products via cooperation with Czech academic institutions as well as specialized companies. TÚU also takes part or organizes several scientific seminars which are also partly dedicated to the public and affected towns.[118] The TÚU has good relations with the public and no conflicts are reported.[119]

In addition, DIAMO publishes annual report on environmental status of impact originating from DIAMO activities on monitored parameters: water management, hydrogeology, air, surface and biological material, waste management, mining residues and rehabilitation of environment.

Moreover, DIAMO issues every month a newspaper where detailed information and updates on concerned sites and new developments are published. The authors are engineers currently employed at DIAMO or former workers. Thus, the articles allow educated insight into the most important events and remediation developments at the mining sites managed by DIAMO.

Furthermore, the international cooperation of DIAMO is quite extensive. DIAMO hosts the International Training Centre of the World Nuclear University - School of Uranium Production. The concept was outlined in 2005 at an OECD/NEA conference, with IAEA as its main partner. The first courses started already in autumn 2006. The participants come mostly from transition countries such as China, Kazakhstan or Latin America. The experience with ISL is a subject of great interest of these countries. Moreover, the cooperation with the German experts where the uranium mining legacies are similar increased in recent years.[120]

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[117] DIAMO Newspaper, Volume XVI (XXXIII), No. 10, October 2011; Vrijen (2006).
[118] DIAMO Newspaper, Volume XII (XXIX), No. 1, January 2006; DIAMO Newspaper, Volume XII (XXIX), No. 4, April 2006.
[119] DIAMO s.p., o.z. TÚU, personal interview, 6 September 2012.
[120] DIAMO Newspaper, Volume XII (XXIX), No. 10-11, October-November 2006; DIAMO Newspaper, Volume XI (XXVIII), No. 11, November 2005.

2.7 Long-term Stewardship

Currently, there are no specific plans for a long-term stewardship after the remediation finalisation in 2042. The after-care will be developed only after a post-remediation risk assessment.[121]

Ideally, after the remediation, the tailings pond will remain the only permanent environmental burden. The airborne pollution originating from radioactive substances can be excluded since the waste contaminated with radionuclides is sufficiently immobilised by adequate covers. The radiation limits at all points of discharge are already in present far lower than required by legal limits.

On the basis of the reports subjected to the Ministry of Environment[122], the following long-term stewardship measures can be considered: Regarding the tailings pond, the most relevant contamination source will remain the drainage water. Therefore, continuing monitoring and decontamination of the water will most likely be necessary. Construction of a new small water treatment station at the tailings pond is a possible option. Furthermore, long-rooted vegetation and other possible damage to the pond cover have to be prevented or removed immediately. Active maintenance will be required also for the infrastructure and other facilities used for monitoring of the pond.

However, even after the achievement of set target limits, the aquifer waters have to be monitored for a long time period. The migration pathways of the chemicals could be subject to considerable alteration since geological, chemical and/or hydrological status of the ores in certain areas are still not entirely known due to the complicated tectonic history of the region.[123] Thus, it is possible that a re-evaluation of current as well as future migration models will be necessary.

[121] DIAMO s.p., o.z. TÚU, personal interview, 6 September 2012.
[122] DIAMO s.p., o.z. TÚU (2005): Využití odkaliště Stráž pro zahlazování následků hornické činnosti [Utilisation of Tailings Pond at Stráž for Remediation of Results of Mining Activities].
[123] DIAMO s.p., o.z. TÚU, personal interview, 6 September 2012.

3. Interim Evaluation and a Stewardship Plan Proposal

In the light of the large environmental damage that occurred due to the application of the ISL method in unsuitable conditions and non-existent protection of the affected aquifers during the operational stage of the ISL mine at Stráž, the problems that have to be addressed in the remediation plan are quite extensive. In the previous chapters, the respective environmental burdens and the adopted solutions were presented. In this section, an attempt to evaluate the approach chosen by the TÚU on the basis of the recommendations from the international community is made. Furthermore, a proposal for a long-term stewardship plan is developed.

First, the preparation stage is analysed. As recommended by the IAEA and OECD, the remediation plan development was preceded by a baseline data collection and a site characterisation lasting for several years from 1990 on, including an assessment of possible remediation impacts. This research commenced while the mine was still in operation. The subsequent development of a remediation plan was based on this site characterisation and baseline data. Concrete remediation goals and maximal allowed concentration limits were set. Moreover, the models used for setting the parameter limits were designed as flexible tools that allow easier actualisations. Environmental parameters to be monitored as well as obligations for regular reporting were determined. Furthermore, alternative treatment system options that would increase the remediation efficiency and decrease the costs are researched at the same time. All these activities follow the best practice.

The first decontamination facilities commenced its operation shortly after the mine closure in 1996, the second essential stage of the decontamination process did not commence its operation until 5 years later. An earlier start would be desirable but was hindered due to financial and also legislative constraints since the laws for environmental protection were developing at the same time.

On the whole, the preparation phase lasted approximately 10 years, from conducting the first environmental analyses to a systematic decontamination process. The reasons for such a long preparation period are manifold, mainly the absence of solid pre-operational baseline data and of previous environmental precaution measures. Hence, basic data and environmental assessment had to be conducted first. Moreover, the first planning steps were made in the period of great financial and political uncertainties of the first years after the end of the communist regime in 1989 that did not allow a faster and more efficient remediation progress.

