EXPLOITATION OF RADIOACTIVE MINERALS IN GREENLAND

Management of environmental issues based on experience from uranium producing countries

Scientific Report from DCE – Danish Centre for Environment and Energy No. 200 2016

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Abstract:	This report provides an overview of the most common potential impacts associated with uranium mining and milling activities and general management strategies targeting identified environmental issues in order to protect the environment now and in the future. The report include also international best practices for environmental and radiation protection and worldwide current legislation, regulation and guidelines.

Keywords:	Greenland, radioactive minerals, mining, milling, environmental protection, radiation protection, waste management, transport of yellowcake
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Preface

This report is the outcome of a collaboration project between the Danish Centre for Environment and Energy (DCE) and the Greenland Institute of Natural Resources (GINR) conducted in 2014 and 2015 following Greenland's decision to lift the so-called zero-tolerance policy on radioactive minerals.

The purpose of the project was to gather knowledge on environmental issues and the management of mining and milling of radioactive minerals worldwide, including current legislation, regulation and guidelines. The project was not targeted for a specific project but for the mining and milling of radioactive minerals in Greenland in general. The project was funded by the Environment Agency for Mineral Resources Activities (EAMRA) in Nuuk for whom this report is prepared.

DCE and GINR are long-time advisors to the Greenland authorities on environmental issues and management of conventional mining and this project is considered a first step enabling DCE and GINR to advice also on issues connected with mining and milling of radioactive minerals.

The report reflects the gathering of knowledge on this complex topic from a variety of sources during the project period: conferences, meetings, workshops, available literature and visits to former and existing uranium facilities (e.g. all facilities at the mine site for uranium mining, milling, storage, waste disposal etc.).

The report is to be considered a compendium of knowledge containing relevant background information that can be used to address the relevant topics, plans and programmes comprising an important part of any modern uranium project.

It is the aim of DCE and GINR that the information in the report is correct and up-to-date. However, DCE and GINR will not be responsible for the correctness and any subsequent use of the information. The information in the report is of general character and is not a specific advisory and cannot replace that.

A condensed description of the work and the most important findings are given in the summary, which can be read separately from the rest of the text. The topics dealing with protection of workers and members of the public are not within DCE and GINR's advisory field but are included for completion of the report and thus only treated superficially.

Abbreviations

ALARA - As Low As Reasonably Achievable
ARD - Acid Rock Drainage / Alkaline Rock Drainage
AMD - Acid Mine Drainage
BAT - The Best Available Technology
BEP - Best Environmental Practice
BPT - Best Practicable Control Technology
CNSC - Canadian Nuclear Safety Commission
DCE - Danish Centre for Environment and Energy
DCRLs - Derived Consideration Reference Levels
EAMRA - Environment Agency for Mineral Resources Activities
EIA - Environmental Impact Assessment
EPA - Environmental Protection Agency
GINR - Greenland Institute of Natural Resources
IAEA - International Atomic Energy Agency
ICRP - International Commission on radiological Protection
ISR and ISL - In Situ Recovery and In Situ Leaching
LD_{50} - Lethal Dose, 50%
LSA - Low Specific Activity
MLSA - Mineral License and Safety Authority
NEA - Nuclear Energy Agency
NORM - Naturally Occurring Radioactive Materials
OECD - Organization for Economic Co-operation and Development
PEPR - Program for Environmental Protection and Rehabilitation
RIPRAP - Loose stones produced by crushing hard rock, used as packing, foundations, in covers etc.
RMP - Radiation Management Plan
RWMP - Radioactive Waste Management Plan
UDEPO - World Distribution of Uranium Deposits
UNSCEAR - United Nations Scientific Committee on the Effects of Atomic Radiation
U.S. - NRC, United States, Nuclear Regulatory Commission
TLD - Thermo Luminescence Dosimeters
TSF - Tailings Storage Facilities
QA and QC - Quality Assurance and Quality Control
WEA - World Energy Agency
WNA - World Nuclear Association
WNTI - World Nuclear Transport Institute

Eqqikkaaneq

Pinngoqqaatinik qinngornernik ulorianartunik akulinnik aatsitassarsiorluni misissuinissamut aamma piiaanissamut akuersaanngilluinnarnissamik politikkeqarneq tamanna tikillugu atuuttoq 2013-imi oktobarimi Kalaallit Nunaanni atorunnaarsinneqarpoq. Aalajangerneq Kujataani Kuannersuarni aatsitassarsiorfimmik, ilaatigut aatsitassanik qaqutigoortunik aamma pinngoqqaatinik uranimik aamma thorium-imik qinngornernik ulorianartunik akulinnik peqarfiusumik, suliassamik ineriartortitsinerup ingerlasup peqatigisaanik pivoq. Kuannersuarni suliassaq maannakkut ima siuarsimatigilerpoq, avatangiisinut sunniutaasussanik nalilersuinermik (taaneqartartoq VVM-imut nassuiaat) naammassisimalluni, taannalu maannakkorpiaq ilaatigut Avatangiisinut Nukissiuuteqarnermullu nunami namminermi sullissivimmit (DCE) aamma Pinngortitaleriffimmit (GN) Aatsitassanik Suliassaqarfinnut Avatangiisinut Aqutsisoqarfik (EAMRA) sullillugu, nalilersorneqarpoq.

Kalaallit Nunaanni aatsitassarsiorfinnut suliassanut VVM-imut nassuiaatit ilaatigut DCE-mit aamma GN-imit EAMRA sullillugu nalilersorneqartarput. Nassuiaatini avatangiisinut sunniutaasussat eqqortumik tamakkiisumillu takutinneqartut, nalilersuinerni qulakkeerneqassaaq. Tamanna suliassaq akuersaarneqarsinnaasoq, naleqqussarneqassasoq imaluunniit itigartinneqarluinnassasoq EAMRA-ip kingusinnerusukkut isummersinnaanissaanut tunngaviussaaq. Piiaanissamut akuersissummik qinnuteqaateqarnernut atatillugu, avatangiisinut sunniutaasussat annikillisinneqarnissaat siunertaralugu, aatsitassarsiorfinnut suliassanut avatangiisinut piumasaqaatinik aamma atugassarititaasussanik aalajangersaanermut DCE aamma GN peqataassapput.

Kalaallit Nunaanni siusinnerusukkut aatsitassarsiorfiusarsimasuni aatsitassanik qinngornernik ulorianartunik akulinnik piiaaneq akuutinneqarsimanngisaannarmat, akuersaanngilluinnarnissamik politikkeqarnerup atorunnaarsinneqarneranut atatillugu aatsitassat qinngornernik ulorianartunik akullit ilaatillugit avatangiisinut sunniutaasartut aamma avatangiisinut maleruagassiisarneq pillugit piginnaasaqarnernik ineriaanissaq ataatsimut isigalugu DCE-mi aamma GN-imi pisariaqartinneqalerpoq.

2014-ip aallartinnerani taamaalilluni aatsitassanik qinngornernik ulorianartunik akulinnik piiaanermut suliareqqiinermullu atatillugu apeqqutit avatangiisinut tunngasut aamma avatangiisinut maleruagassiisarneq pillugit piginnaasaqarnernik Kalaallit Nunaanni atorneqarsinnaasussanik inerisaanissaq siunertaralugu, suliniut DCE-mi aamma GN-imi aallartinneqarpoq. Suliniut 2014-imi, 2015-imi aamma 2016-imi ingerlanneqarpoq aammalu EAMRA-mit aningaasalersorneqarluni.

Nalunaarusiami matumani ulloq manna tikillugu suliniummi paasisat saqqummiunneqarput. Nalunaarusiaq tuluttut allanneqarpoq aammalu quppernernit 200-init amerlanerusunik allaaserisanik imaqarluni. Paasissutissat ataatsimiinnerni, ataatsimeersuarnerni aamma suliaqarluni ataatsimiititsinerni peqataasarnernit, suliassaqarfimmi atuagassianik pissarsiarineqarsinnaasunik misissuinernit aammalu Tyskland-imi aamma Australien-imi uranisiorfinnut siusinnerusukkut ingerlanneqarsimasuni aammalu maannakkut ingerlanneqartuni tikeraartarnernit, pissarsiarineqarput. Ilanngussaq A-mi Issittuni aamma nunarsuarmi sumiiffinni allani uranimik suliareqqiisarfinni avatangiisit mianerineqarnissaat qanoq iliuuseqarfigineqarsimanersoq assersuusiortoqarpoq. Nalunaarusiami ilisimasat, siunissami Kalaallit Nunaanni aatsitassanik qinngornernik ulorianartunik akulinnik piiaaneq suliareqqiinerlu ilaatillugu, siunissami aatsitassarsiorfeqalissappat, avatangiisinut piumasaqaatinik aammalu atugassarititaasussanik aalajangersaanermut atatillugu atorneqarsinnaasut, saqqummiunneqarput.

Ilisimasat ilai nalunaarusiami katersorneqartut siunissami Kalaallit Nunaanni aatsitassarsiorfinnut suliassanut tamaginnut tunngatillugu naleqqutissanngillat. Kisianni ilisimasat katersorneqartut, ilisimasanut tunngavissatut, saffiugassat katitigaanerat, aatsitassarsiorfiup suussusaa, kaanngartiterinermut periaaseq, najukkami avatangiisini pissutsit, illoqarfimmut qanittumiinnera il.il. eqqarsaatigalugit suliassanut ataasiakkaanut siunnerfeqartinneqarsinnaallutik, atorneqarsinnaassasut eqqarsaataavoq.

Qulequttat aamma aatsitassarsiorfimmi suliassami uranimik ilaatitsiviusumi, immikkoortunut tamaginnut atatillugu piumasaqaatinut immikkuullarissunut inassuteqaatit arlalippassuit allaaserineqarput aammalu nalunaarusiami kapitalini qulini imaritinneqarlutik. Matuma kinguliani immikkoortut ataasiakkaat naatsumik nassuiarneqarput:

Kapitali 1-imi nalunaarusiamut kapitalinullu assigiinngitsunut nassuiaassisoqarpoq.

Kapitali 2-ip imarai nunarsuaq tamakkerlugu uranimik tunisassiornerup, aatsitassarsiorfiit suussusaasas assiginngitsut kiisalu atomip nukinganik nukissiorfinnut atatillugu atugassatut uranimik suliarinnittarnerup naatsumik allaaserineqarneri. Uranisiorfimmik ingerlatsinermut tunngatillugu suleriaatsit nutaaliaasut aamma siusinnerusukkut suleriaaserineqartartut, taakkua malitsigisaannik avatangiisinut sunniutaasussanut avatangiisinut maleruagassiisarnermut assersuutit nassuiarneqarput. Nunani arlalinni uranimik tunisassiortarneq aamma avatangiisinut sunniutaasartut naatsumik nassuiarneqarnerat, ilanngussami ilaatinneqartumi ilanngunneqarpoq.

Kapitali 3-imi uranisiorfimmik ingerlatsinermut nunani tamalaani maleruagassiisarnermut killissaliussat allaaserineqarput. Tassani ilaatinneqarput nunani tamalaani kattuffinnit soorlu Nunani tamalaani Atomip nukinganut sullissivik (IAEA) aamma Nunani tamalaani Qinngornernut illersuinermut Kommissioni (ICRP), isumannaallisaanermut malitassat aamma inassuteqaatit kiisalu FN-ip Atominit qinngornerit sunniutaannut ilisimatuussutsikkut Komite-mit (UNSCEAR) suliaqarnermit paasisat. Australien-imi, Canada-mi aamma USA-mi uranisiorfinnik maleruagassiinermut killissaliussanut assersuutit aamma kapitalimi allaaserineqarput.

Kapitali 4 avatangiisinik allanngutsaaliuinermut tunngassuteqarpoq. Aatsitassarsiorfimmi ingerlatanit pujoralannik pilersoqarnissaanik aamma qinngornernik ulorianartunik akulinnik avatangiisinut sunniuttoqarnissaanik pitsaaliuinermut annikillisitsiniarnermullu periaatsit assigiinngitsut kapitalimi nassuiarneqarput.

Kapitali 5 piumasaqaatinut qinngornernut illersuinermut pilersaarummi ilaatinneqartariaqartunut inassuteqaatinik imaqarpoq. Aatsitassarsiorfimmut suliassani tamaginni, aatsitassanik qinngornernik ulorianartunik akulinnik piiaanermik suliareqqiinermillu ilaatitsiviusuni, qinngornernut illersuinermut pilersaarut ilaatinneqartariaqarpoq. Pilersaarummi taamaattumi siunertaavoq aatsitassarsiorfinni ingerlatanit qinngornernik ulorianartunik aniatitsinissaq sunniinissarlu aammalu qinngorfigitinnerit annikillisinneqarnissaat. Qinngornernut illersuinermut pilersaarut aatsitassarsiorfimmut suliassami immikkoortuni tamaginni, ilusilersuinermit ingerlatsinermut, atorunnaarsitsiartuaarnermut, pissusaatut ilersillugu iluarseeqqinnermut aamma sivisuumik alapernaarsuinermut aammalu matusereernerup kingorna patajaallisaanermut, ilaatinneqartariaqarpoq.

Kapitali 6 'yellowcake'-nik tunisassiornerup, pitsaassutsinik qulakkeerinerup naatsumik nassuiarneqarnerannik kiisalu piumasaqaatinik aatsitassarsiorfimmi eqqagassalerinermut pilersaarutip imarisariaqagaannut inassuteqaatinik, imaqarpoq. Pilersaarummi aatsitassarsiorfimmi, aatsitassanik qinngornernik ulorianartunik piiaanermik suliareqqiinermillu ilaatitsiviusuni, eqqagassanik passussineq immikkuullarissumik aallunneqartariaqarpoq. Aatsitassarsiorfimmi eqqagassanut ilaapput saffiugassamik piiaanermit suliareqqiinermillu eqqagassat tamarmik, avatangiisinut qinngornernik ulorianartunik aniatitsisinnaasut, tassaagajullutik taaneqartartut 'tailings', ujaqqat atorneqartussaanngitsut aamma aatsitassarsiorfimmi ingerlatanit imeq kuutsinneqartoq.

Kapitali 7-imi aatsitassarsiorfiup qanittuani, aatsitassanik qinngornernik ulorianartunik piiaanermik suliareqqiinermillu ilaatitsiviusuni, avatangiisinik alapernaarsuinissamut piumasaqaatinut inassuteqaatit nassuiarneqarput. Silaannarmi, immami, nunami aamma uumassusilinni qinngornernik ulorianartunik avatangiisini alapernaarsuineq kapitalimi ilaatinneqarpoq. Aatsitassarsiorfinni suliassanut ataasiakkaanut tunngatillugu naliusunut killissaliussanik aalajangersaanissamut piumasaqaatit aamma sammisaqarput.

Kapitali 8 uranimik akuiakkamik, taaneqartartumik 'yellowcake' tunisassiornermut, poortuinermut, uninngasuutiginninnermut assartuussinermullu atatillugu avatangiisini peqqinnissamillu illersuinermut piumasaqaatinut inassuteqaatinik imaqarpoq. Tunisassiornerup ingerlasarnera, pitsaassutsinik qulakkeerisarneq nakkutiginninnerlu kiisalu Nunani tamalaani atomip nukinganut sullissivimmit (IAEA) aamma 'World Nuclear Transport Institute'-mit (WNTI) inassuteqaatit naatsumik nassuiarneqarnerat kapitalimi allaaserineqarpoq.

Kapitali 9 aatsitassarsiorfiata sumiiffiani, aatsitassanik qinngornernik ulorianartunik piiaanermik suliaqarfiusimasumi, atorunnaarsitsiartuaarnermut aamma pissusaatut ilerseqqillugu iluarsiinissamut pilersaarummi imaritinneqartariaqartunut piumasaqaatit suussanersut inassuteqaatinik imaqarpoq.

Kapitali 10-imi aatsitassanik qinngornernik ulorianartunik ilaatitsiviusumik aatsitassarsiorfimmik ingerlatsinermut atatillugu qinngornerit suminngaaneerfigisinnaasaat pillugit ilisimasat saqqummiunneqarput. Annertussusissanut aalajangersakkanut periaasissaq aamma kapitalimi ilaatinneqarpoq.

Nalunaarusiaq taamaalilluni tamanit, politikkerinit, oqartussanit allanillu Kalaallit Nunaanni imaluunniit nunani tamalaani soqutiginnittunit, paasissutissanik sukumiisunik ujaasisunit imaluunniit sammisanut aatsitassanik uranimik akulinnik suliareqqiinermut atatillugu attuumassuteqartunut paasisimasaqarnerulernissamik kissaateqartunit, ilinniarfissatut atuakkatut atorneqarsinnaavoq.

Oqaatigissallugu pingaaruteqarpoq, suliassami avatangiisini ajornartorsiutit sammineqarmata, aammalu sammisat soorlu sulisunik innuttaasunillu qinngornernut illersuinermut tunngasut, nalunaarusiami qaanginnarsiortumik sammineqarlutik, tassami taakkua EAMRA-p oqartussaasutut suliassaqarfiisa aammalu DCE-p aamma GN-ip piginnaasaqarfiisa siunnersuiffissaasalu avataaniimmata.

Ilisimasat maannamut katersorneqartut pigilerneranni maannakkut ersarissivoq, maleruagassiinissamut periaasissaq nassuiarluagaasoq annertuujusorlu kiisalu tamatuminnga atuutsitsilernissaq, alapernaarsueqqissaarnermik ilaqartinneqartoq, avatangiisitigut illersorneqarsinnaasumik aatsitassanik qinngornernik ulorianartunik akulinnik ilaatitsiviusumik aatsitassarsiorfimmik ingerlatsinissamut, pisariaqartut. Canada-mit, Australien-imit aamma USA-mit assersuutit takutippaat, avatangiisinut annertunerusunik ajornartorsiutitaqanngitsumik uranisiorfinnik nutaaliaasunik ingerlatsinissaq ajornanngitsoq. Kisiannilu nunanit allanit, soorlu assersuutigalugu 2012 sioqqullugu Namibia-mit assersuutit takutippaat, ilaatigut maleruagassiisimannginneq, inatsisit amigartut kiisalu maleruagassanik atuutsitsilersimanngineq avatangiisinut sunniinernik, sumiiffimmi eqqaanniittuni innuttaasunik sunniisinnaasunik, malitseqarsinnaasut.

Sammenfatning

I oktober 2013 ophævede Grønland den hidtil gældende nultolerancepolitik over for efterforskning og udnyttelse af radioaktive grundstoffer. Beslutningen skete samtidig med den igangværende udvikling af et mineprojekt ved Kvanefjeld (Kuannersuit) i Sydgrønland, der indeholder bl.a. sjældne jordarters metaller og de radioaktive grundstoffer uran og thorium. Projektet ved Kvanefjeld er nu så fremskredet, at en miljøkonsekvensvurdering (en såkaldt VVM-redegørelse) vurderes af bl.a. Nationalt Center for Miljø og Energi (DCE) og Grønlands Naturinstitut (GN) for Miljøstyrelsen for Råstofområdet (EAMRA).

VVM-redegørelser for mineprojekter i Grønland vurderes af bl.a. DCE og GN. Vurderingerne skal sikre, at redegørelserne tegner et korrekt og fyldestgørende billede af miljøkonsekvenserne. Dette skal senere danne baggrund for, at Selvstyret kan tage stilling til, om projekter er acceptable, skal modificeres eller helt forkastes. I forbindelse med ansøgninger om udnyttelsestilladelse skal DCE og GN medvirke til at fastlægge miljøkrav og vilkår for mineprojekter med henblik på at minimere miljøkonsekvenserne.

Da tidligere mineprojekter i Grønland ikke har involveret brydning og oparbejdning af radioaktive mineraler, opstod der i forbindelse med ophævelsen af nultolerance politikken et generelt behov for kompetenceopbygning hos DCE og GN om miljøeffekter og miljøregulering af mineprojekter, hvor radioaktive mineraler indgår.

I starten af 2014 blev der således igangsat et projekt hos DCE og GN med det formål at opbygge kompetencer om miljøspørgsmål og miljøregulering i relation til brydning og oparbejdning af radioaktive mineraler, der ville kunne anvendes i Grønland. Projektet fortsatte gennem 2014, 2015 og 2016 og blev finansieret af EAMRA.

Nærværende rapport præsenterer resultaterne af projektet indtil dags dato. Rapporten er skrevet på engelsk og indeholder mere end 200 siders tekst. Oplysningerne er indhentet ved deltagelse i møder, konferencer og workshops, fra studier af tilgængelig litteratur på området og fra besøg ved tidligere og igangværende uranminer i hhv. Tyskland og Australien. I appendix A gives eksempler på hvordan miljøhensyn håndteres på uranoparbejdningsanlæg i Arktis og andre steder i verden. Rapporten præsenterer viden, der bl.a. vil kunne anvendes i forbindelse med fastsættelse af miljøkrav og vilkår ved eventuelle. fremtidige miner i Grønland, hvor brydning og oparbejdning af radioaktive mineraler indgår.

Ikke al den viden, der er samlet i rapporten, vil være lige relevant i forhold til alle fremtidige mineprojekter i Grønland. Men det er tanken, at den indsamlede viden vil kunne bruges som et videns-fundament, der kan målrettes det enkelte projekt under hensyntagen til malmsammensætning, minetype, ekstraktionsmetode, lokale miljøforhold, nærhed til bebyggelse mv.

En lang række emner og anbefalinger til specifikke krav i forbindelse med alle faser i et mineprojekt hvori indgår uran er blevet behandlet og er indeholdt i rapportens ti kapitler. Nedenfor er givet en kort beskrivelse af de enkelte afsnit:

Kapitel 1 giver en introduktion til rapporten og de forskellige kapitler.

Kapitel 2 indeholder en kort gennemgang af uranproduktion på verdensplan, de forskellige minetyper samt oparbejdning af uran til brug i forbindelse med atomkraftværker. Moderne og tidligere tiders praksis i forhold til uranminedrift er beskrevet sammen med eksempler på miljøregulering med deraf følgende miljømæssige konsekvenser. En kort beskrivelse af uranproduktion og miljøeffekter i en række lande er inkluderet i det tilhørende appendiks.

Kapitel 3 gennemgår internationale rammer for regulering af uranminedrift. Dette inkluderer sikkerhedsstandarder og anbefalinger fra internationale organisationer såsom det Internationale Atom Energi Agentur (IAEA) og den Internationale Kommission for Strålingsbeskyttelse (ICRP) samt arbejdsresultater fra FN's Videnskabelige Komite for Effekter af Atomar Stråling (UNSCEAR). Eksempler på rammer for regulering af uranminedrift i Australien, Canada og USA er også givet i kapitlet.

Kapitel 4 omhandler miljøbeskyttelse. Kapitlet beskriver forskellige metoder til at forhindre og reducere dannelsen af støv og frigivelsen af radioaktive stoffer til miljøet fra mineaktiviteter.

Kapitel 5 indeholder anbefalinger til krav, der bør indeholdes i en strålingsbeskyttelsesplan. En strålingsbeskyttelsesplan bør være en integreret del af alle mineprojekter, hvori brydning og oparbejdning af radioaktive mineraler indgår. Formålet med en sådan plan er at minimere frigivelse og effekter af radioaktive stoffer og stråling fra mineaktiviteterne. Strålingsbeskyttelsesplanen bør omfatte alle faser i et mineprojekt fra konstruktion til drift, dekommissionering, rehabilitering og langtidsmonitering og stabilisering af mineområderne efter nedlukning.

Kapitel 6 indeholder en kort beskrivelse af 'yellowcake' produktion, kvalitetssikring samt anbefalinger til krav, som en mineaffaldshåndteringsplan bør indeholde. Planen bør fokusere specifikt på håndtering af mineaffald, hvor brydning og oparbejdning af radioaktive mineraler indgår. Mineaffald inkluderer alle affaldsprodukter fra brydning og oparbejdning af malmen, der potentielt kan frigive radioaktive stoffer til miljøet, typisk såkaldt 'tailings', gråbjerg og afløbsvand fra mineaktiviteterne.

Kapitel 7 beskriver anbefalinger til krav for miljømonitering nær miner, hvor brydning og oparbejdning af radioaktive mineraler indgår. Miljømonitering af radioaktive stoffer i luft, vand, jord og biologisk materiale indgår i kapitlet. Krav til fastsættelse af grænseværdier i forhold til det enkelte mineprojekt bliver også diskuteret.

Kapitel 8 indeholder anbefalinger til krav for miljø- og sundhedsmæssig beskyttelse i forbindelse med produktion, pakning, opbevaring og transport af urankoncentrat, såkaldt 'yellowcake'. En kort beskrivelse af produktionsgangen, kvalitetssikring og kontrol samt anbefalinger fra det Internationale Atom Energi Agentur (IAEA) og 'World Nuclear Transport Institute' (WNTI) er givet i kapitlet.

Kapitel 9 indeholder anbefalinger om hvilke krav en plan for dekommissionering og rehabilitering af mineområder, hvor brydning af radioaktive mineraler har fundet sted, bør indeholde.

Kapitel 10 præsenterer viden om de potentielle strålingskilder i forbindelse med minedrift, hvor radioaktive mineraler indgår. Metoder til dosisbestemmelse indgår også i kapitlet.

Rapporten kan således anvendes som en lærebog for offentligheden, politikere, myndigheder og andre interessenter i Grønland eller internationalt, som søger detaljeret information eller ønsker at øge deres forståelse for emner, som er relevante i forbindelse med oparbejdning af mineraler indeholdende uran.

Det er vigtigt at bemærke, at projektet har fokuseret på miljømæssige problemstillinger, og at emner som strålingsbeskyttelse af arbejdere og befolkningen kun er behandlet meget overfladisk i rapporten, idet dette ligger uden for EAMRA's myndighedsområde og DCE's og GN's kompetence- og rådgivningsområde.

Med den viden, der er indsamlet nu, står det klart, at et veldefineret og omfattende system for regulering samt implementering af dette, ledsaget af nøje overvågning, er nødvendigt for at drive miner med radioaktive mineraler på en miljømæssigt forsvarlig måde. Eksempler fra Canada, Australien og USA viser, at det er muligt at drive moderne uranminer uden større miljøproblemer. Imidlertid viser eksempler fra andre lande, f.eks. Namibia før 2012, at bl. a. mangelfuld regulering, en mangelfuld lovgivning samt manglende implementering af reglerne kan medføre miljømæssige effekter, som vil kunne påvirke befolkningen i de omkringliggende områder.

Summary

In October 2013, Greenland lifted the so-called zero-tolerance policy for extraction of radioactive minerals. The decision was made at the time when a mining project was under development at Kvanefjeld (Kuannersuit) in South Greenland, a deposit that besides rare earth elements, flour and zinc contains the radioactive elements uranium and thorium. The project at Kvanefjeld is now at a stage when an Environmental Impact Assessment (EIA) report and an application for exploitation license are currently being assessed by the Danish Centre for Environment and Energy (DCE) and Greenland Institute of Natural Resources (GINR).