The steps for the development of the remediation plan comply with the recommendations from the international community. However, their realisation took too much time so that the contamination of the environment spread even after the closure of the mine.

The restoration of the underground and thus the remediation as such did not start until 2009 when the NDS ML technology commenced its operation. In the previous years, the process focused solely on stabilisation of the environment to prevent further contamination. The slow progress in installing new remediation technologies was caused by financial uncertainties and the ambiguous legal status of the ISL mining which is discussed later. These issues were not solved until 2011.

The current technologies are efficient from the decontamination point of view. The effort has been made to transform the decontamination products to environmentally stable, sellable or further usable products. With the termination of production of aluminum sulphate, a redundant technology and a source of significant pollution was eliminated. Hence, the efficiency increased, the costs decreased. In addition, the technologies aim at generating as small amount of waste as possible. This also considerably reduces costs due to smaller area needed for storage space at tailings ponds and subsequent simpler and cheaper after-care of these impoundments.

As a possible improvement measure, more efficient radiation protection could be adopted since the annual effective radiation dose on the public living in the area exceeds the optimalisation limit already for five years. Since the covering of the tailings impoundments is the most suitable solution, prioritising of the closure of the I. stage of the tailings pond is desirable.

The information policy of DIAMO can be evaluated as transparent. The monitoring of all relevant environmental parameters is conducted annually and the results are published online. The contact with the public is maintained also via organizing of seminars and other informational events. Moreover, there is a possibility for interested public to take part in excursions of the ISL site free of charge. The TÚU is currently not experiencing any conflicts with the public.

Eventual problems arising at the ISL site are discussed and solved in cooperation with the Czech and foreign academic institutions. Furthermore, DIAMO is in close contact with the international community, especially with the German company Wismut GmbH which copes with similar issues. Moreover, the World Nuclear University - School of Uranium Production which is situated at Stráž offers international cooperation which has been proven to be very beneficial for all parties involved.

The most recent remediation plan is based on an update of previous risk assessments. This considers results of research lasting for more than ten years, including experience from experimental operations of new technologies (e.g. in situ immobilisation of contaminants). New methods as well as new parameters that pose an environmental risk have been identified.
The remediation plan consists of four stages; each of them determines a concrete time frame and a goal to be achieved. The amount of generated waste is also estimated which is crucial for their disposal at tailings ponds and its subsequent remediation. This is in accordance with the IAEA/OECD recommendations. Moreover, the funding for the whole remediation plan has been defined; with a pre-determined funding source and maximal amount to be spent (the financial details are given in the next chapter). While this offers financial security, which is especially important for a state-funded enterprise, it also leads to a lower economic flexibility of the plan which is generally recommended by the best practice. A revision of the current remediation programme is planned for every five years.
The post-remediation period is determined for five years. However, there are no concrete plans for a long-term stewardship of the site which is an important weakness of the current remediation project.

At Stráž, the tailings pond will remain the only permanent environmental burden. After the decontamination of the aquifers, the tailings pond is not likely to be a source of significant pollution due to the stable characteristics of the mining waste and its low radioactivity. At present, none of the contamination values at the surface points of discharge exceeds legal limits. However, the large extent of current contamination of the aquifers and a possible change in hydrogeochemical conditions of the ores still requires a water quality monitoring period of several decades after the remediation.

Thus, it would be recommendable to set up a stewardship plan that determines a time frame, parameters to be monitored (the main concern is likely to remain the water contamination) and which identifies the institution responsible for conducting the stewardship and the authority which would provide funding.

In the following, a proposal for such a long-term stewardship is presented:

As mentioned above, the IAEA does not recommend a programme lasting beyond three generations. Therefore, defining generation as a time period of 30 years, a plan from 2042 until 2132 should be developed according to the risk assessment conducted in the final years of the remediation. The stewardship plan should be drafted as soon as the regular assessments show sufficient environmental stabilisation of the site so that a long-term prognosis can be made. Ideally, the programme is developed together with the last two risk assessments, i.e. ten years prior the closure in 2042.

The post-closure period is likely to concentrate solely on the tailings pond and the underground aquifer contamination levels. The locality to be maintained should be as small as possible and protected with adequate engineered structures (e.g. fences or surveillance cameras) to prevent unauthorised access, especially material theft which currently constitutes a problem due to the large area of the ISL fields.

Since it is likely that a small water treatment station will be necessary for the decontamination of the pond water, its construction should be the initial step in the long-term stewardship. Ideally, this station would be installed already during the final decommissioning activities, so that the existing infrastructure can be adapted to the needs of the water treatment plant. Near the pond, several facilities used for the decontamination including a transport network are already present. Thus, the post remediation water treatment is not likely to constitute a large investment. Furthermore, in this regard, the high population density and the immediate vicinity of a town are of advantage since there will not be a need for additional social infrastructure for the maintenance workers. Academic institutions in Liberec and Prague that participate in the remediation can be reached only in thirty minutes or one hour, respectively, so that scientifically more complex activities or site evaluation will not require significant resources or time expenditure.