DCE and GINR are long-time advisors to the Greenland authorities on environmental issues. This advisory includes evaluation of EIA reports on mining projects. DCE and GINR's evaluation of the EIA reports shall ensure that the EIA reports give a correct and thorough description of the environmental impacts of the project. The final EIA report and the so-called 'White Book', containing comments on the report from public consultations, will later form the basis for the Greenland Government (Naalakkersuisut) to decide for or against a mining project, to define the environmental requirements for the project and whether it has to be modified.

In relation to the possible exploitation license, DCE and GINR provide recommendations on how to set the environmental requirements and conditions in order to minimize any adverse environmental effects. Since previous mining projects in Greenland have not involved exploitation of radioactive minerals, there was a need to build up specific knowledge at DCE and GINR on environmental issues and management associated with mining and milling of radioactive minerals.

In the beginning of 2014, a collaboration project between DCE and GINR was initiated with the purpose of gathering information and knowledge on environmental issues and management of radioactive minerals mining and milling worldwide that can potentially be used in Greenland. The project was continued through 2014, 2015 and 2016. The project was not specifically focused on Kvanefjeld but on mining and milling of radioactive minerals in Greenland in general, both as main product and by-product associated with mining of other minerals. The project was funded by the Environment Agency for Mineral Resources Activities (EAMRA).

This report is prepared to EAMRA and presents the outcome of the project until this date. The report includes more than 200 pages of information gathered at meetings and workshops, through available literature and on field trips to former and existing uranium mines in Germany and Australia, respectively. Examples of the management of environmental and health practices at uranium facilities operating in the Arctic and elsewhere in the world are given in Appendix A. The intention of the report was for it to be a compendium with relevant background information to be used as a checklist for issues to consider in future projects involving mining and milling of radioactive minerals in Greenland.

Not all the information gathered here will be relevant to all potential future mining and milling projects in Greenland but will provide a foundation of

knowledge that can be targeted towards the specific project, taking site-specific factors such as ore-composition, mining type, extraction methods, local environmental conditions, proximity to settlements, etc. into account.

Different topics and recommendations for specific requirements for all uranium production phases are presented in the ten chapters of the report.

Chapter 1 gives an introduction to the report and the different chapters in detail.

Chapter 2 provides a review of uranium production worldwide, different mining methods and steps involved in the production of uranium for use in civilian power generation. Past and modern practices of uranium mining are presented and examples of environmental management at uranium facilities are given. A short description of uranium production and key environmental issues in a range of different countries is provided in the associated appendix.

Chapter 3 presents a review of the international regulatory framework governing uranium mining and milling. This includes safety standards and recommendations from organizations such as the International Atomic Energy Agency, the International Commission on Radiological Protection and work and findings of the United Nations Scientific Committee on the Effects of Atomic Radiation. In the chapter, examples of the regulatory framework governing uranium production in Australia, Canada and the United States are given.

Chapter 4 provides a programme for environmental protection. A description of various methods to prevent and reduce the generation of dust and the release of radioactive contaminants into the environment is provided.

Chapter 5 describes the requirements for a radiation management plan (RMP). The purpose of this plan is to minimize the overall release and effects of radioactive contaminants from the mining and milling activities. The RMP should be an integrated part of any project involving mining and milling of radioactive minerals and should cover all phases of a project from construction to mining and milling, decommissioning, rehabilitation and long-term monitoring and care.

Chapter 6 presents a brief description of yellowcake production flow, quality assurance and control and the requirements of a waste management plan. The waste management plan is targeted specifically at the management of waste products associated with the mining and milling of radioactive minerals. Waste products include all kinds of tailings, waste rock and mine water that can potentially release contaminants into the environment.

Chapter 7 describes requirements for environment monitoring near mines involving mining and milling of radioactive minerals. Monitoring of air, water, soil and biological material for radioactive contaminants in the receiving environment is included as well as monitoring requirements for mine effluents. The requirements for setting threshold values for a specific project are discussed.

Chapter 8 presents requirements for environmental and health protection associated with production, packing, storage and transportation of uranium concentrate, so-called yellowcake. The chapter was prepared for the case that uranium-containing minerals will be processed into yellowcake in Greenland.

The recommendations by the International Atomic Energy Agency and World Nuclear Transport Institute for the safe transport of radioactive materials are also included.

Chapter 9 provides information related to decommissioning and rehabilitation of mining areas associated with the mining and milling of naturally occurring radioactive minerals. Requirements for decommissioning and rehabilitation plans are also included.

Finally, Chapter 10 describes available scientific knowledge on potential sources and pathways of radiation exposure associated with mining and milling of radioactive minerals as well as methods of dose assessment in the environment.

This report contains information that can assist when setting the environmental requirements and conditions for potential new mines involving mining and milling of radioactive minerals in Greenland. It is important to note that this report focuses on the environmental protection and only deals superficially with radiation protection of workers and members of the public as this is not within the authority of EAMRA nor the advisory field of DCE and GINR.

For openness and transparency to the public in Greenland, the report will be made available through EAMRA. Thus, this report may be also used as a useful teaching or training guide by general public, politicians, authorities, education, industry and other stakeholders in Greenland and or international that are seeking detailed information or improving their understanding of all topical areas related to uranium production activities.

Given the present knowledge available, it is obvious that a well-developed regulatory framework and an implementation programme are required to operate a uranium mine in an environmentally safe manner. Experiences from Canada, Australia and the U.S. show that it is possible to operate modern uranium mines without major environmental problems. In contrast, experiences from uranium mines in other countries, for instance Namibia prior to 2012, show that lack of a complete legislative and regulatory framework and absence of programmes for implementation of environmental and health standards are some of the factors that could lead to environmental contamination and potentially pose health risks to residents in settlements near the mine.

1 Introduction

This report provides an overview of the most common potential impacts associated with uranium production activities and management strategies targeting identified environmental issues in order to protect the environment now and in the future. However, uranium recovery as a secondary mineral in small quantities does not constitute the same volume of radioactive materials or risks as a high grade uranium mines and mill complex.

A review of worldwide experiences of environmental issues related to uranium facilities including environmental protection from conventional mines, i.e. open-pit and underground mines, and non-conventional mines, i.e. in situ recovery (ISR) – also known as in situ leaching (ISL) or solution mining, is given in ***Chapter 2***. Examples of common environmental issues such as dust and tailings management of uranium facilities operating from the middle of last century in Russia, Germany, Canada, Australia, France and USA are re-viewed. Furthermore, this chapter highlights examples of modern uranium facilities in Canada and Australia that today produce uranium without major environmental problems. The environmental risks concerning mining of radioactive minerals have a lot of similarities to mining of non-radioactive minerals. For this reason, robust mining laws and practices are an essential pre-requisite for establishing the extra range of regulatory practices that may be required to regulate the exploitation of uranium and other NORM. Experiences from uranium facilities in other countries, for instance Malawi, and Namibia prior to 2012, show that lack of a complete legislative framework and absence of a programme for implementation of environmental and health standards, are some of the factors that may easily lead to environmental contamination and health risks to workers as well as to the residents of nearby towns.

Chapter 3 presents the international regulatory framework governing uranium production for use in civilian power generation. Examples of the regulatoryframework governing uranium production applied in Australia, Canada and the United States are given. Work and findings of the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) and guidelines and recommendations from expert bodies, notably the International Atomic Energy Agency (IAEA) and the International Commission on Radiological Protection (ICRP), are also briefly listed. Laws in force in Greenland and recommendations for further work needed for the regulation of mining and milling of naturally occurring radioactive materials in Greenland are also included.

A description of a programme for environmental protection is provided in Chapter 4. Methods to prevent and reduce the generation of dust and the release of radioactive contaminants to the environment from proposed mining and milling activities are described.

Chapter 5 of this report lists specific requirements to be taken into consideration when developing the radiation management plan (RMP) for operations that handle naturally occurring radioactive materials such as uranium. Before commencement of mining and milling, a RMP must be submitted to the authorities for approval. The radiation management plan should be prepared by the operator and submitted together with the application for authorisation to operate the facility. The general principle ''As low As Reasonably

Achievable (ALARA), which encourages uranium production licensees to make ''every reasonable effort to maintain exposures to radiation as far below the dose limits, as is practical consistent with the purpose for which the licensed activity is undertaken''– 10 CFR part 20.1003'' should be considered when the RMP is developed.

Chapter 6 includes a brief description of yellowcake production flow, quality assurance (QA), quality control (QC) and an overview of the management of radioactive waste generated from mining and milling activities. Specific issues required to be included in a radioactive waste management plan (RWMP) should be developed at the inception of the project to ensure proper management of radioactive waste arising from the operations. Before the commencement of mining and milling, an RWMP must be submitted to the authorities for approval. The RWMP must be directed towards the best practicable technology and take all relevant pathways for dispersion of radionuclides from tailings and for radiation exposure of employees, members of the public and the environment into account.

Requirements for radiation monitoring in the environment are provided in ***Chapter 7***. The main purpose of monitoring is to check for compliance with the authorized limits on discharges and to ensure that the discharges to the environment are part of a well-managed and well-designed operation, to permit estimation of the radiation exposure of members of the public, workers and the environment and to provide early warning of any deviations from the normal authorized operation.

Two categories of monitoring are discussed in this report: 1) monitoring at the source of the discharge (source monitoring) and 2) monitoring in the environment, including monitoring under operating conditions and during the decommissioning and rehabilitation of facilities as well as long-term monitoring. Environmental radioactivity monitoring programmes include radiation surveys and assessment of individual non-radioactive contaminants and radionuclide concentrations in discharged effluents and environmental samples (air, land and water). The monitoring programme should be conducted both on and outside the site. A detailed description of environmental effects monitoring studies should be further developed and should include effluent and biological monitoring studies.

Discharge limits and controlled release of radionuclides to the atmospheric and aquatic environment as a legitimate waste management practice in the mining industry and its related facilities are discussed. Controlled discharges of gaseous and particulate material containing radionuclides and non-radioactive contaminants are usually made through stacks, although for small facilities they may be made through, for example, discharge vents. Controlled liquid discharges are typically conducted via pipelines into rivers, lakes or the sea. Discharge limits are regulatory limits for the release of radionuclides into the environment, encompassing both airborne and liquid effluents from mine sites. These limits should represent the upper limit quantity of radionuclides that a member of the public should be exposed to. The annual effective dose limit for members of the public resulting from the controlled releases should not exceed the regulatory effective dose limit established for members of the public (e.g. 1 mSv / y).

An important and essential element in the control of the discharges is regular monitoring, both at the source of the discharge and in the receiving environment, to ensure protection of the public and the environment.

Uncontrolled release of radionuclides to the atmospheric, aquatic and terrestrial environments may occur from diffuse sources (e.g. ore stock pile, waste rock disposal) or as a result of a radiological accident. A brief description of an emergency preparedness and response plan for a radiological event is also provided but needs to be developed in further detail in the future.

This report does not consider occupational and members of the public monitoring neither dose assessments for workers and members of the public. Detailed monitoring programmes, dose assessment and radiation protection programmes during all uranium facilities phases for employees and members of the public should be developed and carried out by the relevant authorities.

Requirements for environmental protection during packing, storage and transportation of yellowcake are addressed in ***Chapter 8***. Specific IAEA and World Nuclear Transport Institute (WNTI) recommendations for the safe transport of radioactive materials, in this case yellowcake are provided.

Specific requirements for decommissioning and rehabilitation of mine, mill andtailings facilities and the surrounding areas and long-term surveillance after completion of the mine project are discussed in **Chapter 9.** Decommissioning and rehabilitation costs, lessons learnt, successes achieved elsewhere over the last 30 years, how to minimize long-term adverse effects with the aim to protect humans / non-humans and the environment also for future generations and how to minimize restrictions on future land use and reclaimed landscapes (stable and self-sustaining) are taken into consideration.

Sources, stressors, pathways, receptors (non-human biota) as well as biota dose rate risk assessment are further addressed in ***Chapter*** 10. The dose assessment is based on the results of source and environmental monitoring or combinations of these.

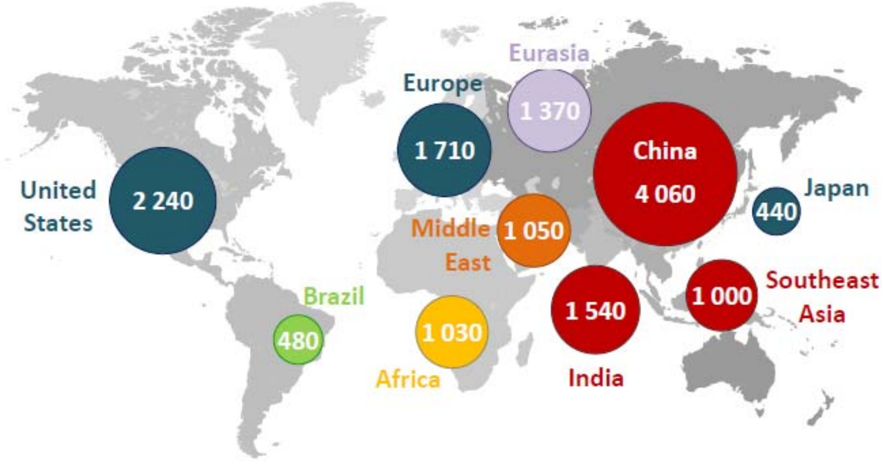
2 Experiences related to environmental protection and remediation from uranium facilities in the Arctic region and worldwide

A short description of worldwide uranium production, mining methods, past and modern practices of uranium mining and milling and examples of successful and unsuccessful practices for managing health and environmental impacts are provided in this chapter. It is important to note that the practices used for uranium mining are highly dependent on, among others factors, the site-specific climate, geography, ecology, ore type and ore grade. The underlying general principles of successful management remain similar.

2.1 Worldwide uranium production

The global energy demand and its distribution will change by 2040 (OECD / IEA-2013). China is currently the main driver of the increasing energy demand, but India, Southeast Asia, the Middle East and sub-Saharan Africa are predicted to take over in the 2030s as the principal engines of growth (Fig. 2.1.1).

Figure 2.1.1. World energy demand, 2035 (Mtoe). Source: OECD/IEA-2013.



Energy generation technologies include coal, oil, gas, solar energy (PV), hydroelectric, nuclear, wind, geothermal energy and biomass. Each technology has advantages and disadvantages with respect to operational cost, environmental impact and other factors (http://ramblingsdc.net/ElecGenProsCons.html). Two-thirds of today's global greenhouse gas emissions are generated by the energy sector (OECD / IEA-2013). Each generation technology produces greenhouse gases (e.g. CO_2) in varying quantities through all phases of the project. Greenhouse gas emissions from nuclear power plants are among the lowest of all electricity generation methods (Fig. 2.1.2). The U.S. President's Climate Action Plan, the Chinese plan to limit the share of coal in the domestic energy mix, the European debate on 2030 energy and climate targets and Japan's discussions on a new energy plan are among the measures adopted to limit growth in energy-related CO_2 emissions and support renewables. Even when considering the measures already announced by governments to improve energy efficiency, energy-related CO_2 emissions are still predicted to rise by 20% by 2035

(OECD / IEA-2013). This leaves the world with a predicted long-term global average temperature increase of 3.6 °C, which is above the internationally agreed 2 °C target.

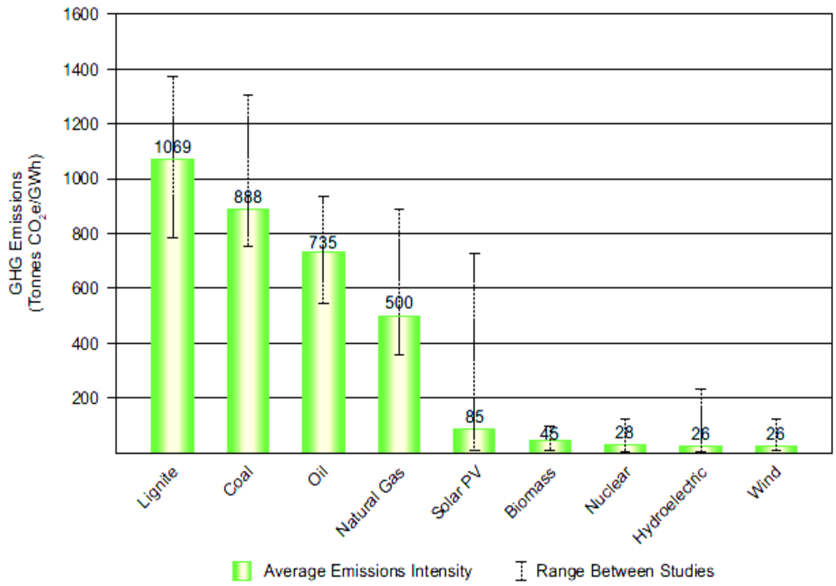


Figure 2.1.2. Greenhouse gas emissions from different electrical generation methods. Source: http://www.world-nuclear.org/Nuclear-Basics/Greenhouse-gas-emissions-avoided/

With 450 nuclear reactors in operation worldwide at the end of 2016, and approximately 60 under construction (http://www.iaea.org/pris/) and many more under consideration, fuel production for these nuclear facilities will be essential for decades to come.

From 2011 to 2013, uranium was produced in 21 different countries. Worldwide 99 uranium deposits (Table 2.1.1) are in operation, 445 in exploration, 274 depleted and 41 closed (https://infcis.iaea.org/UDEPO/About.cshtml). The global uranium mine production is approximately 60,000 tonnes per year (OECD-NEA / IAEA, 2014). Uranium is also supplied from secondary sources such as mine remediation activities, stockpiles and material from dismantled nuclear weapons (http://www.world-nuclear.org/info/Nuclear-Fuel-Cycle/Introduction/Energy-for-the-World---Why-Uranium-/). Results from the most recent review of the world's uranium resources, production and demand were provided by OECD-NEA / IAEA, 2014. An overview of uranium mining (ore geochemistry) worldwide is given by Kalvig et al. (2014), with special focus on comparisons with Greenland: http://mima.geus.dk/mima_rapport_2014-2.pdf. (The mentioned reference does not include the environment).

Presently, about 38% of the world's production of uranium comes from mines in Kazakhstan (2013), followed by Canada (16%) and Australia (11%) (Table 2.1.2).

Table 2.1.1. Number of operating uranium deposits per country. These statistics are generated from: https://infcis.iaea.org/UDEPO/About.cshtml.

Country	Number of operating uranium deposits
Australia	4
Brazil	2
Canada	3
Chile	1
China	9
Czech Republic	1
Finland	2
India	7
Iran, Islamic Republic of	1
Kazakhstan	15
Malawi	1
Namibia	3
Niger	4
Peru	1
Romania	3
Russian Federation	9
South Africa	6
Ukraine	3
United Republic of Tanzania	1
United States of America	8
Uzbekistan	16
In	99

Please note that the list might not include all operating deposits in the world due to lack of data.

Table 2.1.2. World production of uranium (tonnes uranium). Source: World Nuclear Association (WNA) http://www.world-nuclear.org/info/Nuclear-Fuel-Cycle/Mining-of-Uranium/World-Uranium-Mining-Production/.

Country	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Kazakhstan	5279	6637	8521	14020	17803	19451	21317	22451	23127	23800
Canada	9862	9476	9000	10173	9783	9145	8999	9331	9134	
Australia	7593	8611	8430	7982	5900	5983	6991	6350	5001	
Niger	3434	3153	3032	3243	4198	4351	4667	4518	4057	
Namibia	3067	2879	4366	4626	4496	3258	4495	4323	3255	
Russia	3262	3413	3521	3564	3562	2993	2872	3135	2990	
Uzbekistan (est)	2260	2320	2338	2429	2400	2500	2400	2400	2400	
USA	1672	1654	1430	1453	1660	1537	1596	1792	1919	
China (est)	750	712	769	750	827	885	1500	1500	1500	
Malawi				104	670	846	1101	1132	369	
Ukraine (est)	800	846	800	840	850	890	960	922	926	
South Africa	534	539	655	563	583	582	465	531	573	
India (est)	177	270	271	290	400	400	385	385	385	
Brazil	190	299	330	345	148	265	231	231	231	
Czech Republic	359	306	263	258	254	229	228	215	193	
Romania	90	77	77	75	77	77	90	77	77	
Pakistan	45	45	45	50	45	45	45	45	45	
Germany	65	41	0	0	8	51	50	27	33	
France	5	4	5	8	7	6	3	5	3	
Total world production	39 444	41 282	43 764	50 772	53 671	53 493	58 394	59 370	56217	

2.2 Uranium mining methods

Uranium production involves various steps such as exploration, feasibility studies, regulatory assessment and approval process, construction, operation (mining and milling), closure and long-term surveillance. Like all other activities related to exploitation of mineral resources, uranium production may adversely impact the environment. Many of the potential environmental impacts may be significantly mitigated with the implementation of various preventive and mitigation measures during each phase of operation.

Most common uranium exploitation methods include conventional mining and milling (open-pit, underground mining methods and acid or alkaline leaching milling methods) and in situ leaching (ISL) extraction where uranium is processed by conventional uranium milling.

The employed mining methods are site specific and depend on a number of factors such as ore type, ore grade, ore depth (ability to access the ore from the surface by removing the overburden), stability issues, groundwater considerations and the nearby surroundings (lakes and rivers, towns, etc.).

2.2.1 Open-pit, open-cut or opencast mining

Open-pit mining, also called open-cut or opencast mining, is a surface mining technique where rock or minerals are extracted from the earth by their removal from an open pit. Open-pit mining is used when deposits of commercially beneficial minerals or rocks are found near the surface. Open-pit mining occupies vast areas of surface land (e.g. the Ranger Uranium Mine in Australia covers about 6 sq. km) and usually produces large stockpiles of waste rock, sub-economic ore and / or overburden, and the potential for waste water, drainage and seepage to cause environmental problems is significant.

2.2.2 Underground or sub-surface mining

Sub-surface mining involves digging tunnels or shafts into the earth to reach ore deposits. Ore for processing (milling) is removed by drilling and blasting, sometimes crushed underground and brought to the surface for milling. Some processing may be possible underground. At the McArthur River uranium mine in Canada, a remote mining method is employed and the ore, which is of very high grade, is processed to slurry underground to avoid radiological exposure problems at the surface. This slurry is then transported 80 km by road to the mill for further processing at the Key Lake facility. Compared with open-pit mining, underground mining produces smaller waste rock volumes and leaves a smaller infrastructure footprint at the surface. Underground mining issues concern ventilation and the need to manage airborne contaminants and the mine infrastructure design and operation to ensure workers' safety.

2.2.3 In-Situ Leach mining (ISL) or solution mining

Over the past two decades, In-Situ Leach mining (ISL), also called solution mining or In-Situ Recovery (ISR), has become increasingly important. Uranium dissolves in both acid and alkali solutions. This method uses either acid (e.g. H_2SO_4 in Australia) or alkaline solutions (e.g. bicarbonate in the U.S.) to extract the uranium directly from the deposit that must be in the right geological setting (readily leachable and in a confined aquifer). The uranium-dissolving solutions are injected into the deposit and then recovered from the ore-bearing zone using a system of wells. Both reagents may have environmental and safety consequences depending on how they are used and how the disposal of waste is managed.

ISL is relatively cheap to set up under the right conditions, especially for lower grade ores. ISL causes little surface disturbance or waste rock but a relatively small volume of residual waste, for instance sludge, depending on the extraction process. However its biggest challenge is in the decommissioning and flushing of the contaminants and residual leachate from the groundwater regime, which can take years. Use of ISL has been steadily increasing worldwide.

2.2.4 Other mining methods

Other methods applied in uranium production include co-product or by-product recovery from copper, gold and phosphate operations, heap leaching, in-place leaching (also called block leaching) and ion-exchange recovery facilities.

Heap leaching involves use of a leaching facility on the surface once the ore has been mined. In-place leaching entails extraction of uranium from broken ore without removing it from an underground mine. Ion-exchange recovery implies recovery of uranium from mine water treatment facilities and environmental restoration activities. Table 2.2.4.1 shows worldwide uranium production and extraction methods used in 2013.

Table 2.2.4.1. Worldwide uranium production in 2013.

	WNA	OECD (2014)
	U (%)	U(%)
Underground & open-pit	47 (except Olympic Dam)*	44.1
In situ Leach (ISL)	46	47.5
By-product*	7	6.4
Heap leach	0	1.3
Other	-	0.7

*Uranium produced in the Olympic Dam mine in Australia is listed as by-product.

Examples of mining operations, currently producing or having produced uranium as a by-product, are: (1) copper mining operations in, for instance, Australia, South Africa (e.g. Palabora mine) and the U.S., (2) phosphate rock mining operations (and production of phosphoric acid) in Morocco and Florida, U.S., (3) gold mining operations in South Africa, 4) ion-exchange recovery operations in Germany and France and 5) nickel zinc mining in Finland. Potential future mining projects involving uranium as a by-product include projects in Morocco and Jordan (phosphate), Chile and Zambia (copper) and Greenland (rare earth elements).

2.3 Production of uranium for use in civilian power generation

As the precursor to the nuclear fuel cycle, uranium production focuses on extracting (or mining) and processing (or milling) natural uranium ore from the earth. The final product of these operations is a uranium oxide concentrate, often referred to as “yellowcake’, which is then transported to a fuel cycle facility. There, yellowcake is transformed into fuel for nuclear power reactors. In addition to yellowcake, uranium production operations generate large quantities of low-level radioactive waste, called tailings.