The current contamination levels of the surface water are already far below the legal limits. Provided that the tailings disposed at the pond will continue to be environmentally stable and water insoluble as the remediation plan foresees, this is not likely to change considerably. Thus, the treatment of surface water will not be necessary for the whole period of 90 years and the water treatment station could be decommissioned already few years after the completion of remediation in 2042 and replaced by passive treatment such as phytoremediation or natural attenuation.

With the closure of the pond water treatment station, the phase of an active after-care is concluded. However, another condition for the end of the active maintenance is that the coverings of the tailings pond are adequately stable so that intrusion or erosion by natural elements will not lead to fast degradation of the covers and eventual exposure of the contaminated waste. Thus, it is advisable to prioritise in the first years of the long-term stewardship an instalment of a resistant tailings pond cover. In this way, the cost intensive active maintenance stage is shortened to a minimal time span necessary. It can be assumed that the technological development in 2042 will allow a development of such a cover.

After the conclusion of the active post-remediation care, the phase comprising mainly of surveillance commences. The maintenance should be reduced to a level necessary to ensure that the monitoring wells and the tailings pond are in a good physical state. Such control will be required at least once during winter and summer and in case of extreme natural events. Under normal conditions, such monitoring including water sample collection should not be necessary more than twice a year. However, all mentioned measures have to take into consideration the regularly conducted risk assessments. Furthermore, all steps, contamination values and possible threats have to be communicated with concerned public and the owners of the surrounding areas released for unrestricted land utilisation. This will - according to the current plans - involve agricultural and recreational use.

Concerning the monitoring of the pollution levels of the underground (and surface) water, this will be necessary for a period longer than the stated ninety years. Existing monitoring well network can be used focusing on the most endangered area that will be determined in the final risk assessments. A particular attention should be paid to the regions where the ore environment is not fully assessed or where geochemical changes that could affect the flow of contaminated water are likely. The pollutants to be monitored for surface and underground water are already determined by current risk assessments. In case of new scientific findings, the parameter sets can be expanded or reduced.

Regarding the institution responsible for the long-term stewardship, it is recommendable that the current enterprise DIAMO or its subsidiary TÚU, respectively, continues to be responsible for the after-care. The TÚU has considerable experience and knowledge about the mining site and its characteristics. Hence, at this point, it does not seem reasonable to transfer the responsibility to another subject. Since the tailings pond and the neighbouring area is not likely to be released for commercial purposes, the funding should also remain with the state, provided that a comprehensive financial scheme will be developed already before 2042 as an integral part of the drafted after-care programme. In addition, a clear legal status of the ISL site and respective legislation regulating its after-care have to be determined since in the future, the purchase of remediated areas by private entities could lead to legal conflicts.

In conclusion, the strong link of the remediation plan to risk assessments and ongoing scientific research, annual reports, relatively transparent information policy and international cooperation are the most important strengths of the remediation project. As mentioned above, it is advisable to develop a plan for a long-term stewardship which is not likely to be very complex if the presented remediation plan is realised to the full extent.

D. Case Study Part II: Internalization of Remediation Costs in the Nuclear Power Price

In this chapter, economics of the nuclear power generation and the assessment of the price for nuclear power is briefly outlined in order to identify the components incorporated, especially the share of uranium in the overall costs for nuclear energy generation.

Afterwards, the financial dimension of the remediation project of the ISL mining site in the Czech Republic is analysed in order to determine the impact of remediation costs on the total costs for uranium and the nuclear energy in the Czech Republic.

1. Assessment of the Price for Nuclear Power

To date, there are no established standards for costing of the nuclear power price.[124]

In general, there are two approaches how to measure the costs of a nuclear power plant (NPP) and thus of the nuclear energy as whole: the ‘overnight’ costs and the ‘levelised’ costs. The overnight costs account for the material and labour needed for a plant as if it all had been bought at the same time. This approach determines the costs of the capacity to produce electricity. The levelised costs on the contrary count up for the total amount of energy provided by the power plant over its life time divided by the total expenditures. These expenditures comprise of capital, finance and operating costs including fuel, decommissioning and waste disposal costs. Thus, the levelised costs indicate the cost of produced electricity.[125]

In detail, the costs for a NPP in the ‘levelised’ approach are usually divided into capital costs (consisting of planning, preparation and construction); operation and maintenance (O&M); as well as fuel and back-end costs (including decommissiong and dismantling of nuclear facilities and final waste storage). The O&M costs consider also environmental and health issues connected with NPP operation, legal obligations for provision of finances for decommissioning and radioactive waste management (typically in form of a contribution to a fund which accumulates the

[124] Kessides, Ioannis N. (2010): Nuclear Power: Understanding the Economic Risks and Uncertainties, in: Energy Policy 38, pp. 3849-3864.