Production of uranium for use in civilian power generation includes:

- Mining method: Solution (ISL), Surface (open pit), Sub-surface (underground mining).
    - Surface (open-pit) and underground (shaft, ramp) – Drilling and blasting, ore excavation, ore haulage and storage.
        - Potential hazards: radioactive and non-radioactive ore constituents, radon, thoron and daughters, external gamma radiation, waste rock dust, vehicle exhaust, blasting fumes, oil mists, noise and vibrations.
- Mined ore:
    - Sorting of the mined ore at the mine using radiation counters.
    - Crushing (this step is not applied in ISL). The mined rocks are crushed to about 15-25 mm size fine ore. Depending on the hardness of the rock, this may require two or three stages. Potential hazards: radioactive and non-radioactive dust, radon, thoron and daughters, external gamma radiation, noise, etc.
    - Grinding (this step is not applied in ISL and heap leach). The fine ore is ground to usually <0.2 mm in water or other reagents. The size of the end-product is ore and process specific and will vary from project to project. Potential hazards: radioactive and non-radioactive dust, radon, thoron and daughters, external gamma radiation, noise, etc.
    - Physical separation (this step is not applied in ISL and heap leach). Physical separation processes exploit differences in physical properties such as size, density, magnetic properties, surface energy or behaviour of mineral particles to pre-concentrate minerals prior to further processing. Potential hazards: radioactive tailings and non-radioactive dust, radon, thoron and daughters, external gamma radiation, spills, etc.
    - Leaching. The ore-containing slurry is mixed with a leaching solution (acid or alkaline) to dissolve uranium, of which about 90% will be leached. Most conventional mills use a sulphuric acid leach process, but bicarbonate has also been used in, for instance, the Langer–Heinrich mine in Namibia. Potential hazards: chemical mists or spills, radon, thoron and daughters, external gamma radiation, etc.
    - Liquid-solid separation (this step is not applied in ISL and heap leach). Uranium in leachate solution from the previous step is separated from residual solids in a counter current decantation process (CCD). Solids have to be neutralized and pumped as slurry to the tailings storage facility. The liquid portion of the slurry contains other metals and salts in solution (this solution is also called 'pregnant liquor'). Potential hazards: radioactive tailings and non-radioactive dust, radon, thoron and daughters, external gamma radiation, etc.
    - Purification and concentration. 'Pregnant liquor' is filtered and clarified. Uranium is then separated from the solution by specific processes, effectively reversing the previous stage. These processes may involve adsorption onto ion-exchange resin or solvent extraction, for instance, amine in kerosene. Potential hazards: chemical spills, external gamma radiation, slurry spills, etc.
    - Precipitation and drying. The uranium in the aqueous solution is finally precipitated using a variety of agents. Usually ammonia is added to the solution and ammonium diuranate precipitates. This is bright yellow in colour ('yellowcake'). Yellowcake

is then heated in a calciner (650-800°C) to drive off ammonia and dry the product to produce U_3O_8, a dark green powder. Alternative precipitation methods may be used to precipitate the uranium, for example hydrogen peroxide which forms uranium peroxide, $UO_4.2H_2O$, another yellow compound. Calcium or magnesium salts, among others, may also be used. Potential hazards: chemical spills, external gamma radiation, slurry spills, uranium dust from the drying process, etc.

- Packing and transport. Packing of yellowcake is carried out in a reduced pressure atmosphere to prevent leakage to the environment. Workers must wear respiratory masks to avoid potential dust inhalation. This is needed to prevent consequences of a possible radiological event and the inhalation of the heavy metal uranium which is toxic. The final product is drummed and the drums are individually weighed and labelled to allow easy identification. Each individual drum weight and the weight of material inside are recorded along with the name of the mining company, shipper, receiver, etc., so that there can be a constant check to ensure the yellowcake product reaches its final destination in accordance with national and international requirements and safeguards. Drums are transported to a secure storage area where they are packed into containers and shipped to conversion plants. The major potential hazard of yellowcake transport is associated with its chemical toxicity and not its radioactivity. Potential hazards: spills, uranium dust, external gamma radiation, etc.
- Conversion, enrichment and fuel fabrication. The conversion process involves converting the yellowcake powder into pure uranium hexafluoride (UF_6) gas. The UF_6 is then pressurized and cooled to a liquid which is drained into a cylinder where it solidifies after cooling. The UF_6 cylinder is then shipped to an enrichment plant. Mined uranium-235 is enriched from 0.7 to 3.5-5% by gaseous diffusion, gas centrifuge or isotopic separation. Finally, enriched UF_6 is converted into fuel for nuclear reactors.

2.4 Past and current practices of uranium mining and milling

The public perception of uranium mining and milling is usually based on the adverse impacts of past practices when the industry was not regulated.

In the middle of the last century, uranium was suddenly urgently needed by several countries to produce nuclear weapons. During the Cold War and the initial stages of development of nuclear power, uranium facilities was controlled by the government or companies under governmental agreement for military purposes. Uranium was at that time mined without much consideration of environment or health aspects. Early mine practices did not include dust, water and waste management and led to contamination of local watersheds and nearby areas. There are several examples of mines that have been operated in an environmentally very unsatisfactory way in Russia, Germany, Brazil, Australia, Canada and the U.S. Common problems were pollution of air, water and land from badly managed waste rock, mine water and tailings (e.g. emanation of radon from tailings and waste rock). Severe environmental impacts occurred when natural events such as seasonal runoff, intense rainfalls, earthquakes or droughts led to further dispersion of the contaminants. These old legacy uranium facilities rely on the governments to finance the clean-up required to make the sites safe and stable, often at a high cost.

Regarding radiation protection, during the military production boom in the mid-20th century, mining and milling practices did not include proper dust control and ventilation, leading to high levels of radon build-up. Doses exceeding 50mSv/y were common and at times exposures over 100 mSv/y occurred. Consequently, workers were exposed to hazardous levels of radioactive and non-radioactive contaminants, leading to increased lung cancer incidence (Kreuzer et al., 2011; Vance et al., 2014).

Uranium mining and milling in the U.S. started before World War II in 1939 when no regulatory requirements existed. Many mines were small, underground operations located in remote locations, employing locals with no mining experience. Without experience and training, the accident frequency rates of both fatal and nonfatal injuries were high. Experience from early operations drove governments and industry to implement regulations, training and control measures. The Energy Reorganization Act (ERA) was passed in 1974, leading to the creation of the Nuclear Regulatory Commission (U.S. NRC).

The management of environmental and health issues has changed considerably since then. Thus, current uranium production requirements include:

- Environmental impact assessment (EIA).
- Social impact assessment (SIA).
- Financial assurance and decommissioning and rehabilitation plans, including also a long-term monitoring and care plan before mining and milling commences.
- Comprehensive monitoring programmes from early exploration to after closure of the uranium mine.
- A radioactive waste management plan including also release of effluents in the form of gases and liquids.
- Radiation management plan based on the general principle ''As low As Reasonably Achievable (ALARA)', which encourages uranium production licensees to make ''every reasonable effort to maintain exposures to radiation as far below the dose limit, as is practical consistent with the purpose for which the licensed activity is undertaken'' – 10 CFR part 20.1003''.
- Emergency preparedness and response plan for a radiological event.
- Safe transport of radioactive materials.
- Nuclear security and safeguards.
- Public engagement and transparency.
- Non-compliance actions.
- Mine closure plan.
- Other requirements.

Current regulations governing uranium production limit the radiation exposure to members of the public from all facilities and practices at mine sites to 1mSv/y. Occupational exposure is limited to 20 mSv/y (100 mSv over a 5-year period). However, occupational exposure in the industry is typically well below these limits.

Improved working conditions, extensive monitoring and management of modern uranium mines ensure that radiation exposure remains low. A good example is the radiation protection programme at the Olympic Dam mine in Australia. Powerful ventilation systems are used to avoid build-up of radon in the underground mine and workers' doses are closely monitored using Thermo Luminescence Dosimeters (TLD) badges combined with area measurements and regulation of the time that the workers spend at each work location.

In Canada, at the McArthur River underground mine (operated by Cameco Corporation), uranium production started in 1999 after an environmental assessment process and a rigorous review by regulatory authorities. In order to protect the workers from radiation exposure, some operations are conducted using remote-controlled equipment. Safety is a core value and an array of programmes and procedures are employed to achieve high standards of worker health and safety. In 2010, the Cameco Corporation was awarded for having the best safety performance in Canada’s metal mining category.

Members of the public often express concern about being exposed to hazards, particularly when residing close to an active or inactive uranium mining site. As a result, most of the countries regulating uranium production have developed a regulatory framework to ensure that the public as well as land, air and water are protected now and in the future. Considerable effort at all levels of government is usually made to protect and monitor the environment and the public. Leading practices include laws and regulations, compliance with which is ensured by independent authorities and continuous monitoring of emissions or releases both near and far from the mine site. The monitoring data are evaluated and assessed or modelled in detail to ensure that the public and environment are not at risk. These results are further peer reviewed and released for public scrutiny and public information.

Experiences from current uranium mines show that successful companies can develop strategies to manage all potential impacts of mining and milling on workers, communities and the environment in countries with an appropriate regulatory framework, an independent regulatory agency staffed with qualified personnel and a well-established public-involvement programme starting from early exploration. Typically, uranium mines and mill sites are regulated by an independent agency that reports to the head of state or to parliament. This reduces the possibility that political or economic goals influence regulatory decisions.

Most of the countries have developed their regulations and guidelines from IAEA and ICRP recommendations, for instance the effective exposure dose for members of the public is typically set to 1 mSv/y and to 20 mSv/y for workers in the industry (up to 50 mSv/year in a single year and maximum 100 mSv/y over a 5-year period).

Today, operating mines in the U.S., Canada and Australia produce uranium with minor environmental problems although there are concerns raised by environmental organizations about possible consequences of accidents (http://www.environment.gov.au/science/supervising-scientist/monitoring). The Australian Olympic Dam uranium underground mine is located nine kilometres north of the mining town Roxby Downs built in the 1980s to support the mine. The town has a residential population of around 4,500 with an average age of 29 years (http://www.roxbydowns.com/Community/c-home.html). The Ranger uranium mine is located eight kilometres east of the town of Jabiru and 260 kilometres south east of Darwin in Australia's Northern Territory. Located in the 79 square kilometres Ranger Project Area, Ranger mine is surrounded by, but separate from, the World Heritage-listed Kakadu National Park.

Experiences from uranium mines in other countries, for instance Malawi, show that lack of a complete legislative framework for the uranium industry, absence of a programme for implementation of environmental and health standards and not least the high unemployment rate in African countries are some of the factors that may easily lead to environmental contamination and health risks among workers and the residents of nearby towns.

Although current mining practice includes environmental and health precautions, challenges remain, in particular when mines are opened in the vulnerable Arctic environment. The Arctic states include Canada, Russia, Finland, Sweden, Greenland (Denmark), Alaska (United States), Iceland and Norway. Examples of the management of environmental and health practices in uranium mines operating in the Arctic and elsewhere in the world are given in Appendix A. Please note that they do not cover uranium mine sites worldwide.

2.5 Public engagement and transparency

In countries with leading practice uranium mines, public consultation is a requirement in the development of any mine, from the early stages of a proposal through the licensing steps, including the operational stage when monitoring data is made publicly available and the mining companies and regulators are prepared to discuss results with the public and other interested stakeholders. Both the IAEA (2010) and WNA (2006) recognise the importance of public consultation and stakeholder involvement as a crucial component of obtaining and maintaining a social licence to conduct mining. The dissemination of factual information on the operation and the willingness to discuss operational aspects with the interested public are a key component of social responsibility for leading practice uranium mining companies. Effective consultation is a two-way street, in addition to disseminating information the proponent needs to be willing to listen to stakeholders and address their concerns. Since the stakeholders are likely to consist of an extensive group of individuals, businesses and organisations with vastly different skill sets, technical abilities and, most importantly, expectations, specialised skills and resources are required to do this effectively.

An effective public consultation process invokes a dialogue with the public and other interested parties to take into account questions, views, concerns and opinions. This is not just an information programme that just flows outward. Rather, it is a two-way process that actively encourages and documents the questions and answers that arise. The public is a valuable resource to the proponent and the regulatory agencies and should be used accordingly. Public knowledge and support will go a long way in the timely review and licensing of new mines. Public fear and resistance will do just the opposite.

2.6 References

Jakubick, A. et al., 2008. Monitoring and remediation of the legacy sites of uranium mining in Central Asia, Uranium, Mining and Hydrogeology. Springer Verlag Berlin Heidelberg.

Kreuzer, M., Grosche, B., Dufey, F., Schnelzer, M., Tschense, A., Walsh, L., 2011. The German Uranium Miners Cohort Study (Wismut cohort), 1946-2003, Technical Report:
https://doris.bfs.de/jspui/bitstream/urn:nbn:de:0221-201102185211/1/German%20Uranium%20Miners%20Cohort%20Study%20(Wismut%20cohort)%201946-2003.pdf

OECD/IEA, 2013. World Energy Outlook. World Energy Agency: http://www.iea.org/

OECD-NEA/IAEA, 2014. Uranium 2014: Resources, Production and Demand. NEA No. 7209.

Tomášek, L., Darby, S. C., Fearn, T., Swerdlow, A. J., Placek, V., Kunz, E., 1994. Patterns of lung cancer mortality among uranium miners in West Bohemia with varying rates of exposure to radon and its progeny. Radiat. Res. 137: 251-261.

Vance, R., Hinton, N., Huffman, D., Harris, F., Arnold, N., Ruokonen, E., Vostarek, P., 2014.Managing Environmental and Health Impacts of Uranium Mining. Organisation for Economic Co-operation and Development, Nuclear Energy Agency-OECD/NEA, Le Seine Saint-Germain, 12 boulevard des Iles, F-92130 Issy-les-Moulineaux (France).

3 Regulatory framework governing uranium production for the nuclear fuel cycle

The radiation risk to employees, members of the public and the environment arising from uranium production for the nuclear fuel cycle must be assessed and controlled. Exploration, mining, milling and transport of radioactive material should be environmentally friendly, and radioactive waste management and site decommissioning/rehabilitation plans should meet the safety requirements of environmental regulations and societal expectations. Safety means the protection of people and the environment against radiation risk(s) and the safety of activities and facilities that give rise to radiation risk(s). Safety of activities includes but is not limited to: safety in the production (mining, milling and radioactive waste management: discharges of effluents, tailings disposal), transport of radioactive material, decommissioning of facilities, emergency preparedness and response.

Safety of facilities includes but is not limited to: safety of ore handling and processing facilities, safety of radioactive waste management, etc.

This chapter gives some examples of the regulatory framework governing uranium production for the nuclear fuel cycle applied in Australia, Canada and the U.S. Findings by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) and guidelines and recommendations of expert bodies, notably the International Atomic Energy Agency (IAEA) and International Commission on Radiological Protection (ICRP), are also briefly listed. Laws in force in Greenland and recommendations for further work needed for the uranium production fuel cycle in Greenland are included.

Regulation of uranium activities is a national responsibility (IAEA No. GSR Part 1, 2010). The government establishes and maintains an appropriate governmental legal and regulatory framework (Fig. 3.1) for safety and security. As defined by IAEA: '"Safety" is the achievement of proper operating conditions, prevention of accidents and mitigation of accident consequences, resulting in protection of workers, the public and the environment from undue radiation hazards' and "Nuclear security" is the prevention and detection of, and response to, theft, sabotage, unauthorized access, illegal transfer or other malicious acts involving nuclear material, other radioactive substances or their associated facilities'.

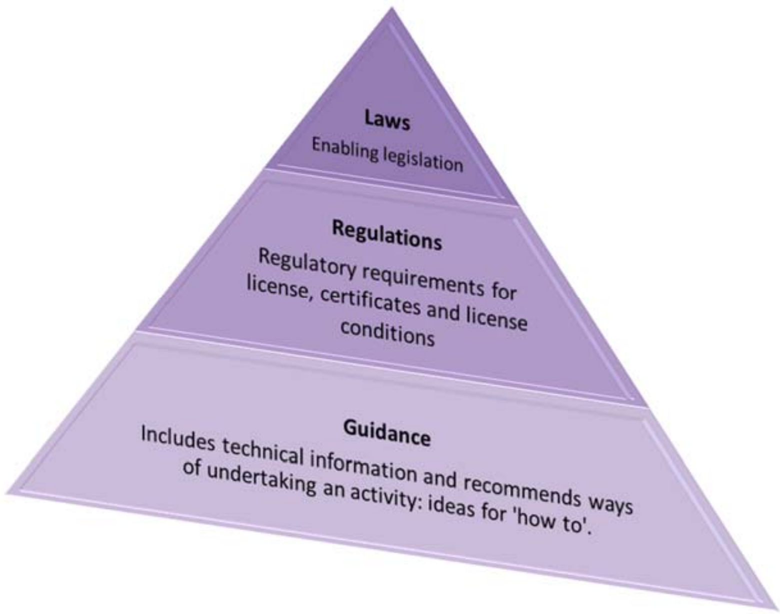
The framework for safety shall include (IAEA No. GSR Part 1, 2010):

- Safety principles for protecting people and the environment against radiation risks, both at present and in the future.
- Establishment of an independent regulatory body (several authorities independent in safety-related decision making) and policy for assessing the legal responsibilities of different regulatory bodies with respect to safety.
- Type of facilities and activities within the scope of the safety framework.
- Type of license required for operation, decommissioning and rehabilitation.
- Specific provisions regarding review, assessment and inspection of facilities and activities and for the enforcement of regulations.
- Specific provisions regarding preparedness for and response to a radiological event (emergency).

- Specific provisions for building and maintaining (training, learning through academic institutions, research and development work) the competence nationally (regulatory body and its support organizations providing services or expert advice) on matters relating to safety.
- Specific provisions regarding management of radioactive waste.
- Responsibilities and obligations with respect to financial provisions for the management of radioactive waste and for the decommissioning and rehabilitation of facilities at the completion of mining and milling.
- Provisions for safety in the transport of dangerous goods, including nuclear material and radioactive material.
- The criteria for site release from regulatory control.
- Specific provisions regarding nuclear security including a state system of accounting for and controlling radioactive material.
- Specific provisions regarding controls on the import and export of radioactive material as well as regarding their tracking within and outside national boundaries.
- Provisions for appeals against decisions of the regulatory body.
- Specifications of offences and the corresponding penalties.

Specific national regulatory bodies have to implement the governmental legal and regulatory framework for safety. Some of the regulations and guidelines for safety are developed in cooperation between different regulatory bodies. The regulatory body reviews, assesses and approves plans for facility design, construction, commissioning, operation (e.g. environmental monitoring and protection plans, radiation protection management, radioactive waste management), decommissioning (or closure in the case of disposal facilities for radioactive waste) of facilities, long-term monitoring and care. Moreover, it oversees, inspects and enforces license conditions and regulations. The objectives of the regulatory body are focused on radiation risk to workers, to the public and the environment for current and future generations and must respond to and control risk(s) to the environment and health. Furthermore, the regulatory body shall be a trusted and influential advisor and have the public's confidence regarding the safety and control of uranium facilities.

Figure 3.1. Elements of the regulatory framework for uranium facilities.



International cooperation in relation to safety and security (e.g. international standards, conventions and multilateral and bilateral agreements) has led to the development of a global safety and security regime. In some countries such as Australia, Canada and the U.S., international recommendations and guidelines (e.g. IAEA, ICRP, etc.) are taken into account when developing the regulatory framework governing uranium activities.

3.1 International Atomic Energy Agency (IAEA)

'The IAEA is the world's centre of cooperation in the nuclear field. It was set up as the world´s 'Atoms for Peace' organization in 1957 within the United Nations family'. The Agency works with several member states and multiple partners worldwide to promote safe, secure and peaceful nuclear technologies. Three main areas of the work of IAEA are: (1) safety and security, (2) science and technology and (3) safeguards and verification (www.iaea.org).

With the aim to ensure the protection of human life and health and the environment from effects of ionizing radiation, the IAEA safety standards establish fundamental safety principles, requirements and measures to: (1) control the ionizing radiation exposure of people and the release of radioactive material to the environment, (2) prevent and limit the likelihood of events (both nuclear and radiological) and (3) mitigate the consequences of such events if they should occur.

IAEA safety standards can be applied to facilities and activities that give rise to radiation risks including, for example, mining and milling (naturally occurring radioactive material – NORM), transport of radioactive material, radioactive waste management, etc.

IAEA security measures (http://www-pub.iaea.org/books/IAEABooks/Series/127/Nuclear-Security-Series) include prevention and detection of, and response to, theft, sabotage, unauthorized access, illegal transfer or other malicious acts involving nuclear and or radioactive material (with or without knowledge of the nature of the material) or their associated facilities. Security issues associated with uranium production in Greenland are under the responsibility of Ministry of Foreign Affairs of Denmark.

Safety and security synergies concern, for example, regulatory infrastructure, engineering provisions in the design and construction of nuclear installations and other facilities, the categorization of radioactive sources, source design, the security of the management of radioactive sources and radioactive material, the recovery of orphan sources, emergency response plans and radioactive waste management.

Safety and security measures, both with the aim of protecting the people and the environment from ionizing radiation, have to be designed and implemented in an integrated manner in such a way that security measures do not compromise safety measures and vice versa (Fig. 3.2).

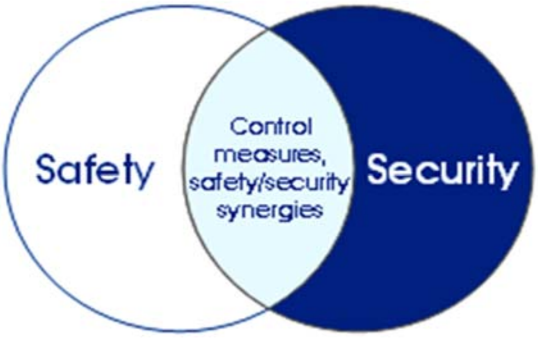


Figure 3.2. Complementarity of safety and security. Source: IAEA (http://www-ns.iaea.org/standards/concepts-terms.asp).

The IAEA safety standards include: (1) safety fundamentals, (2) safety requirements and (3) safety guides for protection of people and the environment from harmful effects of ionizing radiation. The IAEA safety standards are applicable throughout the entire lifetime of facilities and activities utilized for peaceful purposes, and to protective actions to reduce existing radiation risks.

Safety fundamentals present the safety objective and principles for protecting the people and the environment. Safety requirements are governed by the objectives and principles of the safety fundamentals and lay down the requirements that must be met to ensure protection of people and the environment for now and in the future. The IAEA safety guides provide international recommendations and guidance on how to fulfil the safety requirements. Recommendations given in safety guides are expressed as 'should' statements (IAEA, 2004, 2010). The safety guides comprise international best practices and IAEA recommends their users to implement the measures stated or equivalent alternative measures in order to achieve high levels of safety (IAEA, 2006, 2010, 2013). Each safety requirements publication is supplemented with a number of safety guides, which can be used in the development of national regulatory guides.

The IAEA safety standards are used worldwide by regulatory bodies, relevant national authorities (e.g. as a reference for their national regulations related to facilities and activities) and all organizations involved in nuclear activities, production of uranium for the nuclear fuel cycle, nuclear medicine, etc. Those standards are applicable, as relevant, throughout the entire life of all facilities and activities, and all actions are undertaken to reduce existing radiation risks.

IAEA safety fundamentals, general safety requirements, general safety guides and specific requirements and specific safety guides related to uranium mining and milling are listed in Tables 3.1 and 3.2 of Appendix B and can be downloaded from:
http://www-ns.iaea.org/standards/documents/default.asp?s=11&l=90&sub=50
http://www-ns.iaea.org/standards/documents/general.asp
http://www-ns.iaea.org/publications/norm-publications.asp

3.2 International Commission on Radiological Protection (ICRP)

The work of the ICRP helps to prevent cancer and other diseases and health effects associated with exposure to ionizing radiation and to protect the environment. ICRP is an independent, international organization and has, since

1928, developed and elaborated the International System of Radiological Protection used worldwide as the common basis for radiological protection standards, legislation, guidelines, programmes and practices.

The International System of Radiological Protection has been developed based on: (1) the current understanding of the science of radiation exposures and effects and (2) value judgements, for instance societal expectations, ethics and experience gained in application of the system.

ICRP publications, especially fundamental recommendations publications, describe the overall system of radiological protection. Some relevant publications related to radiological protection are listed in Appendix C and can be downloaded from: http://www.icrp.org/publications.asp.

3.3 International Radiation Protection Association (IRPA)

The primary purpose of IRPA is to provide a platform for knowledge exchange and training whereby those involved in radiation protection activities worldwide can communicate and through these processes advance radiation protection globally (http://www.irpa.net/). This includes relevant aspects of science, medicine, engineering, technology and law, to provide for the protection of man and his environment from the hazards caused by radiation, and thereby to facilitate the safe use of medical, scientific and industrial radiological practices for the benefit of mankind.

Other objectives of IRPA are to:

- Support the establishment of radiation protection societies worldwide to achieve international cooperation.
- Provide and support international meetings for the discussion of all aspects of radiation protection.
- Encourage international publications on radiation protection.
- Encourage research and educational opportunities in those scientific and related disciplines which support radiation protection.
- Support the establishment and continuous review of acceptable radiation protection standards or recommendations through the international bodies concerned.

3.4 United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR)

UNSCEAR assesses global levels and effects of ionizing radiation on humans and the environment and provides a scientific basis for radiation protection (http://www.unscear.org).

Reports are being made on medical, public and occupational exposures to ionizing radiation, radiation exposures from accidents, health effects of the Chernobyl accident and radiation effects on non-human biota. These reports are highly regarded as principal sources of authoritative information and research findings are disseminated for the benefit of the international scientific community. Some relevant UNSCEAR publications are:

- UNSCEAR 2012: Biological mechanisms of radiation actions at low doses. A white paper to guide the Scientific Committee's future programmer of work.

- UNSCEAR 2008 Report: 'Sources and effects of ionizing radiation', Volume I, Annex B: Exposures of the public and workers from various sources of radiation and Volume II, Annex C: Radiation exposures in accidents and Annex E: Effects of ionizing radiation on non-human biota.
- UNSCEAR 2000 Report: 'Sources and effects of ionizing radiation', Volume I, Annex B: Exposures from natural radiation sources.

3.5 European Atomic Energy Community (EURATOM)

EURATOM was created with the main aim to coordinate research programmes of the EU member states for the peaceful use of nuclear energy (http://www.euratom.org/).

EURATOM's areas of operation connected with atomic energy comprise: (1) research, (2) drawing-up of safety standards and (3) peaceful uses of nuclear energy.

One of the fundamental objectives of the EURATOM Treaty is to ensure that all users in the EU enjoy a regular and equitable supply of ores and nuclear fuels (source materials and special fissile materials). Greenland was a member of EURATOM but due to its withdrawal in 1985 from the European Community, EURATOM; legislation is not applicable in Greenland.

3.6 Nuclear Energy Agency (OECD)

The Nuclear Energy Agency (NEA) is an agency within the Organization for Economic Co-operation and Development (OECD), an intergovernmental organization of industrialized countries (http://www.oecd-nea.org/). The areas of operation of NEA comprise nuclear safety and regulation, nuclear energy development, radioactive waste management, radiological protection and public health, nuclear law and liability, nuclear science, the data bank and information and communication. NEA cooperates closely with IAEA and the European Commission in Brussels.

The mission of NEA is 'to assist its member countries in maintaining and further developing, through international co-operation, the scientific, technological and legal bases required for a safe, environmentally friendly and economical use of nuclear energy for peaceful purposes. Further OECD aims to provide authoritative assessments and to forge common understandings on key issues as input to government decisions on nuclear energy policy and to broader OECD policy analyses in areas such as energy and sustainable development.

NEA's role is to provide a:

- Forum for sharing information and experiences and promoting international co-operation.
- Centre of excellence which helps member countries to pool and maintain their technical expertise.
- Vehicle for facilitating policy analyses and developing consensus based on its technical work.

3.7 World Nuclear Association (WNA)

WNA is an international organization that promotes nuclear energy and supports companies that comprise the global nuclear industry (http://www.world-nuclear.org/).

The role of WNA is to provide a global forum through actions to:

- Share knowledge.
- Provide a commercial meeting place for leaders and specialists representing all aspects of the nuclear industry.
- Strengthen industry operational capabilities by advancing best-practice internationally.
- Speak authoritatively for the nuclear industry in key international forums that affect the policy and public environment in which the industry operates.

3.8 International Council on Mining and Metals (ICMM)

ICMM was founded in 2001 with the aim to improve sustainable development performance in the mining and metals industry (www.icmm.com). ICMM operates as an agent for change and continual improvement on issues relating to mining and sustainable development.

ICMM has five stated values:

- Care for the safety, health and well-being of workers, contractors, host communities and the users of the materials produced.
- Respect for people and the environment, ensuring that ICMM is sensitive and responsive to the values of host societies.
- Integrity as the basis for engagement with employees, communities and governments.
- Accountability to do what ICMM says that it will do and uphold commitments made.
- Collaboration – working with others in an open, transparent and inclusive way.

3.9 European Economic Community (EEC)

EEC was established by a treaty signed in 1957 by Belgium, France, Italy, Luxembourg, the Netherlands and West Germany (now Germany). The EEC Treaty provided for the establishment of a common market and a customs union and the development of common policies (http://europa.eu/legislation_summaries/institutional_affairs/treaties/treaties_eec_en.htm).

3.10 World Nuclear Transport Institute (WNTI)

WNTI was founded in 1998 to promote the safety and security standards and practices applied to the international transport (road, rail, sea, air and inland waterway) of radioactive materials (http://www.wnti.co.uk/).

The regulatory framework for international transport of radioactive materials includes standards, codes and regulations (http://www.wnti.co.uk/nuclear-transport-facts/regulations.aspx).

3.11 Regulatory framework for uranium production for the nuclear fuel cycle in Australia

Australia is a federation, with jurisdiction resting with both the (six) states and the Commonwealth of Australia. Generally, safety, security and taxes (e.g. mining, milling, waste management and radiation protection) are matters regulated by the states: New South Wales (NSW), Queensland (QLD), South Australia (SA), Tasmania (TAS), Victoria (VIC) and Western Australia (WA). SA, WA and QLD are the states with uranium mines and refinery facilities and deposits or prospective mines: http://www.world-nuclear.org/info/Country-Profiles/Countries-A-F/Australia/. Export, safeguards and taxes are regulated by the Commonwealth.

Australia’s two major mainland territories – the Australian Capital Territory (ACT) and the Northern Territory (NT) – are regulated by the Commonwealth and the Northern Territory governments.

The Australian Radiation Protection and Nuclear Safety Agency (ARPANSA) is the Australian Government's primary authority with responsibility for protecting the health and safety of people, and the environment, from the harmful effects of radiation. ARPANSA regulates the use of radiation by Commonwealth entities and their contractors (http://www.arpansa.gov.au/index.htm). States and Territories are responsible for radiation protection but have agreed to adopt common uniform requirements and use common codes of practice and guidance. ARPANSA regulatory activities include licensing, compliance, inspection and enforcement.

ARPANSA supports the Australian Nuclear Safety Committee (nuclear safety and the safety of controlled facilities) and Radiation Health Committee (radiation protection) in the development of standards, codes of practice, guidelines and other relevant material to ensure radiation protection and nuclear safety throughout Australia. ARPANSA works with state and territory regulators to promote national radiation protection mainly through the Radiation Health Committee (RHC).

The Australian system of radiation protection is based on the IAEA General Safety Requirements and ICRP recommendations.

The Australian Department of the Environment designs and implements the Australian Government’s policies and programmes with the aim to protect and conserve the environment, water and heritage and promote climate action. The environmental framework includes: clean air, clean land, clean water and national heritage.

The Australian Safeguards and Non-Proliferation Office (ASNO) ensures that Australia’s international obligations are met under the Nuclear Non-Proliferation Treaty (NPT), Australia's NPT safeguards agreement with the International Atomic Energy Agency (IAEA), the Convention on the Physical Protection of Nuclear Material (CPPNM) and Australia’s various bilateral safeguards agreements.

The four main areas of responsibility of ASNO in the nuclear area are:

- Application of safeguards in Australia.
- Physical protection and security of nuclear items in Australia.
- Operation of Australia’s bilateral safeguards agreements.
- Contribution to the operation and development of IAEA safeguards and strengthening of the international nuclear non-proliferation regime.

Australian laws, regulations and guidelines governing uranium production for the nuclear fuel cycle are given in Appendix D.

3.12 Regulatory framework for uranium production for the nuclear fuel cycle in Canada

Canada has federal legislation which regulates radiation protection, health and safety and environmental matters within mining and milling of NORM.

The Canadian Nuclear Safety Commission (CNSC) is an independent commission and is responsible for regulating and licensing all existing and future uranium mining and milling operations in Canada. The CNSC's work is undertaken in accordance with the requirements of the Nuclear Safety and Control Act (NSCA) and its related regulations, which reflect Canadian and international safety standards
http://nuclearsafety.gc.ca/eng/uranium/index.cfm.

The CNSC's licensing process for uranium mines and mills follows the stages laid out in the Uranium Mines and Mills Regulations. Using the lifecycle approach to licensing, the CNSC issues licenses for all phases (site preparation and construction, operating, decommissioning and abandonment or release from licensing phases) in the lifecycle of a uranium mine and mill.

Before the CNSC can consider a licensing decision regarding any proposed project, an environmental assessment (EA) has to be completed in compliance with the Canadian Environmental Assessment Act 2012 (CEA Act).

The CNSC exercises regulatory oversight and ensures that each licensee has a financial guarantee in place (for all mine phases) to cover eventual decommissioning/rehabilitation costs.

The CNSC also assesses whether licensees comply with the Nuclear Safety and Control Act (NSCA), regulations and international obligations.

CNSC also conducts annual assessments of all uranium mines and related facilities, including uranium mines and mills, uranium processing facilities and nuclear substance processing facilities. The assessments focus on radiation protection, environmental protection and conventional health and safety. The assessments also include waste management, emergency management and fire protection.

When regulating and licensing all existing and future uranium mining and milling operations, CNSC works together with agencies such as: Environment Canada, Fisheries and Oceans Canada, Indian and Northern Affairs, and Transport Canada plays a federal role. Environmental protection and worker safety may also be the responsibility of local jurisdictions (e.g., territorial, provincial).

Canadian laws, regulations and guidelines governing uranium production for the nuclear fuel cycle are given in Appendix E.

3.13 Regulatory framework for uranium production for the nuclear fuel cycle in the United States

For mining activities, the regulatory responsibility depends on the extraction method that the given facility uses. Conventional mining activities are regulated by The Office of Surface Mining Reclamation and Enforcement (OSMRE), the United States Department of the Interior and the individual states where the mines are located. OSMRE is responsible for establishing a nationwide program (overseeing the programmes in the individual states and developing new tools to help the states administer their programmes) in order to protect the public and the environment from the adverse effects of surface mining operations (http://www.osmre.gov/lrg.shtm).

The Nuclear Regulatory Commission (NRC) licenses and regulates the use of radioactive materials to protect public health and safety, promote the common defence and security and protect the environment (www.nrc.gov).

The U.S. Nuclear Regulatory Commission (NRC) regulates in situ recovery mining and does not regulate conventional mining which is subject to the 1872 Mining Act. However, NRC becomes involved in uranium recovery operations when the ore is processed and chemically altered (milling). This happens either in a uranium mill from a conventional mine or during in situ recovery (ISR). For that reason, the NRC regulates in situ recovery facilities (as stated above) as well as uranium mills and the disposal of liquid and solid wastes from uranium recovery operations (including mill tailings).

The NRC focuses its regulatory actions on protecting the health and safety of the public and the environment during the active life of a uranium recovery operation and after the facility has been decommissioned.

The NRC activities include:

- Development of regulations and guidance for uranium recovery activities.
- Reviewing of license applications and amendments.
- Elaboration of environmental assessments (EAs) and environmental impact statements (EISs) to support the agency's reviews.
- Inspection of uranium (recovery) facilities.
- Reviewing of decommissioning plans and activities.

Uranium milling and disposal of the resulting waste by-product material by NRC licensees are regulated under The Code of Federal Regulations (CFR).

The U.S. Nuclear Regulatory Commission (NRC) currently regulates operating uranium recovery facilities in Wyoming, New Mexico and Nebraska. However, the NRC does not directly regulate the uranium recovery operations in Texas, Colorado and Utah as they are Agreement States, meaning that they have entered into strict agreements with the NRC to exercise regulatory authority over this type of material. Applicants for a license for uranium mining in Agreement States have to forward those applications to governments of the Agreement States and not the NRC. However, the NRC still provides substantial input to decision making and Agreement State regulations must conform to NRC regulations. Penalties for violation of regulations can include but are not limited to: revoking of licenses, injunctions or court orders and criminal sanctions.

The main purpose of the United States Environmental Protection Agency (EPA) is to ensure the public health and protection of the environment.

EPA activities are to:

- Implement environmental laws made by the Congress by developing and enforcing national regulations that span many environmental topics.

- Give grants to state environmental programmes, non-profits, educational institutions and others.
- Identify (laboratory work) and try to solve environmental problems.
- Teach people about the environment and publish information (inform the public about EPA activities).

The US Department of Energy (DOE) takes over the tailings and waste at the end of a mining project when DOE and NRC determine that remedial action at the mine site is completed. Old, unlicensed and abandoned mill tailings sites are identified and cleaned up by DOE with NRC concurrence.

U.S. laws, regulations and guidelines governing uranium production for the nuclear fuel cycle are described in Appendix F.

3.14 Regulatory framework for mineral resources activities in Greenland

This section lists the Greenland laws, regulations and guidelines relevant for mineral resource activities. The Ministry of Industry, Labour and Trade (MILT) is the authority for issues concerning industry and labour policy including social impact assessments (SIA) and impact benefit agreements (IBA) for mineral resources and similar related socio economic issues.

The Ministry of Mineral Resources (MMR) is responsible for strategy-making, policy-making, legal and geological issues and marketing of mineral resources in Greenland. The Mineral Licence and Safety Authority (MLSA) is the one-door authority. The MLSA is the overall administrative authority for licences and mineral resource activities, and is the authority for safety matters including supervision and inspections.

The Environmental Agency for Mineral Resource Activities (EAMRA) is the administrative authority for environmental matters relating to mineral resources activities, including protection of the environment and nature, environmental liability and environmental impact assessments (EIA).

Greenland is a member of the Inuit Circumpolar Council (ICC), the Arctic Council and the Nordic Council (see more: http://naalakkersuisut.gl/en/About-government-of-greenland). Information on Greenland areas of international cooperation and agreements can be found here: http://naalakkersuisut.gl/en/Naalakkersuisut/Greenland-Representation-to-the-EU.

Laws

- Greenland Parliament Act no. 7 of 7 December 2009 on mineral resources and mineral resource activities (the Mineral Resources Act), with amendments from Greenland Parliament Act no. 26 of 18 December 2012, effective as from 1 January 2013, and Greenland Parliament Act no. 6 of 8 June 2014, effective as from 1 July 2014 http://www.govmin.gl/index.php/about-bmp/legal-foundation
- Greenland Parliament Act no. 33 of 9 December 2015 on ionizing radiation and radiation protection.

Regulations

- Rules for fieldwork and reporting in Greenland, http://www.govmin.gl/minerals/terms-rules-laws-guidelines

Guidance

- EIA Guideline,
- SIA Guidelines,
  http://www.govmin.gl/minerals/terms-rules-laws-guidelines

Navigating in Greenland Waters - Legislation and Guidelines

- Act on maritime safety (Consolidated Act no. 903 of 12 July 2007)
- Order no. 417 of 28 May 2009 on technical regulation on safety of navigation in Greenland waters
- Order no. 170 of 17 March 2003 on ship reporting systems in the waters off Greenland
- Technical Regulation no. 169 of 4 March 2009 on the use of ice searchlights during navigation in Greenland waters.

International arrangements

Following international response conventions apply to Greenland:

Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency (1986) – This international assistance agreement, which was developed under the auspices of the IAEA, promotes cooperation between signatories and facilitates prompt assistance in the event of a nuclear accident or radiological emergency. Its purpose is to minimize the consequences of such an accident; practical steps include taking measures to protect life, property and the environment. The agreement sets out how assistance is requested, provided, directed, controlled and terminated.

Convention on Nuclear Safety (1994) - This international convention, which was developed under the auspices of the IAEA, aim to legally commit participating States operating land-based nuclear power plants to maintain a high level of safety by setting international benchmarks to which States would subscribe. The obligations of the Parties cover for instance, siting, design, construction, operation, the availability of adequate financial and human resources, the assessment and verification of safety, quality assurance and emergency preparedness.

Given the knowledge available today, it is obvious that a well-developed regulatory framework and an implementation programme are required to operate a uranium mine in an environmentally safe manner. Greenland already has a regulatory framework for mineral resources activities and thus only needs to add a radiation/uranium part to the existing regulatory framework.

Some of the international standards such as ISO 14001, ISO 14004, recommendations from IAEA, ICRP, EU 2013/59/EURATOM and UN conventions can be used to develop Greenland radiation standards for uranium production (see also Report on the exploitation and export of uranium, October 2013: http://naalakkersuisut.gl/da/Publikationer/2013).

Greenland regulatory bodies have to consider developing radiation standards and requirements for radiation safety matters to be included in license agreements for uranium production in the nuclear fuel cycle. Some examples of what to consider are listed below:

Development of standards for:

- Radiation protection programmes for licensed activities, including protection of employees at the mine site, members of the public and the environment from radiation risks at present and in the future, dose limits for members of the public and for workers and discharge limits for airborne and liquid radionuclides and clearance levels.
- Environmental protection regulations requirements for radioactivity monitoring programmes for all mine phases (including monitoring of effluents and the environment) as well as for detection compliance and corrective action(s), when needed.
- Requirements for radioactive waste management, including requirements for tailings disposal locations, site and design requirements for tailings disposal, requirements for groundwater protection, tailings dam construction and stability, geochemical characterization of radioactive tailings, quantities of radionuclides disposed in tailings facilities, waste treatment, requirements for daily inspections of tailings / waste areas, long term risk assessment.
- Requirements for radioactive airborne emission controls and requirements for radioactive liquid discharges to the environment.
- Inspection and enforcement policies (enforce license conditions and regulations - requirements for inspections of facilities and activities, for instance tailings / waste areas, etc.).
- Requirements for preparedness for, and response to, a radiological emergency.
- Storage and control of radioactive licensed material.
- Transport of radioactive material (regional and international).
- Requirements for site closure criteria including reclamation plan, rehabilitation of the mill tailings, requirements for cover design for closed uranium mill tailings (stability and radon control), radiological criteria for soil and buildings, clean-up during decommissioning, groundwater treatment and monitoring, permeable barriers, long-term stability requirements, surveillance requirements, maintenance and inspections.
- Record keeping and reporting.
- Financial assurance requirements (e.g. a case study: For AREVA's Cluff Lake Project, the financial assurance, in the form of an irrevocable letter of credit for $33,800,000, was held by the Province in conjunction with the Canadian Nuclear Safety Commission (CNSC), assuring the availability of funds for decommissioning and long-term surveillance).

3.15 References

IAEA, 2004. Regulatory Control of Radiation sources, IAEA Safety Guide No. GS-G-1.5.

IAEA, 2006. Application of the Management System for Facilities and Activities, IAEA Safety Standards Series No. GS-G-3.1.

IAEA, 2010. Governmental Legal and Regulatory Framework for Safety, IAEA Safety Standards Series No. GSR Part 1.

IAEA, 2013. Model Regulations for the Use of Radiation Sources and for the Management of the Associated Radioactive Waste, IAEA TECDOC No. 1732

4 Environmental protection

This chapter provides a description of a programme for environmental protection for mining and milling operations that handle naturally occurring radioactive materials. Methods to prevent and reduce the generation and release of liquid radioactive and non-radioactive contaminants into the environment from proposed activities are provided.

4.1 Introduction

Each licensee who processes or refines uranium ores in a milling operation is required to make every reasonable effort to maintain radiation exposures and release of radioactive and non-radioactive contaminants in controlled discharges and unplanned events as low as is reasonably achievable.

Potential impacts associated with proposed mining activities should be identified prior to commencement of mining and milling and shall include: (1) environmental impacts (air, land, water and biota), (2) social impacts (e.g. public health, fire, heritage, use of public resources) and (3) economic impacts (e.g. regional economy, individual landholder income, land value etc.).

Factors taken into account in the assessment process of potential environmental impacts should be:

- Sources / events that may cause an impact, for instance consideration of all relevant radionuclides and non-radioactive contaminants, additional parameters such as pH, sulphates, carbonates, chemical and physical processes of concern.
- Pathways (how the source or an event reaches the receptor, for instance wind).
- Receptor (human, non-humans, for instance fauna, flora, etc.)
- Barrier / prevention (engineering and prevention methods and characteristics of the environment that impede the way to the receptor).
- Impact (quantification of the impact, ability to remediate the contaminated site, outcome, duration, etc.).
- Quantity and geochemical implications of pollution sources generated, for instance original ore, rock waste and tailings.
- Waste management, including also effluents treatment and discharge and waste disposal methods.
- Mine water management (of, for instance, runoff water, fire event water, flood water (extreme event), spills and leaks).
- Hydrological factors such as water balance at the site and measures to prevent groundwater contamination.
- Mining methodology and mining rate, all applied processes during the milling, transport of radioactive material and non-radioactive materials.
- Climatic factors (rainstorms, snow melting events, dry spells).

Sources of pollution

Sources of pollution at an open-pit mine site include but are not limited to:

- Solid wastes:
    - Sands, slimes (finely powdered waste) and solid precipitates including mill tailings from the physical separation and from acid / alkaline leaching plants (ore chemical processing).

- Waste rock from excavation of mine pits.

- Liquid wastes:
  - Waste from physical separation and acid / or alkaline leaching plants and other liquid wastes such as floor washing and laboratory wastes, spills and leaks, pit de-watering and de-watering of tailings.
  - Seepage and decant solution from waste retention systems (tailings, waste rock facilities). Contaminated runoff water from ore stock pile, waste rock, groundwater inflow and dust suppressor's agents, fire water (in event of fire), flood water (extreme event), etc.
- Airborne dust particles and radon / thoron and their decay products from drilling, blasting, conveyor transfer points, ore stock pile, waste rock pile and areas of disturbed ground, spills, crushing and grinding, ore processing (e.g. yellowcake drying and packaging), tailings including tailings treatment (e.g. de-watering) and effluents control, decommissioning and rehabilitation activities, and 'fugitive' dust', dust sources that are not easily defined.
- Airborne mists and fumes from reagent preparation and leaching operations.
- Release of contaminants to the environment via chemical processes (e.g. acid / alkaline rock drainage (ARD) due to the leaching process) and from unforeseen accidents such as fire, slope stability, waste dam failure, radiological events such as accidents at the mill plant facility or transport of yellowcake and natural disasters.
- Material collected by dust extraction systems, scrubber effluents, stacks emissions and contaminated parts of plant and equipment.
- Waste generated during decommissioning and rehabilitation.
- Industrial debris and domestic waste (non-radioactive waste).

Environmental impacts associated with the proposed mining and milling activities may include: contamination of water, land and air through release of contaminants in the form of particulate matter, gases and contaminated effluents to the environment. The proposed mining activities may also affect the biota, cause physical change of the landscape due to mine pits and tunnels, roads, working areas and ports and have cumulative impacts.

Pathways of contaminants to the receiving environment

Significant pathways (see Chapter 10) transporting contaminants to the receiving environment are:

- Spilled radioactive and hazardous substances transported by wind, aquatic and terrestrial ecosystems (e.g. rainfall, dry and wet deposition, biological processes, uptake of contaminants by non-human biota (NHB), for instance via root uptake or atmospheric deposition (depending on soil characteristics, plant type and the chemical properties of the radionuclides in question)). Air transport of radioactive gases such as radon and thoron and radionuclides in dust from drilling, blasting and other activities at the mine site.

4.2 Pollution prevention

Early avoidance of environmental pollution is a best practice that may be achieved through integration of an environmental protection programme into all mine phases. Best practices may include: As Low As Reasonable Achievable (ALARA), Best Available Technology (BAT), Best Environmental Practice (BEP) and Best Practicable Control Technology (BPT).

An environmental protection program should include the proposed measures to prevent / control the release of airborne and liquid contaminants into the environment.

As a further consideration, the environmental protection programme should address environmental emergency preparedness and response in terms of: (1) measures to prevent or mitigate the effects of accidental releases of contaminants to the environment and (2) the health and safety of humans.

Management of associated environmental issues should be an integral part of the whole uranium production cycle from:

- Uranium exploration (baseline studies: site characterization, management of generated waste and dust, radiation risk assessment).
- Feasibility studies (baseline studies: site characterization, management of waste generated, prediction of environmental impacts, radiation risk assessment) and project design (planning for avoidance).
- Mine construction (site characterization, management of dust, water and waste generated, prediction of environmental impacts, air, surface water and groundwater control systems, monitoring and radiation risk assessment).
- Operation (site characterization, prediction of impacts, effective control measures of effluent releases, waste, water and dust management, monitoring and radiation risk assessment).
- Decommissioning and rehabilitation (site characterization, prediction of impacts, water treatment, waste and dust management and monitoring and radiation risk assessment).
- Post-closure (site characterization, monitoring and radiation risk assessment, maintenance, inspections and, where required, long-term collection and treatment).

Furthermore, geochemical modelling of the processes in uranium tailings and prediction of the contaminant discharge / release into the environment, groundwater transport modelling, atmospheric dispersion and deposition modelling, modelling of the fate and transport of radionuclides from the identified sources to the environment, employee training programmes and public information have to be made on an ongoing basis throughout the lifetime of the mine from the exploration phase through post-closure monitoring.

Parameters to be considered when selecting a strategy for pollution prevention are:

- Bio-physico-chemical factors such as climate, topography, hydrogeology, hydrology, pollution source, pathway and site-specific environmental receptors, geochemical characteristics of the deposit, etc.
- Regulatory factors such as regulatory requirements and best practices.
- Cost and risk factors such as available technology, reputational, financial, health and safety factors.

Prevention and mitigation methods are site specific and depend on the type of mining and milling operations, ore geochemistry, hydrometallurgical process, ore production rate, drainage restrictions, climate, etc.

Pollution prevention methods include inhibition, retarding or minimizing the hydrological, chemical and radioactive contaminants, microbiological or thermodynamic processes that may lead to environmental contamination.

Pollution mitigation methods (e.g. engineering, chemical) have been developed and are evolving in response to environmental pollution.

Demonstration of the effectiveness of prevention and mitigation methods should be made through effluent and environmental monitoring programmes and radiation risk assessment. Effluent monitoring should be the primary indicator of performance in terms of release to air and water bodies from facility operations and waste management activities.

Environmental and effluent monitoring should provide confidence that mitigation measures are effective, that health and environmental effects remain acceptably low and that contaminants in the environment do not exceed established threshold levels (see Chapter 7 of this report).

4.2.1 Prevention of air pollution

Airborne dust particles may be radioactive (short- and long-lived radionuclides, for instance uranium, radium-226, lead-210 and polonium-210) and / or non-radioactive (e.g. heavy metals), inhalable and / or non-inhalable, depending on the particle size, and may cause human health hazards when inhaled (e.g. development of lung / respiratory diseases) or ingested as well as environmental pollution.

In the uranium-238, thorium-232 and uranium-235 decay series, there are three radon isotopes, namely radon-222, thoron-220 and actinon-219. All of the radon isotopes are alpha emitters. Radon-222 has a half-life of 3.8 days, thoron has a half-life of 55 seconds and actinon-219 has a half-life of 4 seconds. Actinon-219 is not considered an important hazard due to the very short half-life.

Due to the low solubility of these inert gases in body tissues, nearly all inhaled radon / thoron is subsequently exhaled. Unlike radon / thoron, short half-life radon progeny (polonium-218, lead-214, bismuth-214 and polonium-214) and thoron progeny (lead-212, bismuth-212 and polonium-212) stick to surfaces. If inhaled, radon / thoron progeny adhere to lung tissue and can cause damage to lungs, thereby increasing the risk of developing cancer (ICRP, 2012).

The former position of the radiological community as paraphrased in the principle 'by protecting man from the effects of ionizing radiation, the environment is automatically protected' (ICRP, 1977; 1991) may be untenable (Pentreath, 1998). Within the last few years, the ICRP has begun to formulate its thoughts concerning protection of the environment and an agreed set of numerical values and units, a set of reference dose models, reference dose-per-unit-intake data and reference fauna and flora (RAPs) have been proposed (ICRP, 2005, 2008 2014).

Sources of airborne radioactive pollutants

Uranium production activities from early exploration to the end of the project may generate substantial quantities of airborne dust particles (radioactive) and radon and thoron gases.

Airborne non-radioactive pollutants (e.g. dust particles bearing non-radioactive contaminants, nitrogen oxides, carbon dioxide, sulphur dioxide, water vapour and sulphuric acid mist from the leaching step, organic chemical vapours) are also generated at the mine site. In addition, combustion products may be released from the burning of fuel in the process and heating boilers. Airborne non-radioactive pollutants will not be discussed in this chapter.

Sources of airborne radioactive dust and radon / thoron and their progeny and non-radioactive pollutants at the mine site include: drilling, blasting, ore stockpile, ore handling and processing, waste rock and tailings management, decommissioning and rehabilitation activities. Ore handling activities include: excavation, load and transport of the ore to / into the milling facility. Processing operations include grinding and crushing of the ore, fine ore storage, physical and chemical processes, unloading tailings from haul trucks to tailings deposits (if not transported in a slurry). Tailings management includes tailings treatment methods, effluents release in the form of airborne and liquid to the environment, tailings disposal practices, containment preparation, tailings consolidation, surface water and decant water treatment, seepage control, tailings covers, emergency preparedness and response as well as a programme for monitoring and surveillance of tailings facilities. Decommissioning and rehabilitation activities include decontamination and dismantling of facilities, restoration of areas, rehabilitation of tailings facilities, etc.

The major emission sources of radioactive particulate matter at a uranium mining and mill site include: drilling, blasting, ore handling (conveying), ore storage, crushing and grinding, yellowcake production (especially drying and packaging), waste rock and tailings management, windblown emissions (fugitive dust emissions) and closure activities. Parameters that affect the degree to which dust is dispersed and deposited in the environment are: production rate, meteorological conditions (wind, rainfall, snow and temperature), exposed surfaces, ore composition and physical characteristics, particle size distribution, operational procedures and waste management.