[125] Morton, Oliver (2012): The Dream that Failed, in: The Economist. Special Report on Nuclear Energy, 10 March 2012.

finances) as well as insurance for the case of accidents. In total, according to the estimations of the World Nuclear Agency (WNA), the capital costs account for 60 % of the overall cost for nuclear energy per kWh. The front end fuel costs of current NPPs constitute about 30-40 %. The uranium as such constitutes approximately 14 % of the total costs.[126]

According to the majority view, uranium price has only a little effect on the nuclear power generating costs and that even much higher prices would not significantly threaten the economic competitiveness of nuclear power since it constitutes only a minor fraction of the overall costs compared to coal or gas fired plants. As an illustration, a doubling of the uranium price would lead to 25 % increase of fuel costs and to about 10-15 % increase of the overall nuclear power generation in current operating state-of-the-art NPPs in the US. According to a recent study, uranium price increase can even have positive impact on future nuclear power costs, i.e. the overall price would decrease due to positive learning effects in the nuclear power industry.[127]

Regarding the uranium price, there is no open market for this commodity. The price is negotiated by buyers and suppliers in private contracts. Price indicators that serve as settlement prices for long-term contracts are to some extent released to the public by market consultants Ux Consulting and TradeTech.[128] The European Commission also publishes uranium prices; these are however based only on deliveries made to the EU utilities and the respective contracts.[129]

In conclusion, the basic characteristics of nuclear economics show that while decommissioning and waste disposal are considered in the overall price for nuclear energy and are hence internalised in the electricity price, costs of environmental

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[126] World Nuclear Association: The Economics of Nuclear Power, available at http://www.world-nuclear.org/info/inf02.html, last access 23 May 2012; Kessides (2010); Kahouli, Sondès (2011): Effects of technological learning and uranium price on nuclear cost: Preliminary insights from a multiple factors learning curve and uranium market modelling, in: Energy Economics 33, pp. 840-852.

[127] For instance: Kahouli (2011).

[128] Cameco website, http://www.cameco.com/investors/uranium_prices_and_spot_price/, last access 1 September 2012.

[129] European Commission website, http://ec.europa.eu/euratom/observatory_price.html, last access 9 September 2012.

burden caused during the front end processes are usually not included in the market price.[130] In such case, they constitute a negative externality.

Externalities are defined as costs that are imposed on the society as whole during production and consumption of energy that are not borne by the producers or consumers. Hence, environmental impact of uranium mining which needs to be remediated is a negative externality of nuclear power production that is covered neither by the vendors nor by the consumers and does not affect electricity prices on stock markets.[131]

In general, externalities are only marginally considered in the monetary evaluation of the nuclear life cycle. The most attention has been paid to the role of nuclear power in the climate change mitigation (positive externality) and the risks of nuclear power generation including possible accidents and radioactive waste issue (negative externality).[132]

How the environmental legacy of uranium mining as a part of the NFC is handled in the Czech Republic is discussed in the next section.

2. Nuclear Power Market in the Czech Republic

The energy market in the Czech Republic has been only partly liberalized. The owner of both Czech NPPs and thus the only producer of nuclear power in the Czech Republic is ČEZ a.s. The company was founded in June 1992, financed by the state. In 1994 and 2007, only a minor stake of the company was privatized. In 2003, the ČEZ Group emerged by fusion with distributor companies. At present, the Czech government remains the main shareholder of the ČEZ Group with 69.78 % share. ČEZ produces more than 72 % of electricity generated in the Czech Republic; the share of nuclear energy on the Czech electricity market is 40 %.[133]

As mentioned above, there are two nuclear power plants in the Czech Republic. The Dukovany nuclear power plant commenced energy production in 1985, the last

[130] Nestle, Uwe (2012): Does the use of nuclear power lead to lower electricity prices? An analysis of the debate in Germany with an international perspective, in: Energy Policy 41, pp. 152-160; European Commission (1995), ExternE, Externalities of Energy, Vol. 5: Nuclear, Luxembourg.
[131] Nestle (2012); European Commission (1995).
[132] Kessides (2010).
[133] ČEZ a.s., website http://www.cez.cz/cs/o-spolecnosti/cez/20-let-cez.html, last access 6 June 2012.

fourth unit operates since 1987. The current installed power output is 4 x 510 MW.[134] The second plant, Temelín, has two production units with 1,000 MW output each. The construction works commenced in 1987, Temelín however did not produce electricity until 2000. The power plant was commissioned in 2002.[135] In 2011, both power plants produced 28.2 billion kWh_e.[136]

The fuel of both plants is UO_2, with slightly enriched uranium (2-4%). The natural uranium used originates mostly from the Czech Republic; enrichment, conversion and fuel fabrication is provided by the Russian OAO TVEL.[137] Both plants currently burn up about 80 t of reactor fuel annually.[138]

All uranium produced by DIAMO is sold to ČEZ. The price is subject to a trade secret, so are the overall costs for generation of nuclear energy in the Czech Republic.[139] Thus, the figures for uranium price and costs of nuclear energy which are used in the calculations conducted in the following section are based on the prices published by the EU or on the estimates of the WNA, respectively.

3. Costs of Remediation at the ISL Mining Site at Stráž

According to the legislation, no remediation fund has been established in the Czech Republic; neither are the remediation costs considered in the uranium price. The remediation is thus fully covered by the Czech state.