Ore storage, ore crushing and grinding, and waste rock and tailings management are the major pathways for release of radon and thoron and their decay products. The amount of radon and thoron released through each of the pathways depends on: ore grade (% U_3O_8), ore type, radium and thorium content of the ore, mined area per year (m^2), ore storage procedures, crushing and grinding operations, tailings and waste rock disposal practices, and radon and thoron emanation coefficient and / or exhalation rate.

Ore received at the mill is stockpiled prior to mill operations. The degree to which ore dust is dispersed depends on the quantity of ores stored at the mill, climatic conditions, age in storage, etc. Ore may dry out in the stockpile, making it more susceptible to dust dispersion. Radon release from the ore storage area depends on (1) the characteristics of the ore (ore concentration, grade and size), (2) the area and thickness of the ore pads and (3) the storage time.

Mined ore is blended and successively reduced in size by crushers to permit ready leaching of the uranium. Some of the radon and thoron are released during the crushing and grinding activities. Dust generated during these process steps is not confined within the equipment. When those activities are performed indoors, the generated dust may be controlled by a ventilation system that removes dust (airborne particulates) through, for instance, hoods, hooded conveyor belts, etc., into emission control devices where they are removed from the air streams. The cleaned air is then discharged by fans into the atmosphere through local exhaust stacks. The emission control devices used in ore crushing and grinding operations may include but are not limited to: bag or fiber filters, orifice or baffle scrubbers and wet impingement scrubbers (US. NRC, 1986). Bag or fiber filters remove the dust (particulate matter) from a gas stream by filtering (impaction or diffusion) the particulate matter through a porous fabric. Wet scrubbers remove particulates from a gas stream by effecting intimate contact between the gas stream and scrubbing liquor, usually water. The last stages of grinding are usually done wet to eliminate the free flow of airborne particulates from the finely ground product. Because of the short residence time in the crushing and grinding circuits, usually only a small amount of radon and thoron will be released. Although radon-222 and thoron-230 are chemically inert and have a short half-life, their decay products quickly reach secular equilibrium (e.g. the concentration of each daughter is equivalent to the concentration of all other daughters as well as to the radon / thoron concentrations) and are dispersed and are therefore subject to being breathed in by man and animals.

Processing operations produce yellowcake, a uranium concentrate. If processing operations are conducted in solutions or slurries, particulate emissions are negligible and therefore present little hazard. Since the ore processing steps reject nearly all the radium-226 and thorium-232 to the tailings, very little radon and thoron is released during the production of yellowcake. When dried and packaged for shipment, yellowcake may be an airborne particulate source term contributor. Particulate releases from the drying, calcination and packaging steps are dependent on the control used to prevent release of excessive amounts of uranium in the off gases. Off gases are scrubbed or filtered prior to release via a stack (see 7.6).

Non-radioactive gaseous effluents consisting of carbon dioxide, sulphur dioxide, water vapour and sulphuric acid mist from the leaching step, some of which are toxic, could be released during the processing operations. Organic chemical vapours consisting of kerosene with small amounts of amine and alcohol are released from the solvent extraction step. Ion exchange processes are usually enclosed and chemical vapour releases are therefore negligible.

Tailings are sources of airborne releases in the form of dust and radon. The tailings consist of process reagents, precipitates, liquids resulting from ore processing, sand and slimes.

Factors affecting the release of radon from the tailings facility include: (1) emanating power, (2) diffusion coefficient, (3) moisture, (4) density and (5) tailings thickness. Dust, radon and thoron releases from tailings ponds can be minimized if a sub-aqueous final tailings disposal method is selected.

A fraction of the radon and thoron may escape into the pore spaces among tailings solid grains via diffusion and convection. The radon and thoron release from solid materials to the air-filled pore space is known as emanation. The parameters that quantitatively characterize this effect are the emanation coefficient and / or exhalation rate. The ratio of the amount of radon and thoron that enters pore spaces over the amount of radon and thoron generated is called the emanation coefficient. Some of the radon and thoron in the pore spaces migrates from the point of generation in materials into the atmosphere; that is, the radon and thoron is exhaled from the surface of the materials. The exhalation rate is defined as an exhaled radon / thoron per unit mass or surface area per unit of time (Schery, 1989).

The effects of airborne emissions from all sources at the mine site have to be assessed in an environmental impact assessment at the initial licensing stage and verified throughout a facility's life cycle.

Predictions may be made through air dispersion modelling (e.g. the U.S. Environmental Protection Agency's ISC3 or other similar models – http://www.epa.gov/scram001/dispersion_alt.htm). Those predictions should be based on, for example, the properties of the tailings and tailings management. This should be done to demonstrate that the radiation protection requirements are being met and will be met in the future. To verify that operations meet the predictions based on modelling, comprehensive environmental monitoring programmes should be put in place, including also radon / thoron and their progeny in air and radioactivity in particulate matter.

Without proper planning and control, radioactive and non-radioactive releases from each of these operations have the potential for environmental contamination and doses to the public above regulatory limits.

Methods used to estimate the release of dust particles, radon and thoron

When environmental monitoring data are not available (e.g. initial licensing stage), predictive models are used to evaluate the potential impacts from the operations of new mining and milling projects (new facilities) or significant modifications to existing ones (40 CFR Part 190, http://www.epa.gov/scram001/dispersion_alt.htm).

Estimating radioactive airborne release rates is needed to predict: (1) radiation doses to the public, (2) the extent or degree of effluent control, (3) the environmental impact of mining and milling operations, (4) identify potential problem areas (and the information can be used to establish or modify environmental monitoring programmes and locations) and (5) the degree to which mining and mill operations meet the as low as is reasonably achievable (ALARA) concept.

Studies on emission source inventories, source terms calculations (quantitative estimation of airborne emissions as radionuclides and non-radioactive substances) (U.S. NRC, 1987; U.S. EPA, 1993) and the atmospheric dispersion and fate of contaminants should be performed. The results should be used to evaluate the pollutant's impacts in both flat and rugged terrain and assist in choosing between available techniques for mitigation and control and to determine modifications, if necessary, to improve control methods. The results can also be used to ensure that the regional air quality does not deteriorate due to the mine activities. To verify that operations are meeting predictions based on modelling, comprehensive monitoring programmes (effluent and environmental monitoring, see Chapter 7 of this report) should be put in place, including also radon / thoron and their progeny in air and radioactivity in particulate matter.

Non-radioactive emission source terms may be estimated in the same way as radioactive particulate emissions, with an estimate of the toxic element composition of the ore or tailings.

Information needed to estimate airborne sources and dispersion of pollutants in the environment may include but are not limited to:

- Ore grade, % U_3O_8.
- Radionuclide concentration in ore.
- Mining methodology (e.g. mined area per year (m^2), ore stock pile and storage time, emanating power of ore) and employed hydrometallurgical process.
- Characteristics of airborne releases in terms of radionuclides, particle size and density.
- Climatic conditions such as wind direction, wind speed and frequency distribution, temperature, humidity and precipitation.
- Efficiency of emission control devices installed in stacks (see 7.6) used to prevent releases from all mine facilities.
- Waste management including tailings treatment methods, releases of effluents from the mine facilities and final waste disposal method.
- Decommissioning and rehabilitation activities.

Methods used by mining company consultants for estimating radioactive airborne sources terms, data or assumptions used for estimating emissions and sources, airborne dispersion models (e.g. air quality modelling computer software) have to be reviewed by the regulatory body in order to determine their acceptability.

Dust mitigation methods

Measures have to be implemented at the mine site in order to reduce the generation of dust and gases and emissions from the proposed activities. Before choosing a method or a combination of methods for mitigating and controlling airborne pollutants at the mine site, a study on emission sources (sources inventory) should be conducted and a quantitative estimation made of airborne emissions and atmospheric dispersion and the fate of contaminants.

The following methods may be taken into consideration:

- Appropriate timing for drilling and blasting, according to local wind velocities / directions.
- Use of appropriate equipment and mining techniques such as proper blasting patterns.
- Enclosed and sealed mining cabs with dust collector systems can substantially lower the dust exposure of operators for both drill and mobile equipment (excavation equipment such as bulldozers, front-end loaders and haulage trucks).
- Wetting method (uniform wetting) by using water or different dust suppressor agents such as:
  - Salts (e.g. hygroscopic compounds: calcium chloride, magnesium chloride, hydrated lime, sodium silicates, etc.).
  - Surfactants (e.g. soaps and detergents, surfactants decrease the surface tension of water, which allows the available moisture to wet more particles per unit volume).
  - Soil cements – compounds that are mixed with the native soils to form a new surface (e.g. calcium or ammonium lignon sulphonate, portland cement).
  - Bitumens (e.g. coherex peneprime, asphalt, oils).
  - Polymers (films) that form discrete tissues, layers or membranes (e.g. latexes, acrylics, vinyls, fabrics).
  - Mixture of soil cements, bitumens and films.
- Drilling generates most of the respirable dust; thus, wet drilling systems pumping a wet agent into the air from a wet tank mounted on the drill can

be used. The drawback of a wet drilling system is that when the outside temperatures drop below the freezing point, the entire system must be heated while the drill is in operation. During downtime, the system may be drained.

- Wetting methods have to be managed carefully during winter to avoid potential ice build-up and to avoid resuspension of small-sized dust particles in the air, which can be transported by the wind and pollute the environment.
- When choosing a wetting agent, site-specific parameters (e.g. geochemical, chemical, dust concentration, dust particle size, etc.) have to be considered (Kissell, 2003). For example, some radioactive and / or non-radioactive pollutants may be water soluble. If this is the case, water should be avoided in order to prevent environmental contamination.
- Emission control devices should be installed in ventilation systems of uranium mills and other facilities at the mine site and in mining equipment, where possible, in order to limit the release of airborne particulate matter (e.g. collect all dusts above 1 micron) and gases to the environment and protect the health of workers. Emission control devices may include: (1) devices installed in ventilation systems of the mill and other facilities such as bag or fiber filters (removes particulate matter and gases from a stream by filtering them through a porous flexible fabric), orifice, baffle scrubbers wet impingement scrubbers (removes particulate matter and gases from a stream by effecting intimate contact between the gas and a scrubbing liquor, usually water), venturi scrubbers and water spray systems (water spray is used during crushing and grinding operations to minimize the generation of dust), exhaust monitoring devices (for monitoring of radon / thoron and their decay products) (see more in Chapter 7 of this report), and (2) collection extraction systems for mining machinery (filtration efficiency, inlet capture efficiency, for example dust collector systems for grinding machines and / or crashing equipment).
- All mine facilities such as mills, storage bins, conveyors, crushers, loading facilities, mineral separators, yellowcake drying and packaging, transfer points, etc., shall be fitted with dust extraction / collection systems, ventilation / filters and exhaust monitoring systems.
- An underground crushing and grinding facility will reduce the amount of dust, but a small amount of dust may escape through ventilation exhausts even if the facility is equipped with filters.
- Dust generated from drilling can be controlled with dry collection systems. Dry collection systems require an enclosure around the area where the drill rod enters the ground. This enclosure can be constructed by hanging a rubber or cloth shroud from the underside of the drill deck. The enclosure is the duct to a dust collector, the clean side of which has a fan. The fan creates a negative pressure inside the enclosure, capturing dust as it exits the hole during drilling. However, some dust may escape from the drill dry dust collectors.
- Stockpiles should be located as close as possible to the mining operations and their size should be reduced.
- The stockpiles of ore (may need special containment while stored) and waste rock materials should be kept wet or stabilized by using appropriate surface suppressant agents (crusting agent) before being moved to a disposal area in order to prevent possible spreading of mineral grains and particles. The wetting method will have little effect on radon release from the ore storage unless the ore is kept saturated and not allowed to dry out.
- Tailings surface control, sub-aqueous deposition of tailings.

- Regular campaigns to minimize spillage and routine actions to recover and return spilled material (e.g. small-sized crushed ore) to the process, accumulation and disturbance of dust should be conducted.
- Haul road dust can be minimized by water or chemical application, by applying appropriate vehicle speed limits and by using closed transport vehicles. Also, the trailers must be kept closed at all times other than at loading and unloading, when containing mineral ore and when empty (i.e. by the use of a tarpaulin) and engineering roads. Different types of road aggregate (gravel, sand, road surfaces with a good surface gradation, silt, etc.) determine different approaches to dust control. Track out from an unpaved road to a paved road creates a dust problem, in this case chemical suppressants can be a good choice.
- Appropriate personal protective equipment (PPE) such as respiratory protection for specific employees. Dust generation during the processing and packing of uranium minerals is not significant under normal operational conditions. However, it is recommended that the employees in these areas should wear respiratory protection equipment in case of unforeseen spillage of the product.
- Training related to the appropriate safe handling practices specific for uranium ore shipments, given to the personnel involved in loading, unloading and transport of uranium ore to the milling facility, and emergency response in case of a radiological event during transport of the yellowcake.
- Freeze drying and resuspension of dust particles from tailings and waste rock should be avoided by covering the tailings and in some cases also the waste rock with water or by using a solid cover.
- Dismantling activities during decommissioning of uranium mines should be performed to as high an extent as possible inside the buildings in order to minimize dust release into the environment.
- When the decommissioning of the mine, mill and tailings facilities is completed, the area should be rehabilitated. Various strategies can be used for controlling dust, including vegetative cover, gravel, crushed rock or riprap cover, and combinations of these. Some of these methods are also useful for reducing radon emissions. Progressive reclamation, for instance the practice of drying up and covering tailings piles in sections as they are filled, is an effective method for reducing airborne particulates from the tailings and is used by several mills in the U.S., Canada and Australia.

4.2.2 Water management

Treatment and control of liquid effluents

Local water sources and the terrestrial environment have to be protected from potential radioactive and non-radioactive contamination arising from all phases of the mine activities. In Greenland the term freshwater include also groundwater.

Methods that prevent or reduce the risk of radioactive liquid contaminants entering the environment are site specific and can include but should not be limited to:

- Proper water management. In the early phase of the project (design), the operator has to develop and implement measures for minimizing the generation of contaminated water (radioactive and non-radioactive contaminants). This may include: recycling and reuse of water and liquid effluents generated in the processing of ore, release of liquid effluents to the environment when the contaminant levels and other non-radioactive parameters (e.g. pH) are within regulatory requirements. Hydrological and hydrodynamic controls such as engineering controls to prevent groundwater and freshwater contamination, to treat and rehabilitate those waters if necessary (see Chapter 9), flooding diversion, seals, collecting all runoff water and spillages and sequestering it in, for instance, ponds prior to chemical treatment.

- Proper radioactive waste management – see Chapter 6 of this report.

All liquid effluents generated from the mill operations, such as physical (flotation) and chemical processes and seepage, drainage and runoff water, have to be treated using active and passive treatment methods prior to and after disposal in a tailings pond.

Active treatment methods require a waste treatment facility. Waste treatment facilities are site and project specific. Factors such as physical and climatic conditions, mining and milling processes, waste generation and management, costs for treatment and also for immobilization and disposal of resulting residue from the employed treatment methods should be taken into account when designing the treatment facilities. The aim is to treat or condition, if possible, all types of waste (including runoff contaminated liquid effluents from seepage, drainage systems, pit de-watering, breaks in pumping lines, overtopping, etc.) resulting from the proposed activities.

It is recommended to recycle the water recovered from the waste treatment to the mill and minimize the water for release into the environment when contaminant levels comply with established threshold values (release limits) and requirements. Controlled releases of liquid effluents to the atmospheric and aquatic environment are a legitimate waste management practice in the mining industry (see 7.6).

Sources of pollutants

The types and quantities of pollutants in the liquid effluents generated from proposed activities depend on climatic conditions, mining methods, ore geochemistry, the employed hydrometallurgical process, waste management and mine water management. Liquid effluents are generated at all stages of uranium mining and milling such as crushing, grinding, physical separation, chemical processing (process reagents and liquid waste from leaching, precipitation), tailings disposal and management, decommissioning and rehabilitation activities.

Possible sources of contaminated water may include but are not limited to: liquid effluents generated from ore handling, processing plants, runoff from overburden and waste rock piles, raise waters or seepage from tailings, rock waste, ore stock pile, overtopping tailings water, leaks and spills from tailings pipelines and dust suppressor's agents, fire water (in event of fire), flood water (extreme event), pit dewatering water and domestic water.

Water treatment techniques

Liquid effluents typically contain toxic radioactive contaminants, namely natural uranium, thorium and their progeny, and non-radioactive contaminants such as cadmium, lead, zinc, nickel, arsenic and organic compounds. If not properly handled (e.g. collected, contained, treated, conditioned, safely disposed), these effluents can contaminate the environment. Where pyrite and other sulphidic minerals are present in the ore, acidic solutions may be generated, also known as acid rock drainage. The contaminated water may also contain nitrates, nitrites and ammonia.

Treatment and control of liquid effluents should be an integral part of uranium mine operations (operational phase, decommissioning, rehabilitation and after closure) and must be factored into the total production costs. Treatment costs must consider not only the treatment process but also the immobilization and disposal of resulting contaminated residues such as sludge.

Generally, the preferred approach for treatment of collected liquid effluents is to produce an acceptable water quality (low levels of contaminants), with low volumes of resulting residue, and possibility of changing the physical and / or chemical form of the contaminants in the residue thus changing their mobility. When possible, it is recommended that the treated effluents are recycled back to the processing circuits for reuse.

The treatment method to be used is site and project specific and depends on factors such as regulatory requirements, conservation of water (involving recycling, minimization of usage and limitation of quantities requiring disposal), cost, local climate, the length of time during which the control measure is to remain effective, diversity of potential contaminants and their concentrations in the effluent to be treated due to differences in ore type and grade, hydrometallurgical processes used to extract uranium and pH levels. A single treatment technology may not work for all potential contaminants and, therefore, use of different combinations of treatment strategies may be required.

Active and passive systems for effluent treatment are applied during the operation and decommissioning and rehabilitation.

During the operational phase, active systems are used for effluent treatment. Active systems require continuous operation, such as a treatment plant, and may include lime treatment (neutralization), ion exchange, macropore resins, filtration, nanofiltration, multi-stage chemical precipitation / co-precipitation, flocculation, pH adjustments, membrane separation techniques, etc.

During the closure of the mine and after closure, passive systems are used for effluent treatment. Passive systems are intended to function without intervention by man. Examples of passive systems include permeable reactive walls for groundwater remediation, in situ microbial and biological treatment, and artificial wetlands (IAEA, 2004; Moffett and Barnes, 1974; Jian, 1982).

Active chemical treatment methods

Lime treatment

Neutralization of acidic liquid effluents / slurries resulting from mill processes with lime ($CaO/CaCO_3$) at pH 10-11 prior to discharge into the tailings dam / or monitoring pond is a common preferred treatment method and is used also for treating acid mine drainage and seepage water from acid uranium mill tailings and other disposal facilities. Neutralization results in precipitation of most contaminants, both non-radioactive such as heavy metals, dissolved salts and approximately 90% of most radionuclides, excepting radium isotopes.

The low density sludge (uncompacted) generated from the neutralization process requires large storage volumes. The sludge retains a significant moisture fraction (large quantities of water), thus limiting the quantity of water available for recycling. Studies performed in Australia and China have shown that recycling of the sludge derived from the neutralization process by blending it with lime slurry results in high-density sludge (HDS), reduces reagent consumption, increases the volume of water recycled and reduces storage volume requirements due to a 50-65% reduction of the sludge volume (IAEA, 2004).

Barium chloride treatment

Barium chloride ($BaCl_2$) treatment is widely used in the uranium industry to remove radium from liquid effluents. Radium-226 and 228 remaining in the liquid effluent from the neutralization process are usually removed using barium chloride and thus co-precipitate barium-radium sulphate.

Radium concentrations below 0.3 Bq/L can easily be achieved for wastewater containing sulphate ions. At pH values between 6 and 8, barium sulphate ($BaSO_4$) has a low solubility and readily precipitates out, co-precipitating radium at the same time. Chemical treatment with $BaCl_2$ has proved to be effective in controlling radium mobility.

Case study of mill effluent treatment at Key Lake, Canada:

The acidic mill effluent treatment at the Key Lake uranium mine consists of four main steps: solvent extraction raffinate neutralization (lime being added to progressively raise the pH from 1 to 7, inorganic and organic constituents removal), radium removal (barium chloride/lime), pH adjustment (10.5-11) and tailings neutralization (reducing the pH to slightly below neutral prior to discharge in the monitoring pond). The treated effluents are then discharged to the monitoring ponds (Fig. 4.2.2.1). When the monitoring pond is filled, an effluent sample is collected and analyzed in the laboratory. The results are compared with the license parameters such as levels of radioactive and non-radioactive contaminants, total suspended solids, carbonates, ammonia, pH, etc. Based on the analysis results, the liquid effluent in the pond is either released to the environment or sent back to re-treatment. The pH of the slurry resulting from the treatment process is adjusted to 10.5-11 with lime prior to disposal in the tailings holding tanks and pumped to the tailings thickener by either a three-stage centrifugal pump installation or two positive displacement diaphragm pumps (www.cameco.com).

Figure 4.2.2.1. Key Lake uranium mine. Source: www.cameco.com.

Contaminated effluents, such as mine water, de-watering and / or drainage from waste dumps and groundwater inflow, rain that falls on ore stockpiles, the mine pit and other areas around the process plant, do not need neutralization treatment; thus, for these other treatments methods must be employed for contaminants removal.

Ferric chloride treatment

This method is widely used in the uranium industry for removal of arsenic from wastewater. Most of the arsenic (As) present in wastewater is precipitated out with lime treatment, but the remaining arsenic levels in the water may still exceed acceptable release limits. If so, ferric chloride treatment can be added to the slurry during bulk neutralization to precipitate out arsenic.

The reaction takes place in solution at a pH of less than 7:

AsO_4^{3-} (aq) + $3H^+$ (aq) + $FeCl_3$ -------------> $FeAsO_4$ + 3HCl (aq)

Ion exchange

Anion exchange resins are usually applied to reduce heavy metal levels, including also uranium in liquid effluents. The ion exchange treatment method includes use of organic or inorganic resins (solids based on synthetic resins and inorganic substrates such as zeolites) with chemically reactive sites that are either positively (cations) or negatively (anions) charged. The used resins can bind with radioactive and non-radioactive contaminants, thus removing them from the wastewater. This method is driven by the relative ion concentrations of the competing contaminants, their electric charge and their relative affinity for the exchange site. After treatment of the wastewater, the resins may be recovered by regenerating by back-washing with, for example, strong acids. The advantage of ion exchange resin is that it removes a wide variety of contaminants and / or reduces the contaminants to very low levels. The method is expensive.

Ion adsorption

Ion adsorption is similar to ion exchange, except that the solid materials used are not regenerated as the ion exchange resins. An example of ion adsorption is a uranium-specific, high-molecular polymer called GOPUR 3000, which has been used for removal of uranium from wastewater. At pH values between 4 and 11, the reactive surfaces undergo chemical change with the uranyl ion, and the resulting insoluble matrix precipitates out of the solution. The sludges can then be dewatered using conventional dewatering techniques.

Membranes filtration separation

Reverse-osmosis (RO) may be used as a water purification technology. RO was applied for removal of nickel at the Key Lake uranium mine.

Nanofiltration is a membrane separation technique falling in-between ultrafiltration and reverse osmosis in terms of species separated. It separates chemical species based on their molecular size and / or charge. Different nanofiltration membranes are used for removal of contaminants that have an effective diameter of around one nanometre or grater from uranium mill effluents. Examples of such contaminants are uranium, radium and multivalent non-radioactive ions such as calcium, aluminium, iron, magnesium, manganese and sulphate.

Macropore ion exchange resins were tested (Jianguo et al., 2004) for removal of uranium from mine and mill liquid effluents.

Case study of liquid effluent treatment at Wismut, Germany:
Uranium, radium and arsenic from contaminated water from the Helmsdorf (Wismut) tailings pond are removed by using ion exchange, membrane filtration and precipitation (of radium and arsenic). Some of the generated waste residue from the water treatment was conditioned by mixing it with fly ash and cement, after which it was filled into a container. The conditioned residue was then deposited on the tailings surface that was covered by a solid dry cover in the rehabilitation phase.

Removal of uranium, radium, arsenic, manganese and sulphate from contaminated mine water from Schlema-Alberoda (Wismut) is achieved by selective precipitation / flocculation. $BaCl_2$ solution is used for Ra removal as a $BaSO_4$ co-precipitate. Uranium is separated at a pH of 5.8 by flocculation. Removal of iron and arsenic is achieved by precipitation with $FeCl_3$ solution (Kiessig et al., 2004). Mn is removed by using $KMnO_4$ solution at pH 7.5 adjusted with NaOH. The resulting sludge is pre-thickened and dewatered by a filter press. The dewatered slurry is mixed with cement to form mortar and cast into a square block and disposed of in an engineered section of a mine dump (Kiessig et al., 2004).

Passive treatment methods

Bioremediation

Nutrients such as sugars, fats, alcohols and phosphates are added to mine wastewater over a period of time in order to increase natural bacteria growth. Phosphate addition may encourage growth of algae that function as a source of organic carbon to the water body. Natural bacteria in the liquid effluent metabolize the added nutrients and respire dissolved materials in the water in the following order: dissolved oxygen, nitrates, selenium complexes, dissolved uranium and other metals. Dissolved metals precipitate on the water bottom, increasing metal concentrations in the bottom sediments. Experiments have been conducted in order to assess the bio-sorption of radium on the microbe *Penicillium chrysogenum* in the form of granules (Mathur and Murthy, 2004). The results showed that *Pencillium chrysogenum* is a selective fungus for ^{226}Ra bio-sorption. Approximatively 50-68% of the radium was bio-absorbed by *Penicillium chrysogenum*. Radium removal was enhanced by up to 88% by chemical treatment of the biomass with acrylamide.

Artificial wetlands

Treatment of mine drainage containing radionuclides, heavy metals and sulphate using artificial wetlands is a technology that has been used over the last 20 years. Worldwide experience with operating wetlands suggests that wetlands may reduce the construction, monitoring and annual operating costs for water treatment by one order of magnitude, but there are no reliable cost estimates available on long-term maintenance.

The constructed wetland at Ranger RP1 (http://www.energyres.com.au/ourapproach/2684.asp) is used to treat ore stockpile runoff and water from the pit dewatering. It holds 50,000 m^3 water in nine cells varying in size from 2,050 to 17,500 m^2. Contaminants such as UO_2, Mn, NO_3 and SO_4 from mine drainage are effectively removed in RP1 (http://www.energyres.com.au/ourapproach/2684.asp). Addition of low cost compost (biomass – green algae – *Scenedesmus* sp.) was necessary to enhance the SO_4 reduction process and thus improve its removal (IAEA 2004).