In the years 1995 until 2000, a combined funding approach was adopted by the government. Activities related to uranium mining and processing were covered by the revenues from the sale of the uranium concentrate. Remediation of the environmental impact was financed solely from the state budget according to the respective legislation. Moreover, the state took over the arising social cost, for example unemployment welfare. In the period 2001-2006, the remediation was

[134] The 4 x 510 MWe output was installed in May 2012. Before, the capacity was 440 and 500, respectively.
[135] ČEZ a.s., website http://www.cez.cz/en/power-plants-and-environment/nuclear-power-plants.html, last access 6 June 2012.
[136] ČEZ a.s, personal communication, 4 September 2012.
[137] ČEZ a.s., website http://www.cez.cz/en/power-plants-and-environment/nuclear-power-plants.html, last access 6 June 2012.
[138] ČEZ a.s, personal communication, 4 September 2012.
[139] ČEZ a.s, personal communication, 6 September 2012; DIAMO s.p., o.z. TÚU, personal interview from 6 September 2012.

financed by the state and from the internal sources of DIAMO (e.g. revenues from sale of commercially usable by-products of the remediation).[140]

Since 2006, the remediation is covered by the state budget, internal DIAMO sources and also by the revenues from privatisation of state property as well as by profits arising from state share in enterprises.[141] Such combined approach was chosen so that the remediation costs are not fully provided directly from the yearly determined state budget.

It can be stated that from 1990 until 2011, no financial stability in form of a financing concept was provided to the TÚU. In comparison, funds for remediation of the uranium mines in Eastern Germany were determined already in 1991.[142] Since the remediation at Stráž is covered by the state, the availability of finances was always dependant on the respective political situation. Thus, the funds had to be increased ad hoc several times due to unforeseen or miscalculated costs or simply because the provided finances were not sufficient for the operation of the decontamination facilities. This situation was also partly caused by the unclear legal status of ISL mining in relation to other mining methods.[143]

The lack of finances posed substantial constraints to the remediation progress. In consequence, until the construction of the NDS ML, the remediation was practically limited to the prevention of further aquifer contamination since the mother liquor from neutralisation processes had to be re-injected into the ground and thus no restoration of the underground environment was possible.[144]

These uncertainties vanished only after the adoption of the newest remediation plan that defined funds for the whole duration of the future remediation. The finances for the period 2012-2042 come from the privatisation revenues and profits from the state-owned shares in companies, to the maximum amount of 32 billion CZK [1.28 billion EUR].[145]

The following table gives the overview of current and expected (for the period 2012-2042) costs of the remediation:

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[140] Czech Chamber of Commerce (2011); NEA; IAEA (2002).
[141] Czech Chamber of Commerce (2011).
[142] Hagen, M.; Jakubick, T. (2011): The Uranium Mining Legacy of Eastern Germany: From Remediation to Regional Development, in: The Uranium Mining Remediation Exchange Group (UMREG) Selected Papers 1995-2007, Vienna, pp. 110-124.
[143] DIAMO, TÚU, personal interview, 6 September 2012.
[144] DIAMO, TÚU, personal interview, 6 September 2012.
[145] Czech Chamber of Commerce (2011).

Table 9. Overall Estimated Costs for the Remediation of the ISL Mine at Stráž

	Costs in Given Years in million CZK
1990-2005	5,600
2006-2012	8,000
2012-2042	32,000
TOTAL	**45,600**
Total in EUR	**1,824,000 000 EUR**

Source: *Czech Chamber of Commerce (2011); DIAMO s.p., (2010): Environmental Burdens under the Administration of DIAMO, s.e., Stráž pod Ralskem, Stráž pod Ralskem.*

4. Impact of Remediation Costs on the Czech Nuclear Energy Price

Since the clean-up costs of the Stráž ISL mining site are not incorporated in the uranium price, these remediation costs can be qualified as a negative externality.
The issue of negative externalities is very complex, especially for the NFC due to the long-term horizon of radiological pollution and could be addressed in this thesis only on a very simplified exemplary basis. The calculations are based solely on figures provided by DIAMO or published in respective reports and do not consider other important aspects such as state subventions in form of tax reliefs, favourable interest rates, research support and others.
Moreover, only a fraction of negative externalities of uranium mining at Stráž was examined. As the impact indicator expressing the monetary value of the environmental damage, solely the finances spent on the remediation were considered. For more conclusive results, a comprehensive model including the impact on human health and environmental damage not incorporated in the claimed remediation costs would require monetary valuation. An economic methodology for such valuation specific for NFC were provided for instance in the *ExternE* report of the European Commission, with the emphasis on radiological impacts of the NFC.[146]

The here conducted calculations focus on the time period 1990-2011. This time period was chosen mainly due to the data availability and for the following reasons:
Firstly, until 1990, the uranium was sold exclusively to the Soviet Union. The determination of revenues (if any) from sale of uranium to the Soviet Union is very

[146] European Commission (1995): ExternE, Externalities of Energy, Vol. 5: Nuclear, Luxembourg.