Permeable reactive barriers for groundwater remediation
Permeable barriers are used for groundwater remediation. A constructed permeable barrier is installed (placed) across the flow path of a contaminant plume, either surface or underground, allowing the water from the plume to passively move through the wall and prohibiting the movement of contaminants. The permeable barrier contains a reactive or adsorptive medium that helps remove the contaminants from the plume as the groundwater flows through it. Materials such as granular iron, activated carbon, bacteria, compost or peat, chemicals and clays are used as adsorptive medium. The radioactive and non-radioactive contaminants may be either degraded or retained in concentrated form by the barrier material.

The primary advantage of permeable barriers is their passive 'capture and treat' mode of operation and the resulting potential for long-term cost savings.

Case study liquid effluent treatment at Wismut, Germany:
To reduce the long-term costs of water treatment, passive treatment methods such as permeable reactive walls for groundwater remediation, in situ microbial (using microorganisms) treatment of contaminated groundwater and biological treatment of mine water in a constructed wetland have been used and evaluated at Wismut in Germany. Oxidation of Fe(II) and precipitation of iron hydroxide were performed. The resulting precipitate was allowed to stand for sedimentation. Iron precipitation was accompanied by adsorption of arsenic and radium. The remaining liquid effluent was passed through two compartments with gravel filters. The material serves both as filter and provides a surface for the establishment of microorganism populations. To promote the growth of microorganisms, nutrients were built into the compartments. The biomass can act as a sorbent agent for radium and uranium or as a catalyst for initiation of precipitation. The last process step of the constructed wetland system is a compartment which was filled with compost-like matter and gravel on which helophytes were planted. The prime aim was to raise the oxygen content in the compartment. In addition, the plants and the microorganisms in the root zone of the helophytes remove the remaining contaminants (Kiessig et al., 2004).

Acid/alkaline mine drainage (AMD) – mitigation and control methods

The aim of preventive strategies is to avoid, for example, generation of acidic liquid contaminated effluents (waste water) during the mining, milling operations and mine closure.

An important source of pollution at the uranium facilities around the world is potential generation of acid / alkaline mine drainage (AMD). AMD at uranium facilities occurs from waste rock facilities and tailings containments. The resulting acid / alkaline pH may enhance the mobility of radionuclides and non-radioactive contaminants (e.g. heavy metals) that are present in the waste, and the contaminants may be transported into the environment.

Acid mine drainage (AMD) is the result of three types of processes / factors:

1) Acid generation by chemical / biological processes, for instance when sulphide-bearing geologic material is exposed to air (oxygen) and water.

2) Factors that control the products of the oxidation reaction, such as acid neutralization or reaction with other minerals.
3) Physical aspects such as pit walls, waste rock piles or tailings impoundments that influence the oxidation reaction, migration of the acid and consumption.

Sources of acidity are metal-sulphide minerals, CO_2, H_2S, inorganic ions such as Fe^{3+}, Al^{3+} or HSO_4^-, dissolved organics such as humic and fulvic acids, clays and some metal hydroxides. Exposed materials include ore stockpile and waste, such as waste rock and tailings, or mine structures, such as underground and open pits. Acidic drainage will not occur if the sulphide minerals are non-reactive and neither will it occur if the rock contains sufficient base potential to neutralize the acid or if appropriate control measures are implemented.

Alkaline mine drainage may be due to high carbonate or silicate ore minerals, neutralization of acid by engineering factors (e.g. introduction of lime), etc.

To predict AMD at the mine site, laboratory studies on waste rock and tailings (e.g. static and kinetic tests) and on-site investigations (e.g. water quality monitoring) should be conducted by the operator during all stages of a mine operation (U.S. EPA, 1994; TDOT, 2005, 2007) and especially during the feasibility studies.

Available control measures of AMD include: (1) control of acid generation, (2) control of AMD migration and (3) collection and treatment of AMD.

Common practices (Skousen et al., 1998; Nural, 2012) to prevent and mitigate acid generation and to control acid / alkaline mine drainage are:

- Minimizing reaction rates through control of chemical and biological processes by:
    - Waste segregation and blending or the use of base additives to control pH.
    - Temperature (an increase in temperature accelerates the rate of reaction, and sulphide oxidation reactions are exothermic. As a result, oxidation of sulphides can lead to a temperature increase in the system, which again increases the rate of oxidation).
    - Particle size (surface area) and morphology.
    - Oxygen supply.
    - Presence of bacteria to control bacterial oxidation of sulphide minerals (a decrease of pH to below 2.5 leads to an increase in the number of bacteria that catalyze the iron and sulphur oxidation reactions).
- Removing / reducing the presence of sulphide minerals (for AMD) by conditioning the tailings and waste rock.
- Minimizing the oxygen supply by using seals and covers (including water cover).
- Covering and sealing of waste rock to exclude infiltration of precipitation.
- Minimizing leaching and transport of pollutants and drainage.
- Preventing subsequent migration of weathering products.
- Applying active or passive systems for surface and ground water collection and treatment.

Other waste treatments and conditioning methods include:

- Waste segregation according to its degree of contamination.
- Compaction, conditioning and dewatering. Compaction aims at reducing the volume and increasing the stability of solid waste for storage and disposal. Conditioning produces a more stable physical or chemical form.
- Self-remediation of contaminated groundwater (based on the sorption characteristics of the soil).
- Solidification, embedding and / or encapsulation. Cementation and bituminization are the most typical solidification technologies used for radioactive waste generated from the nuclear industry. Sometimes waste rock and cement may be mixed with the uranium mill tailings to improve structural stability (IAEA, 2002, 2004).

Each of these measures has advantages and disadvantages in terms of both effectiveness and cost.

Other preventive AMD strategies that should be considered when planning mine closure activities:

Surface impoundments of mine waste materials:

- Divert surface water by developing channels.
- Cap impoundments to limit infiltration of atmospheric precipitation.
- Place waste materials selectively to facilitate containment.
- Install reactive inter-layers (crushed limestone) to control pH.
- Encourage development of anoxic conditions by adding bacterial growth media such as manure or wood chips.

Open-pit mines:

- Install clay seals to prevent infiltration to underlying strata.
- Add lime to raise pH values.
- Seal boreholes to prevent infiltration into underlying strata.
- Backfill the mine pit to avoid accumulation of surface runoff.

4.3 Management of risk event(s) associated with proposed mining and milling activities

The operator must identify and describe all potential impacts / risks, including also worst case scenario events associated with the proposed activities (all mine phases), and should deliver acceptable outcomes for local communities. Examples of associated risks include impacts on soils, hydrogeology, air quality, flora and fauna, and heritage as well as third party issues and radiological aspects. Identified risks shall be described in terms of likelihood and severity of the consequences of events. The likelihood of an event occurring should be determined based on past experience, available environmental data, modelling data, etc. Severity of the consequences for each event should be determined based on the scale of the event, the range of affected parties, duration and difficulty in remediating the impact, etc.

Control measures and management strategies should be put in place by the operator in order to manage all possible impacts that are associated with the proposed mining activities and pose a threat to each of the elements of the natural environment. The proposed management strategies and control measures should be commensurate with the risk of the impacts, achieve compliance with applicable statutory requirements, be technical and economically achievable and promote progressive rehabilitation, wherever possible. To achieve the mine rehabilitation outcomes, the proposed strategies should be self-sustaining in the long term.

Management strategies and control of identified risks can include but are not limited to:

1) Eliminate the risk.
2) Substitute the material and / or the process with a less hazardous material / process.
3) Design engineering controls, for instance barriers to control the risk such as enclosure of crusher systems and prevention of unauthorized access by the public via fencing and signage.
4) Manage controls such as induction and provision of training to new and existing personnel to ensure environmental awareness.

Assessments of the residual post mine completion risks to the environment and contingency strategies must be conducted. Residual risks are the risks associated with various impact events and still remaining after all control measures have been applied. Residual risks must be estimated, for instance as to whether the risk is low, moderate or high.

A justification of residual risks must be included and should demonstrate that the remaining risks are as low as reasonably practicable. The justification of the residual risks may be done by assessing whether: (1) there are no practical control measures available and the risk(s) is / are considered acceptable within the surrounding environment and given the other benefits that will result from the proposed mining activities or (2) the cost of implementing further control measures (including a description and evaluation of alternative control measures) is excessive compared to the benefit obtained.

Environmental and rehabilitation outcome(s) with associated measurable assessment criteria must be established for each identified potential impact (natural, social and economic). Recognized standards, codes of practices or legislative provisions shall be used as criteria when setting the outcome(s).

The outcome(s) should be set based on identified residual risk(s) and must be a commitment to the extent to which the proposed mining and milling operation will limit the impact on the environment. Outcome measurement criteria (including mine rehabilitation outcomes) expressed in quantitative and qualitative terms should clearly define the achievement of the environmental outcomes. It may include specific parameters to be monitored by the operator (including also monitoring locations, frequency, background or control data to be used, internal acceptable levels of the specified parameters, etc.). The measurement criteria should drive the development of a monitoring plan (what will be measured, accuracy of measurements, responsibility (who will measure), where to measure (including controls and baseline environmental data), how to measure, frequency of measurement, report keeping, frequency of reporting to management and any external parties) (see Chapter 7 of this report). Table 4.3.1 shows examples of potential impact events, assigned risk levels, control and management strategies, outcomes and measurement; however, the decision on which measures are appropriate should always be considered relative to the specific project.

Table 4.3.1. Potential impact events, risk levels, contingency measures and outcome and assessment criteria. Source: MG6 (2012).

	Potential impact event	Risk level	Contingency measures	Residual risk level	Outcome and assessment criteria
Water		Likelihood:		Likelihood:	
Surface water/ groundwater	Contamination of water (surface water and groundwater, including radiological water) arising from proposed activities, runoff water and pit percolation, waste dump, process plant; tailings facility.	Consequence: Risk:	Monitoring of contaminated water for established parameters such as radionuclides and non-radioactive, pH, salinity, SO_4^{2-} ,etc. A plan for relevant studies in order to design suitable treatment options should be discussed with appropriate authorities. Compliance with RWMP.	Consequence: Risk:	No compromise to the environmental values of the target aquatic environment. Monitoring of water quality (established environmental parameters) shall demonstrate no compromise as a result of mining operations.
	Spillage and release to the surface water body of hazardous substances during a radiological event.				
Land					
Soils	Chemical and radiological contamination of soils and sediments from waste rock, ore stock pile, dust and tailings.		Topsoil and turf removal (mechanical, manual), remediation of acid/alkali affected soils (if required), neutralization, burial or covering of the soil that is radiologically affected above the operational contamination criteria. disposal of tailings, regular inspection of tanks used to store and transport or transfer chemicals, implementation and regular updating of emergency response procedures and training of emergency response personnel; Incident reports, continuous monitoring of areas affected (soil (depth or thickness) and vegetation,; monitoring of established control parameters such as spill dimensions, chemical parameters, including radiological parameters, off-road incidents, compliance with RWMP		Contaminated soil from the mining activities restored to pre-mining conditions or safely disposed of. Clean-up of soils assessed as soon as practicable and carried out in accordance with the requirements of the appropriate authority. requirements
	Spillage of hazardous substances during transport; storage and handling, resulting in contamination of soil.				
	Soil disturbance due to excessive off-road vehicle movement which may result in compaction of soil, erosion etc.		Rehabilitation of disturbed soils, ripping of compacted areas and replacement of affected soil, when needed, measures to reduce potential erosion, runoff and sedimentation issues, stabilizing soil surface, where necessary, to prevent movement of soil,		Disturbed soil from the mining activities restored to pre-mining conditions. Rehabilitation of soil affected will be carried out in accordance with the requirements of the appropriate authorities.

(Table 4.3.1 continued)

	Potential impact event	Risk level	Contingency measures	Residual risk level	Outcome and assessment criteria
Vegetation	Contamination of local native vegetation due to the proposed activities.	Likelihood: Consequence: Risk:	Vegetation cutting/removal and replacement/cover with clean materials, etc. Continuous measurement of the local environment, etc.	Likelihood: Consequence: Risk:	Vegetation contaminated by mining activities restored to pre-mining conditions or safely disposed of. Remediation measures are assessed as soon as practicable and should be carried out in accordance with the requirements of the appropriate authority.
	Reduction and/or loss of local native vegetation species due to the proposed activities and accidents (fire, spill of radiological and non-radiological contaminants).		Vulnerable vegetation identification and protection prior to progressive and final revegetation; undertaking flora surveys to identify trends; annual aerial photography and comparison with photos from previous years (baseline) to assess site-wide vegetation changes; training of personnel in order to identify potential change; monitoring of established control parameters such as the number of species and density, annual disturbance, area burnt and distance from boundary, emergency preparedness and response exercises.		Demonstrate that clean-up actions are assessed as soon as practicable and are carried out in accordance with the requirements of the appropriate authority. No permanent reduction and loss of abundance or diversity on or outside the area.
Fauna	Reduction and/or loss of regional native species density and diversity caused by mining activities, well field development and mining accidents (fire, spill of radiological and non-radiological contaminants).		Fauna surveys to identify trends; rescue of trapped fauna; fencing patches of vegetation to protect seed stock and habitat; monitoring of established control parameters such as number of species and their abundance at the site; emergency preparedness and response exercises.		No adverse impacts from mining activities on regional fauna abundance or diversity. Fauna surveys show no change in trends (reduction and/or loss of regional fauna) related to the mining activities.
Air	Radon/thoron, their progeny and radioactive and non-radioactive dust release from the mine, mill and tailings facility.		Radon/thoron and their progeny and dust monitoring and review; ventilation systems in all facilities at the mine site; ambient, dust and radon/thoron modeling; dust, radon and thoron suppressors; regular maintenance of process equipment including clean-up of any spills; seepage, etc.		No impacts on the environment due to radon/thoron and dust release. Estimated radiation doses within applicable limits as defined by the appropriate authorities.

(Table 4.3.1 continued)

	Potential impact event	Risk level	Contingency measures	Residual risk level	Outcome and assessment criteria
Other issues					
Potential cumulative effects	Site and project specific and can include air emissions, water release, disturbance to wildlife, employment and business, etc.	Likelihood: Consequence: Risk:		Likelihood: Consequence: Risk:	
Third party	Damage to adjacent public or private infrastructure, including an emergency event from the mine activity.		Installation of gates in fence; maintenance or replacement of gates and fence; repair of any accidental damage to third party property and infrastructure; fire-fighting equipment on site; warning signs on adjacent tracks, etc.		No damage to adjacent public or private property and infrastructure including the cases from emergency event from the mine site, any reports of public injuries or deaths are investigated to determine if the incident was caused by mining activity and could have been avoided.
	Injury or death of a member of the public caused by mine activity.				

4.4 Operator capability

The operator must demonstrate its appropriate experience in managing the environmental risks associated with mining and milling (including also radiological aspects). Who will take responsibility for operations on the site, for instance current or planned practices and procedures that the operator and contractors would follow on the site? The past experience of the operator in managing similar mining and milling operations should also be summarized.

The importance of the operator's capability shall be thoroughly assessed and monitored by the regulatory authorities. Authorisations should not be issued until the operator has demonstrated that its control measures and systems adequately manage the health and environmental risks for all proposed activities, and will ultimately achieve required end state criteria. The amount of information and the rigor of the assessments should be commensurate with the nature and extent of the hazards, and based on the regulations and the guidance. In turn, the regulator will need sufficient expertise to determine if the information provided by the proponent is adequate to demonstrate an understanding of the risks and the controls necessary to manage those risks.

Operator capability should also be assessed as part of the site or activity safety assessment (IAEA 2009).

4.5 Management Systems

A management system - quality assurance (QA) programme must be implemented throughout all facility phases and activities of the operator to ensure that radiological and non-radiological protection will be maintained.

Best practice principles require that projects incorporate management systems into design, operations and closure. Standards particularly relevant in the area of management systems and environmental performance improvement are found in IAEA (2006). The management system shall achieve and enhance safety by bringing together in a coherent manner all the requirements for managing the organization and ensuring that health, environmental, security, quality and economic requirements are all considered together.

The QA programme should, as a minimum, include the following:

- Organizational responsibilities should be defined and understood, description of attributions, duties of external organizations involved in the decommissioning process.
- Control of waste facilities.
- Regular auditing of the design, its implementation and the operation of the waste management.
- Everyone involved in the design, construction, commissioning, operation and closure of waste management facilities and whose performance could influence safety should be trained to an appropriate and verified level.
- Models and codes used in the safety assessment should be validated and verified to the extent possible.
- The effectiveness of the protection achieved in the management of waste should be assessed periodically.
- Description of action to be performed in the preparation, review, approval and control of instructions and procedures.
- Procedures for identifying and controlling materials, equipment and field and laboratory samples.
- Description of the programme to ensure that all monitoring is performed according to approved procedures.
- Incident investigation and corrective action(s).
- Other.

4.6 References

IAEA, 2002. International Atomic Energy Agency, Management of Radioactive Waste from the Mining and Milling of Uranium and Thorium Ores, IAEA Safety Guides No. WS-G-1.2, Vienna.

IAEA, 2004. Treatment of liquid effluent from uranium mines and mills, IAEA-TECDOC-1419.

IAEA, 2006. The management system for facilities and activities, IAEA Safety Standards No.GS-R-3

IAEA, 2009. Safety assessment for facilities and activities, IAEA Safety Guide, G.S.R.4

ICRP, 1977. Recommendations of the International Commission on Radiological Protection. Publication 26. Oxford Pergamon Press (Oxford) (1977)

ICRP, 1991. Recommendations of the International Commission on Radiological Protection. Publication 60. Annals of the ICRP 21. Oxford Pergamon Press (Oxford) (1991)

ICRP, 2005. The Concept and use for Reference Animals and Plants for the purposes of Environmental Protection. Draft for discussion. Annals of the ICRP. Available from: www.icrp.org/

ICRP, 2008. Environmental Protection - the Concept and Use of Reference Animals and Plants. ICRP Publication 108. Ann. ICRP 38 (4-6).

ICRP, 2012. Effective dose from inhaled radon and its progeny. Ann. ICRP 2012, 41: 378.

ICRP, 2014. Protection of the Environment under Different Exposure Situations. ICRP Publication 124. Ann. ICRP 43(1).

Jian Wen, J.I., 1982. Treatment of effluent from uranium mining, Removal of uranium and radium, Nuclear energy publisher, p. 298–301.

Jianguo, Z., Shaoqiang, C., Jing, Q., Song, R., 2004. Study on the technology for the development of macroporous resin adsorption for high purification of uranium effluent. Beijing Research Institute of Chemical Engineering and Metallurgy, Beijing.

Kiessig, G., Gatzweiler, R., Jakubick, A.T., 2004. Remediation options and the importance of water treatment at former uranium production sites in eastern Germany WISMUT GmbH, Chemnitz, Germany.

Kissell, F.N., 2003. Handbook for Dust Control in Mining, U.S. Department of health and human services, Information Circular (IC) 9465.

Mathur, A.K., Murthy, V.K., 2004. Biogenic treatment of uranium mill effluents. Atomic Minerals Directorate for Exploration & Research, Department of Atomic Energy, Begumpet, Hyderabad, India.

MG6, 2012. Guidelines for miners: preparation of a program for environment protection and rehabilitation (PEPR) for extractive mineral operations in South Australia.

Moffett, D., Barnes, E., 1974. Radium-226 removal by precipitation and sedimentation in setting ponds, CIM Bulletin 74(832): 128-134.

Nural, K., 2012. Acid mine drainage prevention and control options. Golder Associates Ltd. International Mine Water Association 2012.

Pentreath, R.J. 1998. Radiological protection Criteria for the natural environment. Radiation Protection Dosimetry, 75, 175-179.

Schery, S.D., Wilkening, M.H., Hart, K.P., Hill, S.D., 1989. The flux of radon and thoron from Australian soils. J. Geophys. Res. 94: 8567-8576.

Skousen, J., Rose, A.,Geidel, G., Foreman, J., Evans, R., Hellier, W., and et al., 1998. A handbook of technologies for avoidance and remediation of acid mine drainage.

TDOT, 2005. Standard Operating Procedure for Acid Producing Rock. Investigation, Testing, Monitoring, and Mitigation, revised July 2005. Location: Tennessee Department of Transportation, Geotechnical Engineering Section.

TDOT, 2007. Guideline for Acid Producing Rock Investigation, Testing, Monitoring and Mitigation. Prepared by Golder Associates, Inc., Lakewood, CO. October, 2007.

U.S. EPA, 1993. Drilling and blasting operations, June 1993.

U.S. EPA, 1994. Acid Mine Drainage Prediction; Technical Document. (EPA-530-R-94-036; available NTIS PB94-201829). Washington, D.C.: U.S. Environmental Protection Agency, Office of Solid Waste.

U.S.NRC, 1986. General Guidance for Designing, Testing, Operating, and Maintaining Emission Control Devices at Uranium Mills, Regulatory guide 3.56, U.S. Nuclear Regulatory Commission. Task CE 309-4, 3.56.

U.S. NRC, 1987. Methods for estimating radioactive and toxic airborne source terms for uranium milling operations, Regulatory guide 3.59, U.S. Nuclear Regulatory Commission. Task WM 407-4.

5 Radiation management plan (RMP)

The following chapter provides guidance on the development of a radiation management plan (RMP) for the purpose of controlling the exposure to radiation of employees, members of the public and the environment from the proposed practices.

The RMP must address operational aspects of radiation safety. Sometimes (for small projects), the RMP includes also the management of radioactive wastes generated from the proposed activities. The RMP, also called Radiation Protection Plan, should take into consideration protection of the health and safety of workers, protection of members of the public and the environment during all mine phases.

Each responsible person at a mining and processing operation must ensure that adequate measures are taken to control and keep the exposure of employees, members of the public and the environment to radiation as low as reasonably achievable (G-129, 2004). The general principle ''As low As Reasonably Achievable (ALARA), which encourages uranium production licensees to make ''every reasonable effort to maintain exposures to radiation as far below the dose limits, as is practical consistent with the purpose for which the licensed activity is undertaken''- 10 CFR part 20.1003'' should be considered when the RMP is developed.

The RMP should be prepared by the operator before all mine phases and submitted to the appropriate authority for approval. The operator should implement the approved RMP. The plan should be considered a 'living' document. The level of detail should undergo further revision to reflect the progress of the project as well as changes in technology and / or standards or legislation. Future revisions should also consider input from consultations with communities and other stakeholders on methods to be used and potential uses for project infrastructure, etc. Any significant changes to the RMP must be authorized by the regulator.

The regulators have to maintain surveillance of implementation of the RMP and conduct site visits and inspections for this purpose. The regulators have to periodically submit (e.g. Australia: quarterly and annually) reports on radiation monitoring and environmental monitoring and reviews regarding compliance with action levels, dose limits and operating procedures as established in the plans.

The RMP must be in accordance with the ICRP fundamental principles for managing radiation exposures, Best Available Technology (BAT), Best Practicable Technology (BPT) and Best Environmental Practice (BEP) and take into account the potential dose delivery pathways. It is important that BAT, BPT and BEP are incorporated into the design of facilities at a mining and processing site (NORM-2.2 – 2010; IAEA 1010b).

The ICRP fundamental principles for managing radiation exposures are:

- Justification – No activity involving ionizing radiation for any purpose can be justified unless it can be demonstrated that it will lead to a positive net benefit.

- Optimization – All exposures shall be kept as low as reasonably achievable, economic and social factors being taken into consideration (the ALARA principle).
- Limitation – The maximum acceptable occupational exposure of any individual must not involve a radiation risk to that individual greater than the risk that arises in working in what is generally regarded as a 'safe' industry.

The RMP should comprise:

- Scope and introduction.
- The reason for the RMP and radiation safety background information.
- A description of the company and of the infrastructure required (expected duration of construction, mining, processing of minerals and decommissioning, closure and rehabilitation).
- Description of the proposed operations to which it applies, including type of mining and / or mineral, processing activities, expected duration of mining and / or milling, waste management, provision of appropriate equipment, staffing, facilities and operational procedures. A block diagram of broad functional activities, showing inter-relationships, may also be included in the RMP.
- Workforce information and radiation safety resources, here including also the organizational measures aimed at identifying and ensuring the availability of qualified experts in radiation protection.
- Critical group information.
- Sources and pathways of radiation exposure.
- Control measures.
- Radiation monitoring: the frequency of measurements, the accuracy and uncertainty of measurements, the areas to be monitored, evaluation and reporting of monitoring results, the specifications / capabilities and number of radiation monitoring equipment available as specified in the radiation monitoring plan, the number of staff engaged in carrying out the RMP.
- Dose assessment (description of radiation monitoring programmes: occupational, members of the public, effluent and the environment and methodologies for dose assessment).
- Transport of radioactive materials.
- Employee training programmes should include topics specific to radiological protection in operations in the mining and processing of raw materials and an emergency preparedness and response programme.
- Record keeping and reporting (weekly, monthly, quarterly and annual radiation reports provided to, for instance, members of the public, management staff and regulatory bodies).
- A plan for dealing with incidents, accidents and emergencies involving exposure to radiation and incident reporting mechanisms. The regulatory authorities have to specify the types of incidents (e.g. all incidents) that must be reported by the operators.
- A system of periodic review and auditing of the adequacy and the effectiveness of procedures instituted under the RMP to ensure currency and to facilitate a process of continuous improvement.
- Appendices (e.g. figures, background data, monitoring details, reporting criteria, dose calculation methodology, incident management, etc.).

5.1 Workforce information and radiation safety resources

The number of the employees and detailed workforce stratification such as function, gender and company and / or contractor employee at the facility should be included in the RMP. The proposed shift roster system (job rotation), expected average annual working hours and employees or categories of employees who will be designated should be included.

The RMP should include details on:

- Staff with adequate qualification and experience in all aspects of radiation protection.
- Qualifications of relevant staff, including the radiation safety officer (RSO) and a list monitoring personnel. The RSO should have a degree in physical science or equivalent as well as experience in radiation protection, preferably within the mining and mineral processing industry. The main duties of the RSO are advising the management on the implementation of the RMP and all matters related to radiation protection of employees, the public and the environment. Where the RSO is also undertaking air monitoring, it is important that she / he has, as minimum, qualifications corresponding to a surface ventilation technician. Radiation protection staff should have access to continuous training and professional development.
- A list of monitoring equipment and facilities (model of the equipment, purpose of the particular equipment and its applicability, calibration methods, frequency and traceability to standards, maintenance and replacement schedule). Equipment and facilities may include, but are not limited to radiation field and contamination monitoring instruments, personal dosimetry equipment, protective clothing and, where appropriate, ventilation controlling devices such as fans, fume hoods and glove boxes. In addition, decontamination facilities, such as showers and washbasins, may limit the spread of radioactive contamination. Resources for monitoring the environment beyond the workplace should be provided.