complicated and cannot be considered in this thesis. Generally, it can be stated that the uranium industry in the Czech Republic was mostly economically unfeasible and had to be heavily subsidised by the state. According to the official figures issued by the former Federal Ministry of Fuel and Energy of the Czechoslovak Socialist Republic, the uranium sale profit in the period 1945-1989 amounted to 10 billion Kčs (Czechoslovak crowns) [350 million USD]. This figure, however, does not include the state subventions that are estimated to 19.6-35.9 billion Kčs [700-1,300 million USD]. The overall financial balance of the uranium industry 1948-1989 thus results in a loss of 9,6-25,9 billion Kčs [350-950 million USD].[147]

Secondly, the uranium produced in the Czech Republic was used for the domestic power generation only since late 80s when the first nuclear power plant commenced its operation. Thus, the remediation costs for uranium production cannot be linked to the nuclear fuel consumption in the Czech NPPs before 1990 and thus to the costs for nuclear power generation as such.

Lastly, the first environmental remediation steps were not conducted until 1990.

The following calculations were carried out with the aim to estimate the impact that the remediation costs have on the overall costs of nuclear energy generation in the Czech Republic. This impact was identified on the basis of the share of uranium price in the overall costs for nuclear energy.

The method applied were basic mathematical computations according to the following steps: i) determination of the uranium amount consumed in the Czech NPPs; ii) determination of the hypothetical increase of the uranium spot price if the remediation costs calculated per kg uranium consumed were internalised; iii) determination of the costs for uranium purchase for each year (1990-2011) exclusive and inclusive the remediation costs; iv) determination of the uranium costs per GWh of nuclear energy produced exclusive and inclusive the remediation; v) comparison of the costs.

The following assumptions underlie the calculations:

- Natural uranium for both nuclear power plants (NPPs) was provided by DIAMO.

[147] Tomek (2000).

- The uranium spot price for the period 1990-2011 is based on the numbers provided by the EU[148] which consider only deliveries made to the EU utilities. However, compared to the data from Ux Consulting and TradeTech, these figures roughly comply with the world prices. The spot prices rather than the multiannual contract prices were chosen because in 1990, the uranium market in the Czech Republic had to be re-established since the uranium export to the sole purchaser Soviet Union stopped abruptly and new customers had to be found. Thus, it is more likely that the new contracts were re-negotiated on the basis of spot prices.
- The uranium consumption was estimated according to the assumption that fabrication of 1 kg of UO_2 requires 8 kg of natural uranium.
- The nuclear fuel consumption was based on the respective fuel load data for each NPP.

The fuel load data and the detailed calculations are listed in the Annex.

The results are presented in the following tables.

Table 10. Main Results: General Figures for 1990-2011

Figures for 1990-2011	**Amount**
Total production of uranium	16,041 t U
Maximum yield possible from produced uranium	461,337,000 EUR
Remediation costs	544,000,000 EUR
Remediation costs per kg U produced	33.9 EUR
Total nuclear energy produced	413 TWh*
Estimated average price for nuclear energy	0.022 EUR/kWh
Uranium consumed in NPPs	11,843.2 t U
Uranium needed per 1 GWh	0.029 t U

** Source: Ministry of Environment of the Czech Republic, ISSaR website, http://issar.cenia.cz/issar/page.php?id=1564, last access 9 September 2012.*

[148] European Commission website, http://ec.europa.eu/euratom/observatory_price.html, last access 9 September 2012.

Table 11. Main Results Concerning Nuclear Power Generation at Czech NPPs

	Costs in EUR	
	exclusive remediation costs	**inclusive remediation costs**
Remediation costs per kg U consumed	-	45.93
Costs per 1 kg U consumed	46.14	92.07
Overall costs for U consumed	546,407,600	1,090,401,306
Costs (uranium share) per 1 GWh	1,322.29	2,638.55
Total increase in costs for each parameter	**100%**	

The results show that if the remediation costs for the period 1990-2011 were internalised in the costs per GWh of nuclear energy, the costs for uranium per GWh would increase by roughly 100 %. Thus, provided that the costs for uranium constitute 14 % of the price of nuclear power generation, the costs for nuclear energy production and thus the current overall nuclear energy price should be higher by 14 %. This number would be even larger if the remediation expenses for all uranium mining sites in the Czech Republic (about 20) would be considered. The remediation of the ISL site, however, constitutes the absolute majority of these costs. In consequence, since the remediation leads to costs increase for the nuclear power production, the Czech state provides by covering the expenses without internalising them in the uranium price de facto a subsidy to the nuclear power sector.

In respect of the period 1990-2042, in which 1,824,000,000 EUR in total have to be invested in the clean-up activities at Stráž, remediation costs would increase to about 82 EUR per kg uranium produced, provided that the uranium production stays at the current level of 200 t uranium per year[149]. Regarding the implications for the nuclear energy price, no estimation can be made since the uranium consumed is likely to highly exceed the uranium produced in the Czech Republic so that the assumption that DIAMO is the only source for natural uranium for the Czech NPPs would not be tenable anymore.

[149] The uranium produced would amount to 22,241,000 kg U.