5.2 Critical group information

The critical group concept was first introduced by ICRP in Publication 7 (ICRP, 1966). Critical Group means the group of individuals reasonably expected to receive the highest radiation doses from a particular operation.

Critical group may consist of a single individual or a group of members of the public comprising individuals who are relatively homogeneous with regard to location, age distribution, dietary habits (e.g. special foodstuffs and amounts consumed), behavioural characteristics (e.g. time spent indoors, frequency of personal washing and laundering of clothes) and the type of dwelling (e.g., shielding characteristics) that may affect the doses received and who are likely to receive the highest radiation doses from a particular operation.

According to ICRP (1966): 'Such groups in the population may be in the vicinity of the installation or at some distant location; they may include adult males, adult females, pregnant women, and children; they may be individuals who eat foodstuffs produced in a particular location; or they may be people in a particular industry'.

Usually, the critical group does not consist of one individual nor would it be very large for then homogeneity would be lost. The size of a critical group will usually be up to a few tens of persons (ICRP, 2006; IAEA, 2010). In a few cases, where large populations are uniformly exposed, the critical group may be much larger.

In some cases, critical group cannot be identified as distance from the proposed site is too far for a group to receive any measurable radiation dose. In such situations, a reference plant / animal (ICRP, 2008 and 2014) may be selected as a 'critical group' after consultation with the appropriate authority.

In order to verify that members of the public are not exposed to radiation from operations at the mine site, the operator must include the following information related to critical group in the RMP:

- Identification of the critical group.
- Location, size and demographics of the critical group.
- Radiation exposure (effective dose from proposed operations).
- The location of critical group should be shown on a suitable location plan.
- Land use maps (if any).

5.3 Sources and pathways of radiation exposure

The information included in the RMP should ensure that all significant exposure sources and pathways are identified and controlled.

The information needed to be included in RMP for identification of exposure sources, stressors and pathways is:

- Plans of the mine, processing plant, waste treatment facilities and tailings facilities.
- Description of the equipment (included also specifications of the instruments) to be used in the mining and mineral processing and the processes involved.
- Estimation of radionuclide concentrations in process streams.
- Estimation of thorium and uranium series radionuclides (physical, chemical and radiological, quantities, implication of waste characteristics) in the tailings.
- Assessment of the potential for accumulation of radioactive materials such as sludges inside the processing vessels or other places.
- Estimation of radiation levels to which various categories of employees and critical group(s) could be exposed using appropriate exposure pathway models. Information regarding the exposure issues for yellowcake production in covered in Chapter 8.

5.4 Control measures

The RMP should include the measures (e.g. engineering, management and administrative) that will be implemented to control radiation exposures.

The radiation issues have to be considered when planning any changes to or development of the operation, and the results of monitoring should be made available promptly to the management so that corrective measures can be taken, as required.

Continuous review and assessment of, for example, doses, including trends over time for both the operation as a whole and for smaller areas, review of monitoring plan, review of administrative procedures and work practices should be performed to continuously optimize radiation protection.

Engineering controls

The main components of operations that need to be considered for controlling radiation exposure include:

- Control measures such as quality in the design of, for example, a plant processing radioactive minerals, installation, maintenance, operation, administrative arrangements and instruction of personnel should be used to the maximum extent.
- In the design of mine facilities (e.g. crushing and screening plants, processing plants), aspects that: (1) minimize the generation of airborne or liquid contaminants, (2) prevent the release of contaminants to the environment and (3) prevent the build-up of contamination must be considered. The design shall facilitate maintenance work for the removal of any contaminants that do accumulate. Materials used in the construction of processing plants, refinery facilities and in equipment in general.
- Physical separation of processes containing elevated concentrations of NORM from frequently occupied areas.
- Engineering control technology, such as specifications of the equipment and location details of dust control systems, where applicable.
- Using equipment with minimal maintenance requirements in processes involving significantly elevated concentrations of naturally occurring radioactive materials.
- Preventive maintenance measures for equipment, schedules for repair work, monitoring and recording of radioactive contamination of equipment. During equipment maintenance and repair operations, care should be taken to control and minimize potential exposure arising from dust accumulation on internal and external surfaces of the equipment, in pipes and vessels and enclosed areas.
- Accessibility of equipment for the purpose of maintenance, repair, removal and replacement.
- Automation degree of identified critical processes (e.g. handling and packaging of yellowcake / radioactive material).
- Mining and mineral processing equipment to which engineering control methods will apply (ventilation, dust or fume control measures and time, distance and shielding).
- Dust control and mitigation measures should be an integral part of the environmental management system. Appropriate techniques for dust suppression at the source to prevent release of the radioactive material into the environment and to minimize potential exposure (see also Chapter 4 of this report). Location of dust-generating activities include drilling and blasting, excavation, conveyor transfer points, crushing, grinding, screening, sizing and processing of minerals, leaching operations and yellowcake drying and packaging. Measures taken to avoid resuspension of dust as a result of high air velocities.
- Ventilation systems are the most effective means of minimizing the exposure to airborne radioactive substances. Ventilation control systems in all facilities at the mine site, effluent control devices and efficiency.
- Monitoring (occupational (internal and external monitoring – individual dosimeters, continuous monitors with warning lights, area / time monitoring), members of the public, the environment and discharges of radioactive airborne and liquid effluents).
- Standard operating procedures for critical operations from a radiation protection perspective. Written standard operating procedures and implementation programme for return of the radioactive material spilt in the process. Procedures for the clean-up of spill, to be followed in the event of

any significant radiation hazard arising from the loss, escape or release from uranium facilities, for instance processing, waste management and transport. Any spill of radioactive material in a processing facility should be cleaned up as soon as practicable in order to minimize the spread of contamination. The area should be decontaminated by the removal of all loose material, where practicable.

- Procedures for off-site transport of radioactive materials (e.g. product or samples for analysis or testing). Procedures for transport of contaminated equipment from a site.
- Methods used for the movement of materials (conveyors or through pipes) such as transporting and loading of the ore to / into the milling facility, process / concentrate plant, unloading material from haul trucks and transport of crushed ore to tailings deposits after treatment.
- Personal protective equipment should be selected with due consideration of the hazards involved.
- Other aspects (it may not be a complete list).

Administrative controls

The RMP should include a description of the operational procedures and practices:

- Assignment of responsibilities to the radiation safety officer (RSO) and classification of designated employees relative to levels of radiation exposure and radiation work permit. Designation of supervised, controlled and restricted areas.
- Procedures for access control and work rules (e.g. physical barriers, signs, special work permits) in designated areas – supervised, controlled and restricted. Restricted areas are those in which gamma dose rates or airborne concentration limits may be approached or exceeded.
- Work practice instructions, safety meetings, supervision, inspections to ensure that work practices and procedures are being followed, minimal age limit for workers.
- Use of personal protective equipment (e.g. respiratory protection, shower and change facilities, personal contamination monitoring). Use of personal protective equipment may be needed in emergencies, for repair and maintenance and other special circumstances. The reason for the need of protective equipment, its type and expected frequency and duration of task performance should be detailed in the RMP.
- Dose assessment for both occupational and members of the public (control of workers and public exposure to radiation, control (quantity and concentration) of any radioactive material released to the air, surface water and ground water and action(s), when required).
- Medical surveillance monitoring programmes for workers, personal hygiene monitoring and first aid procedures must be clearly described. Measures that will assure adequate control of radiation exposure (e.g. dose limits, investigation and action levels).
- Action level. Action level can be defined as a specific dose of radiation or other parameter that, if reached, triggers a requirement for a specific action to be taken (G-228, 2001). Internal (set by the mining company) investigation levels and action levels for the radiation protection must be developed for all facilities at the mine site (Regulatory guides G-228 (2001) and G-218 (2003), http://www.nuclearsafety.gc.ca/eng/acts-and-regulations/regulatory-documents/). Investigation and action (corrective) levels are typically site and facility specific and are based on annual dose limits. When

the radiation monitoring results indicate that the radiation levels measured have exceeded the internal investigation level, an investigation should be made to find out the reasons for the elevated radiation levels. When the radiation level exceeds the action level, specific actions should be taken to rectify the problems that are responsible for the elevated radiation levels. Investigation levels are set lower than action levels and act as 'early warning' prior to radiation increasing to levels that may be problematic.
- Radiation warning systems at the mine site such as caution signs at the mine site, especially in controlled and supervised areas, and physical security measures to control access and exit from the site. Site security may include fencing and signs.
- House-keeping measure(s). Good housekeeping and cleanliness should always be maintained. Use of paint colours for walls, handrails, equipment, furniture and other objects that are distinctly different from the colours of the materials and products being processed aids good housekeeping and cleanliness.
- Tailings disposal facilities and waste monitoring programme (erosion, seepage, waste dam stability). Solid, liquid and gaseous wastes from the proposed operations should be managed in accordance with procedures approved by the regulatory body for the protection of workers, the public and the environment.
- Stockpiles location (whether temporary or permanent) on a map, size, shape and height of ore, method of placement, method of erosion control.
- Waste treatment facilities (collect and treat all contaminated mine waste such as liquid and solid tailings, runoff water from tailings facilities and waste rock, pit de-watering, etc.).
- Emergency planning and response to accidents (fire, radiological events, e.g. natural disaster, accidents during yellowcake packaging and transport, etc.).
- Radiation clearance.
- Incident and accident investigations.
- Procedures for visitors.
- Requirements for storage and transport of radioactive materials.

Management controls
- Risk assessments.
- Preparation of ALARA-programme ('Keeping radiation exposures, and environmental risks, at levels as low as reasonably achievable') (including investigation and actions level(s), an auditing programme that shall ensure and document that discharges and emissions to the environment comply with established threshold values and requirements to equipment and activities as well as management plans).
- Work and process controls.
- Training programmes.

5.5 Radiation monitoring

5.5.1 Occupational, public, environment and effluents monitoring

A description of occupational, public and environmental monitoring programmes specific for each phase of a facility's life should be part of the RMP.

The monitoring programmes should list the following for each radiation-related parameter (external radiation, airborne radioactivity, waterborne radioactivity, radon / thoron and their decay products and surface contamination):

- Location, task and employees to be monitored. 'Designate' employees (employees who are likely to receive significant doses greater than, for instance, 5mSv per annum) are monitored more intensively and their doses are assessed individually. Non-designated employees are monitored less intensively and their doses are assessed as an average of their relevant work group(s).
- Occupational (internal and external) monitoring – individual dosimeters, continuous monitors with warning lights, area / time monitoring, etc.
- Environmental ecosystems (air, water, terrestrial) to be monitored. (e.g. maps showing geographical coordinates for environmental samples).
- Monitoring of emissions and discharges of gases / liquid effluents from the mine site and their effects, continuous monitoring of the receiving environment.
- A list of all radiological and non-radiological parameters to be measured. The choice of parameters to be measured should be site specific.
- Sampling methodology (sampling locations, number of samples, sampling techniques such as grab / continuous sampling and others) should be designed to give a representative picture of the medium to be sampled.
- Type of sampling, (personal, gamma levels, air, dust, radon, thoron and their decay series, particulate matter, freshwater, drinking water, seawater, soils and sediments, biota) and sampling equipment and calibration records.
- A list of monitoring equipment including a model of the equipment, purpose and its applicability, calibrations and traceability frequency and maintenance and replacement schedules.
- Frequency of measurements. In the case of a new operation, an initial monitoring programme should be exhaustive in order to characterize the radiological environment and identify any locations and work practices requiring special attention. When the radiation levels stabilize and it is established that a facility operates under normal conditions, monitoring frequencies and locations should be adjusted in such a way as to reflect the level and variability of radiological parameters.
- Laboratory analysis methods, QA and QC of the monitoring programme.
- Investigation levels, action levels and corrective action(s) when dealing with non-compliance.
- Surface contamination should be an integral component of the monitoring programme. It is the primary method used to assess housekeeping standards, to check equipment prior to maintenance and to control release of potentially contaminated equipment from the site (gate control).
- Results assessment, reporting to authorities and the public.
- Environmental control plans or maps indicating the location of the following: environmentally sensitive areas on and adjacent to the site, waterways including drains, erosion and sediment control measures, vegetation that requires protection in case of contamination, working areas, vehicle and machinery parking, chemical stores, tailings facilities, monitoring locations and other relevant sites.
- Management of records / reports (e.g. records / reports of environmental incidents, environmental training, waste register, non-compliance, corrective and preventive action(s) reports, site inspection checklist, monitoring checklist, complaints reports, etc.).

Environmental compliance programmes should include but not be limited to:

- Quality and specification of sampling equipment and laboratory tools.

- Quality assurance and quality control of laboratory instruments and analytical methods.
- Preventive maintenance of equipment and laboratory tools.
- Training of the employees in use of equipment and instruments.
- Training of auditor.
- Traceability of monitoring results.
- Inspections, procedures, review and auditing.

5.6 Dose assessment

The RMP should include management of doses and dose records of individual employees, members of the public and strategies and measures taken in order to minimize the dose. Appropriate dosimetric models with all parameters and assumptions that are used to estimate radiation doses should also be detailed. Non-human biota radiation risk assessment should also be included in the RMP.

The RMP should also include a statement on how the monitoring results (environmental, effluent, occupational and members of the public) are used in the dose assessment.

Occupational and members of the public monitoring, dose assessment and radiation protection programmes should be developed in detail with support from the relevant authorities.

5.7 Transport of radioactive materials

The RMP should include a detailed description of all procedures for transport (regional and international) of radioactive materials (IAEA, 2002, 2012, http://www.wnti.co.uk/nuclear-transport-facts/regulations.aspx). The transport of Radioactive Material is also covered extensively in Chapter 8 of this report.

The information that has to be in place to ensure safe transport of radioactive materials both within and out of Greenland comprises:

- Related documents for safe transport of the radioactive material.
- Classification of material including physical, chemical and radiological characteristics of the transported material.
- Classification, types of packages, when applicable, and marking, labelling and placarding.
- Frequency of transport.
- Details of containers and mode of transport.
- Requirements and controls for mode of transport of radioactive material.
- Requirements for packaging and testing.
- Approval and administrative requirements.
- Radiation protection, the numbers of employees involved in the transport of radioactive material, their estimated exposure time and doses.
- Training of the employees involved in the transport of radioactive material.
- Transport routes (rail, road and air), estimated exposure time and doses to members of the public and the environment for safe transport.
- Ensuring that rail, road and air transport ‘vehicles’ have appropriate equipment to enable communication at all times with the company, transporter, local police, emergency services and company security staff.

- An emergency response plan has to be developed for spills and accidents during transport (regional and international) by both the operator and relevant national and / or international organizations. The emergency plan should include communication with relevant authorities and agencies and with the public, training of consignor, consignee and carrier regarding first response in order to minimize the impacts and ensure the presence of qualified response units along the transportation route who are trained to deal with radioactive material, to assess the accident and to implement protective measures and other regulatory requirements.
- Requirements for transport and storage in transit.
- Summary of measures taken to ensure strict compliance with transport safety regulations.
- Other regulatory requirements.

5.8 Employee education and training

All employees, contractors and subcontractors should undergo an appropriate training programme (environmental and radiation safety awareness). Training should, among other things, ensure that all employees, contractors and subcontractors understand and can contribute to the reduction and control of doses. The training programme should enable all employees to understand the risk from exposure to radiation and the methods of controlling doses.

In addition, an appropriate training programme for members of the public in basic radiation safety principles should also be considered.

The qualification and experience of the person conducting the training (if not the RSO) should also be provided. Records of all training programmes should be maintained and include information on the person trained, period of training, the trainer and a general description of the training content.

The RMP should list the specific training programmes designed for specific employees and the information needed to be included such as a summary of the topics covered, duration and frequency.

Training programmes should include:

- Training of new employees – induction programme. All new staff should complete an induction programme including description of working environment, radiological protective measures, training on local equipment, tasks related to their specific role, etc.
- Targeted training for specific personnel.
- Periodic retraining.
- Training of management personnel.
- Training of administrative, designer and planner employees.
- Emergency response and preparedness training.

The nature and the extent of the training programme depend on the employee(s), job requirements and responsibilities. The need for additional or revised training programmes should be identified and the possible revised programme should be implemented.

It is important that all employees commit to radiation safety. This commitment should be demonstrated by adherence to radiation protection practices and procedures derived from written policy statements. In this way, the employees will protect themselves, their fellow workers and the environment.

5.9 Emergency preparedness and response plan

Emergency preparedness programmes (EPP) to prepare for, to respond to and to recover from the effects of fire, natural disaster and accidental releases of radiological/or hazardous substances from uranium mine or mill facilities and transport activities (e.g. transport of final product) have to be developed and implemented at the mine site by the operator. An emergency response plan should also be established by a relevant regulatory authority. The main goals of the EPP are to prevent escalation of the accident and mitigate the consequences, prevent human health effects, render first aid and to manage the treatment of fire/radiation and non-radiological injuries and to protect the environment.

Aspects to be considered when developing an EPP are:

- Analysis of the risks and hazards that the EPP will address.
- Management aspects that ensure the effectiveness of the EPP and that arrangements are in place to ensure a timely, coordinated and effective response to any emergency.
- Preparedness – description of how people, equipment and infrastructure will be ready to execute a response according to the emergency response plan and procedures.
- Emergency response plan and procedures should be validated and should include emergency response staff responsibilities, organization interface and support, instructions and contact details for notifying relevant government authorities (prompt notification), local councils and public information, emergency assessment, response facilities and equipment, steps to follow in order to minimize damage and control an emergency, emergency personnel protection, countermeasures and recovery.

5.10 Record keeping and reporting

An RMP should include:

- A list of the required records and reports (regarding format, amount of records and type of storage and frequency of data reports (e.g. quarterly, annually and non-periodic in the case of spills and emergencies).
- A description of the typical report content.
- Personnel responsible for preparing the reports.
- Communications protocols.
- Document control procedures. The records should be retained for a period of minimum 30 years.

Record requirements that have to be addressed in the RMP are:

- Environmental radioactivity monitoring including airborne (radionuclides in dust, radon/thoron and their decay products in air), waterborne, terrestrial radioactivity monitoring and gamma radiation surveys, effluents (liquid and gaseous) release monitoring, airborne, waterborne and terrestrial non-radiological parameters, surface contamination and inventory of radioactive materials, QA, QC and external checking (third party) of the monitoring and its interpretation.

- Dose assessment for employees and members of the public (external and internal radiation doses and methods for dose assessment).
- Health monitoring results.
- Investigations and corrective action(s) (an assessment of data against action levels, investigation levels and dose limits, a description of actions taken to investigate and mitigate triggers of action / investigation levels).
- Implementation of a radiation and environmental protection programme including safety assessments of relevant operations, equipment and instruments, standard operation procedures, training programmes, quality assurance of the monitoring programme and data reports of all external audits.
- QA and QC – yellowcake production, packaging, storage and dispatch (checks should include the vehicle as well as drums and containers).
- Emergency events (radiological, fire and natural disaster) and incidences (e.g. spills, radiation levels and concentrations of radioactive material exceeding the legislative limits, exposure where doses are exceeded).
- Reporting of waste treatment and disposal methods for tailings and waste rock (quantities and radionuclides and no -radioactive contaminants present in the waste rock and tailings generated in the milling process). Internal and external inspections / auditing reports.
- Compliance and non-compliance statements.
- Changes in management and update status.
- Public information records.
- Any reports required by government agencies.

Individual occupational exposure data records that should be included in the RMP are:

- Individual identification (mine health surveillance).
- Exposure for the current year and, where possible, exposure for a five-year period.
- Measurements for assessing external radiation doses.
- Measurements for assessing internal radiation doses (monitoring of personal dust and radon / thoron and their progeny).
- Allocated dose for lost or damaged monitors or samples.
- Any possible radiation exposure received by an employee.
- Formal declaration of pregnancy and methods applied to keep the effective dose to individuals under a certain level imposed by regulatory bodies (e.g. 1 mSv during the remaining period of pregnancy).

5.11 Management systems

A quality assurance programme compliant with Greenland regulatory requirements should be implemented in all phases of the project (See also Sec. 4.5).

5.12 Figures to be included in the RMP

Examples of relevant figures to be included in the RMP:

- Geographical location, diagram of operations and facilities.
- Plan of the site / infrastructure.
- Geographical location of critical groups of members of the public.
- Maps showing the geographical location of sampling sites (airborne, waterborne and terrestrial).
- Geographical locations and diagrams including relevant engineering details of the radioactive waste disposal facilities.

- Geographical location and details of engineering control equipment used during various stages of the operation and milling process.
- Maps showing the supervised, controlled and restricted areas.
- Examples of warning signs used on the site and their locations.
- Diagram showing process flows, including also potentially radioactive streams.

5.13 Tables to be included in the RMP

Examples of relevant tables to be included in the RMP:

- Summary of the site history.
- Workforce stratification.
- Radiation sources, radionuclide mass balances and pathways of radiation exposure.
- Radiation monitoring programme (occupational, visitors, members of the public).
- Results of the radiation monitoring programme.
- Radiation monitoring instruments.
- Employee training programmes.
- Dose calculations and exposure pathways.
- A list of radiation signage and their locations.
- A list of radiation protection standard procedures.

5.14 References

G-218, 2003. Preparing Codes of Practice to Control Radiation Doses at Uranium Mines and Mills, Regulatory Guide. Canadian Nuclear Safety Commission, Ottawa.

G-129, REVISION 1, 2004. Keeping Radiation Exposures and Doses ‘As low as Reasonably Achievable (ALARA), Regulatory Guide, Canadian Nuclear Safety Commission.

G-228, 2001. Developing and using Action Levels. Regulatory Guide, Canadian Nuclear Safety Commission.

IAEA, 2002. Planning and Preparing for Emergency Response to Transport Accidents Involving Radioactive Material. Safety Standards Series No. TS-G-1.2 (ST-3), IAEA, Vienna.

IAEA, 2010a. Setting Authorized Limits for Radioactive Discharges: Practical issues to consider. IAEA-TECDOC-1638.

IAEA, 2010b. Best Practice in Environmental Management of Uranium Mining, No. NF-T-1.2.

IAEA, 2012. Regulations for the Safe Transport of Radioactive Materials. IAEA Safety Standards Series No. SSR-6. Specific Safety Requirements.

ICRP, 1966. Principles of Environmental Monitoring related to the Handling of Radioactive Materials, ICRP Publication 7. (This publication was Superseded by ICRP Publication 43).

ICRP, 2006. Assessing Dose of the Representative Person for the Purpose of the Radiation Protection of the Public. ICRP Publication 101a, Ann. ICRP 36 (3), 2006.

ICRP, 2008. Environmental Protection - the Concept and Use of Reference Animals and Plants. ICRP Publication 108. Ann. ICRP 38 (4-6).

ICRP, 2014. Protection of the Environment under Different Exposure Situations. ICRP Publication 124. Ann. ICRP 43(1).

NORM-2.2, 2010. Department of Mines and Petroleum, 2010. Managing naturally occurring radioactive material (NORM) in mining and mineral processing _ guideline. NORM_2.2 Preparation of a radiation management plan -mining and processing: Resources Safety, Department of Mines and Petroleum, Western Australia, 29pp. http://www.dmp.wa.gov.au.

6 Uranium Processing and Radioactive Waste Management Plan (RWMP)

6.1 Uranium processing

Conventional milling includes crushers and grinders, conveyors, processing facilities and ancillary buildings (e.g. acid plant, powerhouse, etc.). A generalized uranium mill process is shown in Figure 6.1.

The initial step in conventional milling involves:

Crushing (and grinding) of the ore (1): Crushing and grinding serve to produce an ore particle size suitable for physical separation (step 2). The grinding process may be wet or dry. Often, water is added during this stage to control dust and associated radiation hazards. A liquid medium used to selectively extract uranium from ore bodies (lixiviant) may also be added to facilitate the extraction process from coarse particles, which are recirculated in the milling circuit. If dust is not suppressed by the addition of water or lixiviant, it is in most cases collected by emission control devices (Chapter 7.6). After crushing and grinding, the ore processing takes place using physical and chemical separation methods.

Physical separation processes (2): Physical separation processes exploit differences in physical properties such as size, density, magnetic properties and surface energy or behaviour of mineral particles. The bulk of the mineral is not chemically altered although chemical reagents may be used to help in the separation process. Commonly used physical separation processes are:

- Gravity separation: Minerals can be separated on the basis of differences in density. Gravity separation may also be used to pre-concentrate metallic minerals prior to further processing. Gravity separation tends to require the use of smaller amounts of process reagents than other ore separation methods.

- Magnetic separation: Minerals can be separated on the basis of differences in magnetic susceptibility. Like gravity separation, magnetic separation requires the use of smaller amounts of process reagents than other ore separation methods.

- Flotation separation: Flotation is used for the separation of a wide variety of minerals on the basis of differences in surface properties of minerals in contact with air and water. It is the dominant process for the recovery of base metal ores and uranium. To separate minerals using flotation, fine air bubbles are introduced into a mixture of fine-grounded ore in water, known as slurry. In this slurry, mineral particles collide with air bubbles, and minerals that favour contact with air attach to the air bubbles and float to the surface of the flotation cell. As air bubbles accumulate at the surface, a froth forms and eventually overflows as the flotation cell concentrate. Minerals that favour contact with water remain in the slurry and this fraction of the flotation process constitutes the tailings. A number of chemical reagents are used to aid the process.

Chemical separation processes (3): Chemical separation processes involve the preferential leaching of one or more minerals. Processes usually used for separation of individual metals are:

- Alkaline leaching
- Acid leaching.

The employed leaching method depends on the geochemistry of the ore mineral.

The slurry from the physical separation is usually leached with sulphuric acid or a base in case of alkaline leaching to dissolve the uranium oxides, leaving the remaining rock and other minerals undissolved as mill tailings.