E. Conclusions

In this thesis, the environmental remediation and the after-care of uranium mining sites were discussed on the basis of a case study. The analysis focused on the ISL mining method and its application at the mine Stráž pod Ralskem in the Czech Republic. In particular, the aspects examined were the remediation technologies used; the development of the remediation programme; and the financial dimension of the project. In the following, the findings from the respective chapters are summarised and interconnected.

The ISL mining method as well as its environmental remediation is well documented in best practice guidelines developed by experts from international institutes. The analysis of the Stráž case showed that the extensive environmental damage which occurred at the site was caused by gross negligence of recommended environmental protection measures during the mine operation, namely the insufficient site assessment, failure to maintain the crucial negative hydraulic gradient in the aquifers and the utilisation of inadequate equipment. Accordingly difficult was the development of the remediation programme at Stráž which commenced in 1990, nineteen years after the first ISL application in 1971.
The remediation milestones and the respective plans were determined relatively soon. First robust remediation target values were available in 1997, one year after the mine closure. However, the realisation of the plan progressed very slowly. For instance, the combination of necessary remediation technologies and the final remediation strategy were identified already in 2003 but the first essential step (construction of NDS ML) was carried out in 2008, the second in 2012 (operation of NDS 10). Hence, the time span between the first pre-remediation site assessment to the beginning of an efficient remediation is eighteen or twenty years, respectively.
The examination of the remediation plan development revealed that the scientific and technological knowledge allowed to follow the best practice and therefore did not pose a significant problem in the course of the remediation. Thus, it can be stated that the major constraint for an efficient remediation was the lack of secure funds. The first legally based long-term funding scheme was provided by the Czech government in 2011. In contrast, such financial security for the Eastern German remediation programmes was granted already in 1991.

It has to be borne in mind that in the beginning, the turbulent political and economic situation of the early 90s did not allow a development of a long-term funding concept. However, after the stabilisation of the political system, a decision-making process to pursue a quick and efficient clean-up of the environmental burden was lacking. In consequence, the duration of remediation was prolonged by several years, leading to low efficiency and higher costs.

As the financial analysis demonstrates, the costs for the remediation of the ISL site are considerable. The crucial factors for the high remediation costs at Stráž are the high degree of groundwater contamination due to false application of ISL; the utilisation of acidic leaching method; high importance of the affected aquifer as a drinking water source; and high population density around the mining site.

The environmental damage caused by the ISL mining was in this thesis identified as a negative externality which is considered neither in the market price of uranium nor the nuclear power. In order to highlight the economic dimension of the environmental burden, the remediation costs were internalised in the price of nuclear energy generation.

Calculated for the uranium produced in the period 1990-2011 in the whole Republic, each kg of uranium carries additional costs of 33.9 EUR related to the remediation. Until 2005, the world uranium spot price was far lower than this figure. Accordingly, the negative difference between the maximal yield achievable from the sale of all uranium produced and the costs needed solely for the remediation of the Stráž ISL mine amounts to almost 83 million EUR. In regard to the generation of nuclear energy in the Czech Republic, the calculations indicate that the costs for uranium purchase double if the Stráž remediation costs are internalised. Thus, under given assumptions, the price for generation of nuclear energy should be higher by 14 %. In consequence, by funding the remediation without a uranium price adjustment, the state de facto subsidises the Czech nuclear power industry.

The overall evaluation of the current remediation plan at Stráž furthermore displayed an absence of considerations for a long-term stewardship which is recommended by the international community. In this thesis, a possible stewardship programme with the most important issues to be addressed was developed. The proposal of the after-care plan indicates that even though a site monitoring for a significant time period, presumably over hundred years, will be necessary, it is not likely to require large investments if the current remediation plan is implemented to the full extent.

In conclusion, the here examined case shows that in countries on an adequate scientific and technological level, the fast course of action which is essential for an efficient remediation can be ensured only by providing a sufficient degree of financial security. In case of a delay, the remediation costs increase and can even exceed the uranium price on the market, leading to considerable financial losses for the mine operator. If there is a strong interlink between the uranium vendor and purchaser as in the Czech Republic, the high remediation costs have also a direct impact on the nuclear energy price.

Consequently, a concrete and comprehensive financial plan should be an integral part of every remediation programme. Ideally, the remediation design procedure including a funding scheme is legally established and standardised. In this manner, greater transparency and accountability of the decision-making process can be assured. This is beneficial for all stakeholders involved – the environment in particular.

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ANNEX

Assumptions:

- The nuclear fuel consumption was based on the following fuel load data:

NPP Dukovany

Fuel load	**4 x 42 t**
Fuel replacement cycle	**Fuel spent per year**
3-year cycle (1990-1999)	56 t
4-year cycle (1999-2003)	42 t
5-year cycle (2003-present)	33.6 t

NPP Temelín

Fuel load	**2 x 92 t**
Fuel replacement cycle	**Fuel spent per year**
4-year cycle, 1 reactor in operation (2000-2002)	23 t
4-year cycle, full operation (2002-present)	46 t

Calculations:

Year	Overall uranium production in t U	Uranium spot price in EUR/kg U	Yield	U consumed in NPPs (t)	Costs exclusive remediation	Figures incl. remediation costs for the time period 1990-2011 (544,000,000 EUR): Spot price increased by remediation costs in EUR/kg U	Figures incl. remediation costs for the time period 1990-2011 (544,000,000 EUR): Costs inclusive remediation
1990	2400	19.75	47400000	448	8848000	65.68	29425984
1991	2100	19	39900000	448	8512000	64.93	29089984
1992	1750	19.25	33687500	448	8624000	65.18	29201984
1993	1500	20.5	30750000	448	9184000	66.43	29761984
1994	1000	18.75	18750000	448	8400000	64.68	28977984
1995	500	15.25	7625000	448	6832000	61.18	27409984
1996	600	17.75	10650000	448	7952000	63.68	28529984
1997	600	30	18000000	448	13440000	75.93	34017984
1998	610	25	15250000	448	11200000	70.93	31777984
1999	612	24.75	15147000	336	8316000	70.68	23749488
2000	507	22.75	11534250	520	11830000	68.68	35715160
2001	456	21	9576000	520	10920000	66.93	34805160
2002	465	25.5	11857500	704	17952000	71.43	50288832
2003	452	21.75	9831000	636.8	13850400	67.68	43100534.4
2004	412	26.14	10769680	636.8	16645952	72.07	45896086.4
2005	408	44.27	18062160	636.8	28191136	90.20	57441270.4
2006	359	53.73	19289070	636.8	34215264	99.66	63465398.4
2007	306	121.8	37270800	636.8	77562240	167.73	106812374.4
2008	263	118.19	31083970	636.8	75263392	164.12	104513526.4
2009	258	77.96	20113680	636.8	49644928	123.89	78895062.4
2010	254	79.48	20187920	636.8	50612864	125.41	79862998.4
2011	229	107.43	24601470	636.8	68411424	153.36	97661558.4
TOTAL	**16,041.00**		**461,337,000.00**	**11,843.20**	**546,407,600.00**		**1,090,401,305.60**

Remediation costs 1990-2011 in EUR: 544,000,000.00

Remediation costs per kg U consumed: 45.93

Remediation costs per kg U produced: 33.91

Overall costs per kg U consumed in EUR: **46.14** **92.07**

Costs difference: **543,993,705.60**

Procentual difference: 0.996

Production of Nuclear Energy

Year	GWhe produced by NPPs	Fuel consumption in t	t U spent
1990	12585	56.00	448
1991	12132	56.00	448
1992	12250	56.00	448
1993	12627	56.00	448
1994	12977	56.00	448
1995	12230	56.00	448
1996	12250	56.00	448
1997	12494	56.00	448
1998	13178	56.00	448
1999	13357	42.00	336
2000	13590	65.00	520
2001	14749	65.00	520
2002	18738	88.00	704
2003	25872	79.60	636.8
2004	26325	79.60	636.8
2005	24728	79.60	636.8
2006	26047	79.60	636.8
2007	26172	79.60	636.8
2008	26551	79.60	636.8
2009	27208	79.60	636.8
2010	28998	79.60	636.8
2011	28200	79.60	636.8
TOTAL	**413,258.00**		**11,843.20**

kg U needed for production of 1 GWhe: 28.66

Costs (uranium share) to produce 1 GWhe in EUR:

exclusive remediation costs: 1,322.29

inclusive remedition costs: 2,638.55

Average Electricity Prices for Households

Year	USD per kWh	Exchange rate EUR/USD	EUR per kWh	% of nuclear energy in overall electricity production	Price for nuclear energy	Price inclusive remediation costs
1990	0.027	1.27	0.021	0.20	0.0054	0.0062
1991	0.03 *	1.24	0.024	0.20	0.0060	0.0069
1992	0.03 *	1.3	0.023	0.21	0.0062	0.0071
1993	0.03 *	1.17	0.026	0.21	0.0064	0.0073
1994	0.03 *	1.19	0.025	0.22	0.0066	0.0076
1995	0.037	1.31	0.028	0.20	0.0074	0.0085
1996	0.038	1.27	0.030	0.19	0.0072	0.0083
1997	0.037	1.13	0.033	0.19	0.0072	0.0082
1998	0.05	1.12	0.045	0.20	0.0101	0.0115
1999	0.051	1.07	0.048	0.21	0.0106	0.0121
2000	0.054	0.92	0.059	0.18	0.0100	0.0114
2001	0.06	0.9	0.067	0.20	0.0119	0.0135
2002	0.081	0.95	0.085	0.25	0.0199	0.0227
2003	0.089	1.13	0.079	0.31	0.0277	0.0315
2004	0.111	1.24	0.090	0.31	0.0346	0.0395
2005	0.116	1.24	0.094	0.30	0.0347	0.0396
2006	0.137	1.26	0.109	0.31	0.0423	0.0482
2007	0.192	1.37	0.140	0.30	0.0570	0.0650
2008	0.192	1.47	0.131	0.32	0.0610	0.0696
2009	0.192	1.39	0.138	0.33	0.0635	0.0724
Average					**0.0218**	**0.0248**

* These figures are only estimated due to missing data.

Source: http://www.eru.cz/user_data/files/statistika_elektro/rocni_zprava/2010/pdf