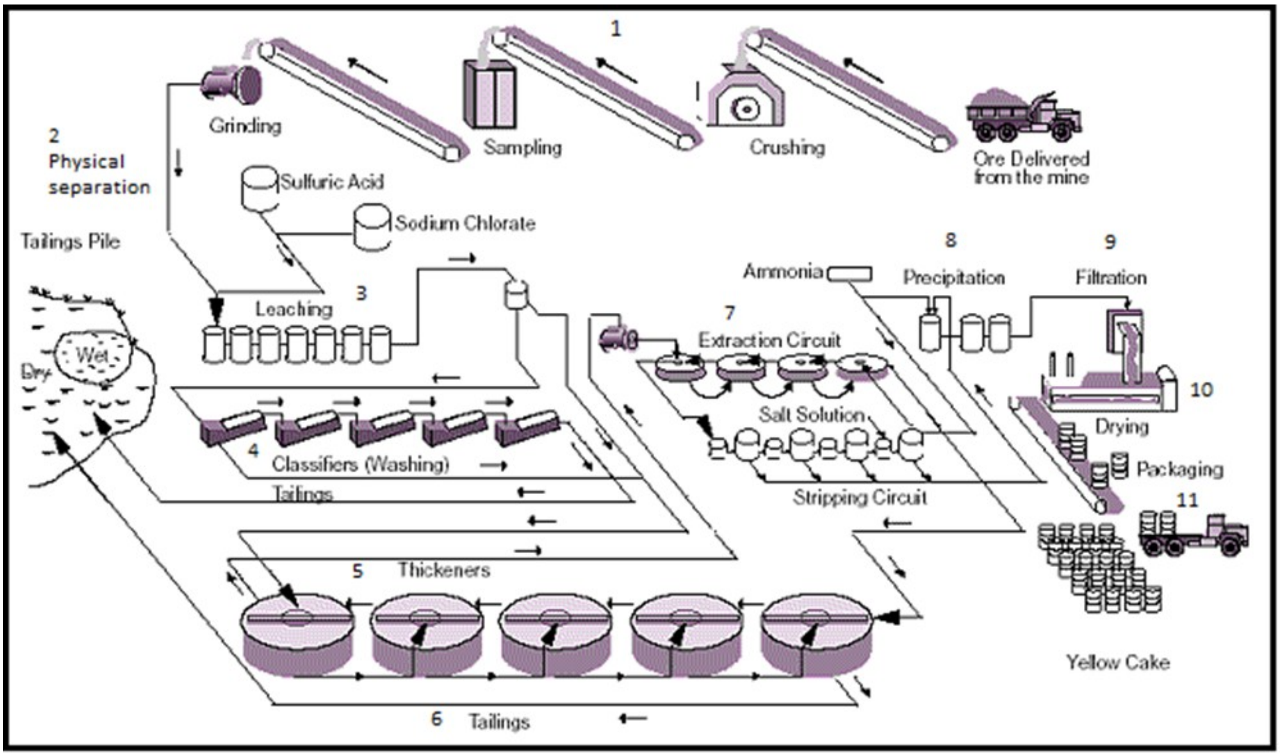


Figure 6.1. Generalized uranium milling process. Source: http://www.epa.gov/radiation/docs/tenorm/402-r-08-005-voli/402-r-08-005-v1.pdf.

The end product of leaching, often called pregnant liquor, contains uranium, other radionuclides and non-radioactive contaminants dissolved in it. The leached solution is transferred to classifiers (4) and thickeners (5). The solution is allowed to set for a period of time to allow any solids to settle. After treatment, the solids and slime are pumped to a tailings pond (6). The uranium at this stage of the process is in the form of uranyl sulphate for systems that use sulphuric acid or uranyl carbonate for the alkaline treatment method.

The liquid is transferred to a solid-liquid separation and purification circuit (7) and the uranium is then separated by using either solvents like tertiary amines in mixer settles or ion exchange resin, or both, from the pregnant liquor. The majority of conventional uranium mills recover uranium by solvent extraction using tertiary amines. A potential environmental impact of solvent extraction is contamination of process liquor by organics and subsequent release to the environment.

After this, uranium is precipitated (8) from the solution using, for instance, ammonia solution to produce ammonium diuranate (ADU), sodium or magnesium hydroxide, and hydrogen peroxide (U.S. EPA, 1995).

The precipitate is pumped to filter presses (9) that remove the excess water. The pressed material is sent to a calciner or furnace (10) and dried at elevated temperatures to produce a uranium oxide concentrate. Several types of drying equipment are used, including single or multiple hearth dryers, drum dryers, belt dryers, screw dryers and radiant heat dryers.

The recovered dried uranium oxide concentrate is then sealed in drums (11). An overall description of the packing process is found in Chapter 8. The product is called yellowcake but can be any uranium concentrate: UO_4, U_3O_8, ADU, MgDU, uranyl peroxide, etc. Yellowcake may be coloured reddish, orange to yellow naturally or dark green to grey or almost black when calcined (in a furnace). The yellowcake is sent to an enrichment facility where the uranium-235 isotope is raised from the natural level of 0.7% to about 3.5% to 5%. Finally, enriched uranium, for example UF6, is transported to a fuel fabrication plant where it is converted to uranium dioxide (UO_2).

6.2 Waste generated from production of uranium

The radioactive waste management should aim to remove and / or isolate the waste from the environment in order to prevent harm to humans or the environment, both now and in the future.

Management of radioactive waste is one element of the overall site strategies to manage waste. There will be radioactive waste, and non-radioactive waste generated on a site (Table 6.2) with naturally occurring radioactive materials. Opportunities to segregate the wastes, shall be assessed. However, on sites where there are small volumes of very low activity radioactive waste, combining them into a waste storage area to manage all the wastes (e.g., tailings) may be efficient and effective, and should be considered and assessed.

The following sections cover detailed information on tailings and waste rock management and requirements for development of RWMP. Not all sites are the same, and the RWMP will be different depending on the waste streams, volumes and risks involved and assessed.

The RWMP should be prepared by the operator and submitted to the authorities together with the application for authorization to operate the facility.

Table 6.2. Potentially generated waste from production of uranium.

Phase	Potentially generated waste
Exploration	Wastewater from washing of vehicles and equipment
	Drilling muds
	Slurries from core cutting
	Spills of drilling fluids or cutting fluids
	Possible contaminated groundwater from the exploration activities
	Radioactive samples taken in excess or returned analytical samples
	Contaminated equipment and containers and contaminated soils from, for instance, spills of drilling or cutting fluids
Construction	Waste rock (low grade, sub-economic mineralized material)
	Domestic and industrial debris such as batteries, oils pipes and filter cloths. Industrial debris and domestic waste have to be treated in, for instance, a sewage/incinerator plant or handed over to a waste handling facility for further disposal.
Mining	Waste rock (low grade, sub-economic mineralized material) (especially for open-pit mines)
	Mine water, for instance runoff and seepage from stockpiles
	Contaminated materials
Milling	Tailings, process water (liquid and solid residues)
	Material collected by dust extraction systems, scrubber effluents, stack emissions
	Waste water
	Sludges
	Contaminated materials
Water treatment	Sludges
	Contaminated materials
Decommissioning and rehabilitation	Contaminated materials, parts of facilities, equipment, pipelines
	Waste water
	Sludges

6.2.1 Tailings classification

Classification of radioactive waste for disposal is related to the safety aspects of the management of the waste and should include long-term risks to members of the public and the environment. Items that should be considered include the processes generating the waste, the characteristics of the site, the type of waste, the expected generated volumes, physical and chemical properties (quantities of radionuclides and non-radioactive contaminants, chemical forms) and minerals in the waste and the radiological and biological properties of individual radionuclides. An example of important parameters of radioactive waste that may be considered when classifying tailings from uranium milling is presented in Appendix H.

Radiological properties include activity concentrations of radionuclides, the half-lives of the radionuclides contained in the waste, taking into account the hazards posed by different radionuclides and the type of radiation emitted and / or dose or dose rate. Activity levels may be expressed in terms of activity concentrations or specific activity. The higher the level of activity content and half-lives of radionuclides in the waste, the greater the need to contain and isolate the waste from the environment. The half-lives of the radionuclides contained in the waste may range from a short (seconds) to a very long time (millions of years). According to IAEA (2009), ‘’a radionuclide with a half-life of less than about 30 years is considered to be short lived.’’ Dose criteria used for the management of waste containing naturally occurring radionuclides may be developed on the basis of considerations of optimization of protection.

Uranium tailings are characterized by their relatively large volumes and contain: 1) radioactive nuclides with relatively short half-lives such as Po-218, Po-214, Po-210 and Pb-210 and 2) less radioactive nuclides with long half-lives such as natural uranium, natural thorium and Ra-226.

Mill tailings are classified as: (1) fine-grained, sandy material that remains from the physical separation, (2) solid residues from the chemical processes and (3) liquid effluents from physical and chemical processes. The key activities of the mine operations phase that produces tailings are described in Section 6.1.

Solid tailings

The solid mill waste called tailings, a mixture of fine crushed rocks and water, includes: (1) primary ore and gangue minerals resulting from physical separation (e.g. magnetic, floatation), (2) slimes, coarse sands and tailings from chemical refining in the form of solids emerging after uranium extraction from the ore, (3) precipitates and sludge from the treatment facility, (4) secondary minerals (e.g. silicates, ferrihydrite, gibbsite) formed during weathering and (5) chemical precipitates formed after disposal in the tailings storage facility. The mill solid wastes comprise most of the original ore and contain most of the radioactivity in it.

The solid tailings can be crystalline, poorly crystalline and / or amorphous in nature, and they contain radionuclides, heavy metals, other contaminants such as organic matter and metalloids (Pichler et al., 2001). The quantities of those contaminants in the solid tailings depend on the ore geochemistry and thus vary with the project. Uranium tailings undergo chemical reactions in a tailings depository. Over time, the tailings mineralogy and pore water composition may change. Dissolved radionuclides, metals and metalloids may: a) persist in solution, b) precipitate or co-precipitate by interacting with other components in the tailings or c) be absorbed by organic matter (e.g. humic substances), quartz, kaolinite, clays or amorphous substances that are present in the tailings (Landa, 1999).

Generally, in the tailings the radionuclides (i.e. thorium and radium isotopes, natural uranium), metals and metalloids (Lottermoser, 2010) may occur as:

- Ion exchangeable forms
- Carbonate and readily available forms
- Iron and manganese hydrous oxides
- Fluorides
- Alkaline earth sulphates
- Organic matter
- Sulphides
- Arsenates
- Other.

The mobilization of radionuclides and non-radioactive contaminants from tailings solids into tailings liquids and further into the environment via different pathways (see Chapter 10) can be induced through various processes (Landa and Gray, 1995):

- *Acid leaching.* Sulphide minerals may oxidize in the tailings impoundment. The acid-producing reactions may not be sufficiently buffered by acid neutralizing reactions, and this will lead to the formation of AMD. The development of AMD will enhance the dissolution of uranium minerals and the mobility of radionuclides.

- *Presence of process chemicals.* Hydrometallurgical processes add significant amounts of sulphuric acid, alkaline materials, nitrate, chloride and / or organic solvents to the processed ore. The process reagents can leach host phases and act as sequestering agents for radionuclides and heavy metals. The contaminants may be mobilized from their host minerals and dissolved in tailings waters.
- *Reduction of iron and manganese oxyhydroxides.* Depending on the ore, iron and manganese oxyhydroxides represent important host phases to radionuclides, metals and metalloids, in particular arsenic. These hosts can become unstable under acid or reducing conditions. Acid or reducing conditions in uranium tailings may lead to dissolution of oxyhydroxides and to the mobilization of the previously fixed radionuclides, metals and metalloids.
- *Presence of clay minerals.* Clay minerals act as sinks for contaminants, for instance barium and strontium cations in the tailings. The cations are incorporated into the clay structure, which prevents the formation of insoluble alkaline sulphates and co-precipitation of Ra-226 as $Ba(Ra)SO_4$.

Other processes include adsorption-desorption (ion exchange), precipitation-dissolution and co-precipitation reactions, which are affected by parameters such as pH, redox, solid surface properties and biological reactions that are often both time and space dependent (Landa and Gray, 1995).

The solid tailings can be subdivided according to particle size into slimes and sands. Each of these components (e.g. sands, slimes) has distinct chemical, mineralogical and radiological properties. The table below (Table 6.2.1.1), showing the radiological properties of the uranium mill tailings components, is just an example.

Liquids tailings

The liquid tailings may contain radionuclides, heavy metals and reagents used in the hydrometallurgical process and metalloids. Usually, tailings are treated before final disposal. For example, liquid tailings of an acid leach uranium processing plant are partly or completely neutralized with lime prior to final disposal. Gypsum and other elements (e.g. As, Ni, Fe, Cu, Mn, Mg) may, if they occur in solution in the acid process water, precipitate as a result of the neutralization process. Consequently, metal hydroxides, gypsum and arsenates (Mahoney et al., 2007) precipitates may form. If acidic liquid tailings react with aluminosilicate minerals present in mineral deposits or host rocks, then secondary clay minerals, jarosite and alunite will be produced. These minerals will plug pore spaces and decrease the permeability of the tailings. On the other hand, liquid solutions from acidic tailings may react with clay liner placed at the bottom of the tailings storage facility. A breach of the clay liner may then be possible (Shawn and Hendry, 2009).

Table 6.2.1.1. Typical properties of uranium mill tailings (U.S. EPA, 2006). Please note that the table below is just an example. The radiological properties of the uranium tailings depend on ore geochemistry, hydrometallurgical processes and the tailings treatment methods employed prior to final disposal.

Tailings component	Particle size (µm)	Chemical composition	Radioactivity characteristics U	Radioactivity characteristics Ra-226	Radioactivity characteristics Th-230
Sands	75 to 500	SiO_2 with <1 wt. % complex silicates of Al, Fe, Mg, Ca, Na, K, Se, Mn, Ni, Mo, Zn, U and V; also metallic oxides	0.004 to 0.01 wt. % U3O8[a]	Acid leaching: 26-100 pCi Ra-226/g	Acid leaching: 70 to 600 pCi Th-230/g
Slimes	45 to 75	Small amounts of SiO_2, but mostly very complex clay-like silicates of Na, Ca, Mn, Mg, Al and Fe; also metallic oxides	U_3O_8 and Ra-226 are almost twice the concentration present in the sands	Acid leaching:[b] 150 to 400 pCi Ra-226/g	Acid leaching: 70 to 600 pCi Th-230/g
Liquids	*c*	Acid leaching: pH 1.2 to 2.0; Na^+, NH_4^+, SO_4^{2-}, Cl and PO_4^{3-}; dissolved solids up to 1 wt % Alkaline leaching: pH 10 to 10.5; CO_3^{2-} and HCO_3^-; dissolved solids 10 wt %	Acid leaching: 0.001 to 0.01% U	Acid leaching: 20 to 7,500 pCi Ra-226/L Alkaline leaching: 200 pCi Ra-226/L	Acid leaching: 2,000 to 22,000 pCi; Th-230/L Alkaline leaching: essentially no Th-230 (insoluble)

[a] U_3O_8 content is higher for acid leaching than for alkaline leaching.
[b] Separate analyses of sands and slimes from alkaline leaching processes are not available. However, total Ra-226 and Th-230contents of up to 600 pCi/g (of each) have been reported for sands and slimes combined.
[c] Particle size does not apply. Up to 70% of the liquid volume may be recycled. The recycle potential is greater in the alkaline process.

6.2.2 Radioactivity in the tailings

Depending on ore geochemistry and the employed hydrometallurgical process, the waste generated from uranium production activities contains low activity-, long lived radionuclides such as uranium (if uranium is not 100 % recovered), thorium and their decay daughters. The generated waste often contains hazardous non-radioactive contaminants, such as arsenic, nickel, lead and other heavy metals that occur in the original ore as well as inorganic and organic compounds used as reagents in the milling processes. The presence of such contaminants in the tailings may require more comprehensive waste management than the measures employed for radioactive contaminants. Thus, both radiological and non-radiological aspects have to be taken into account in uranium waste management. However, management of non-radioactive waste resulted from mining and milling will not be included in this chapter.

Uranium tailings are of particular environmental concern as:

- Uranium mill tailings are characterized by very large volumes of low activity (IAEA, 2004) radionuclides. The volume of the tailings generated during the lifetime of the mine can easily become several hundreds of millions of cubic metres.
- The radionuclides have long half-lives.
- Uranium mill tailings contain non-radioactive contaminants such as reagents used in the flotation or mill processes, heavy metals from original ore, etc.

- Uranium mill tailings may contain sulphidic minerals which may generate AMD.
- The size of the tailings makes them readily leachable.

During the milling process, the per cent of the uranium contained in the ore removed depends strongly on ore geochemistry and on the employed hydrometallurgical process. In the milling process, the uranium ore is ground to a very fine (e.g. 5-10 µm) material, promoting release of contaminants and thus their release to the environment. Leaching is usually enhanced by acid formation (AMD) and in some cases by acid rain.

The long half-lives of the radionuclides present and the very large volumes of generated tailings are of particular importance. The radiological hazards in the tailings are long lived uranium and thorium and their decay daughters. Tailings retain the majority of the radioactivity of the ore from which they are derived, as much as 80-90 % of the original radioactivity of the ore (U.S. EPA, 2006; Abdelouas et al., 1999; Landa, 1999; OECD, 1999). The produced yellowcake is weakly radioactive and contains around 10 to 15% of the original total radioactivity of the ore (OECD, 1999); if there is thorium in the ore it is less than 15%.

Radium-226, which is a water soluble isotope, is of significant concern in uranium mining and milling. It tends to be concentrated in the fine fraction of uranium tailings (Landa and Gray, 1995) and needs to be treated before disposal. A standard method of removing radium-226 and lead-210 is to add barium chloride, which may effectively remove some of the dissolved radium-226.

Radon emissions occur from tailings and mine waste at all stages. Despite of its short half-life of 3.8 days, radon-222 presents a potential long-term hazard as the decay of thorium-230 ($T_{1/2}$ of 75380 y) constantly produces radium-226 ($T_{1/2}$ of 1600 y), which again constantly produces radon-222. Radon generation may continue for thousands of years because of the long half-lives of the thorium-230 present in the uranium mill tailings.

Radon is an inert gas that is soluble in water and can reach the ambient atmosphere when free circulation of air in the tailings and mine waste is possible. Once released from the tailings facility, it may be transported by the wind, dispersed and diluted into the atmosphere. Radon release, dispersion and dilution into the atmosphere are affected by climatic factors such as wind speed, air temperature, relative humidity and soil moisture content. A cover over the tailings and mine waste inhibits release of radon to the surrounding air. Water, soil, clay and rock layers can greatly reduce the release of radon from the tailings (SENES, 2008).

Dust emissions from the tailings disposal and other mine waste are another concern. Tailings and mine waste are made up of very fine particles that may contain long-lived alpha emitters, heavy metals and silicates. If the tailings are allowed to dry, especially during the winter, this fine particulate material is dispersed as dust to the environment. Dust emissions can be minimized by maintaining an adequate cover.

Gamma radiation originates from uranium and thorium mineralized materials and tailings and is not a contaminant. Except for people working or living adjacent to orebodies and / or stockpiles, the environmental and public health risk arising from gamma radiation is generally very low. During the operational phase, members of the public are generally excluded from close proximity to the facility. Because gamma exposure decreases with distance from the source, this is generally a negligible pathway during the operational phase. Covering (wet or dry) the waste rock (if containing radioactive materials) and the tailings is generally sufficient to shield the gamma radiation.

There have been cases where sand and grained or crushed rock tailings containing radionuclides have been used in the construction of buildings and roads. Radon released from the construction material may therefore be trapped in the building's structure, resulting in increased exposure of its occupants to radon emanation from the structure and to gamma radiation from the material. The waste material can also be removed or disturbed by burrowing animals, spreading contamination throughout the surrounding area.

6.3 Waste management strategies

Possible release of contaminants from, for instance, tailings to the environment depends strongly on the waste management strategy. The preferred management depends on site-specific factors, ore characteristics, mining and milling, tailings characteristics, etc. This assessment approach on waste management is universal, and can be used regardless if the ore contains radioactive minerals or not.

Appropriate waste management will minimize the release of contaminants to the environment, shield the gamma radiation and minimize the cost for rehabilitation of the waste facilities.

An initial safety assessment of the radioactive waste management should include the following elements:

- An outline of the operation and the waste-generating processes.
- Estimation of the radioactive and non-radioactive waste generated per year / entire duration of the proposed mining activities should be assessed.
- Characterization of waste types, chemical, physical and radiological issues, quantities and rates of generation. Predicted waste inventories over time. Waste implications: leaching of radionuclides, potential for off-site migration and prevention measures. Detailed guidance and considerations regarding waste characterization are given in IAEA 1992.
- Detailed characterization of the environment (baseline monitoring programme): climate, geology, chemistry (including here also radionuclides), hydrology, flora and fauna, seismological activity, etc. Identifying and characterizing site options for mining and milling waste disposal will allow determination of the generation of contaminants and their transport from the site. Appropriate source term models and contaminant transport models should be developed and the parameters used should be provided to the relevant authorities for assessment.
- Tailings management such as alternative tailings storage methods, selection of preferred tailings storage facility (TSF) (including here also dam stability, maximum rate of rise (m / y)), emergency ponds, pipelines, groundwater (in Greenland: surface water) monitoring bores, method of tailings discharge, tailings treatment and dewatering, depth of cover, cover material, TSF water balance.
- Information on the design, operation and expected performance capability of the disposal facility and its exact location.

- Emergency measures for natural events, incidents, equipment and operational failures, temporary closure of operations.
- Identification of hazards such as instability and failure of embankments, liners, seepage of process liquor or water cover into, for instance, the groundwater, overtopping of TSF, erosion of tailings slopes by surface water runoff causing embankment instability, dust generated from TSF, radiation – in terms of exposure of personnel (radon emissions or inhalation of radioactive windblown dust) and fauna to TSF, water and rainfall.
- Management of identified hazards.
- Waste monitoring programmes, assessments of results and reporting.
- Proposed closure plan for the site, including decommissioning, decontamination and rehabilitation concepts. On completion of the mining and milling operations, the tailings and mine waste should be drained (if the water cover is used during the operation) and consolidated before closure, and a permeable envelope (a mixture of clay and topsoil) should be used to cover the facility. If possible, the area should be re-vegetated. This will reduce both gamma radiation levels and radon emanation rates to levels near those normally experienced in the region of the ore body (see Chapter 9 of this report). The annual effective dose to the members of the public from rehabilitated site should not exceed the regulatory limit. For example, Canada, Australia, Denmark and Romania have set an annual effective dose to the members of the public from rehabilitated mine site of 1mSv/y.
- Institutional controls to be implemented, such as long-term monitoring and record keeping.
- Description of hazards such as intrusion, farming, building on areas where waste was previously managed and use of radioactive waste as well as natural events such as erosion, weathering, flooding and earthquakes, and other processes such as acid generation, failure of the containment slope, etc.
- Cost – capital and operating costs.
- Community involvement.

Strategies for waste management include:

- Waste minimization at all stages from exploration through to decommissioning. The quantities and the activity of radioactive waste should be reduced to a level as low as reasonably achievable.
- Waste pre-treatment which may include waste collection, segregation, etc.
- Waste treatment such as, for example, volume reduction and removal of contaminants (see Chapter 4).
- Waste reuse and recycling if the clearance criteria are met.
- Long-term waste management.

Current long-term waste management practices include tailings characterization, design and containment preparation (liners, water control structures such as spillways, decant towers), tailings preparation, tailings discharge and deposition, tailings consolidation, tailings surface water treatment, decant water treatment, seepage control, tailings covers, emergency preparedness and response in the event of, for instance, containment failure and cover failure, and a programme for monitoring and surveillance of tailings facilities (IAEA, 2002; 2004).

6.3.1 Ore, waste rock and tailings characterization

Uranium deposits, waste rock and associated tailings encompass a wide range of mineralogy and geochemistry. Generalizations of their properties can be made, but substantial variations may occur, even within an individual deposit. Hence, the ore, waste rock and tailings specifically related to the project must be properly characterized prior to mining and milling to assess the particular types and concentrations of potential contaminants and implications for waste geochemistry (acid formation and leaching of heavy metals and radionuclides, etc.). This characterization allows identification of environmental impacts and provides the opportunity to minimize the identified impacts.

During the exploration / feasibility studies and operation phase, comprehensive characterization of ore, waste rock and tailings (chemical and physical characteristics), implications of waste geochemistry (acid formation, leaching of heavy metals and leaching of radionuclides, etc.) should be performed in order to maximise the opportunities to manage these materials for the best environmental outcomes, not only throughout the operational phase, but, more importantly, for the long term once the operation has been closed out (EIA 2015). Examination of longer term legacy issues globally has shown that lack of adequate information on the chemistry of waste rock is the prime cause of long term environmental issues at closed-out mine sites.

Characterization of original ore, waste rock and tailings should be based on a series of laboratory studies and shall be conducted during the feasibility studies.

The following tests should be considered:

- Static tests: Element composition (Induced Coupled Plasma (ICP), Atomic Adsorption (AA), X-ray, fluorescence (XRF)), mineralogical analysis (simple visual examination of core, petrographic microscope techniques, X-ray diffraction (XRD)), permeability, porosity, shear strength, compaction, article size analysis (mineralogical examination of size fractions of tailings, shape and angularity, bulk density, particle density), Modified Acid Base Accounting (MABA, if this method is selected, the inorganic carbon content has to be determined) or standard Acid Base Accounting (ABA), shake flask extractions (SFE) and other tests.
- Kinetic tests: Tailings humidity cell tests, sub-aqueous column tests (for sub-aqueous disposal of tailings), tailings aging tests, among others.
- Toxicity test: Acute lethality testing using relevant species (e.g. algae, *Daphnia* and fish) and other tests.

In addition, parameters and processes such as oxygen diffusion, redox conditions, concentrations of other ions and organics, pH and temperature provide valuable information if sub-aqueous tailings deposition is selected. Radio-analytical, radiometric and analytical techniques should be applied for analysis of uranium and thorium radionuclides and non-radioactive contaminants in original ore, waste rock and tailings.

6.3.2 Tailings disposal

Tailings from mill operations are generally disposed of as slurry containing about 20-50% solids on the site of its generation into a purpose-built water retaining structure or impoundment, either above or below grade.

Tailings contain all the radionuclides in the original ore and a portion of uranium. Approximately 75% of the original radioactivity present in the ore is rejected to the tailings.

Less favoured options for uranium tailings disposal include valley containment and marine disposal. Valley deposition is a less favoured tailings management strategy due to proximity to used land (e.g. agricultural land in the area), the potentially high levels of water flow from flood events and extreme rainfall into the tailings facility, increasing the volume of contaminated water to deal with and also the risk of catastrophic dam failure. The main argument against marine disposal of tailings is that the general principle that protection of humans from radiation exposure will automatically protect non-human species is not valid. Large doses could be delivered to marine species without approaching the human dose limit owing to the remoteness of any humans from the deep ocean environment.

Current tailings disposal practices aim at: a) isolating tailings for a long period of time from the surrounding environment, b) preventing leakage from the repository and c) protecting ground and surface waters from contamination (Lottermoser, 2010). The disposal of long-term radioactive, fine-grained, sulphidic or even acidic mine wastes requires more attention.

Current available options for tailings disposal fall into three categories:

- Above-ground disposal - ring dyke type impoundments; side hill containment (tailings dams).
- Below-ground disposal - backfilling the tailings into a mined-out open pit or underground mine.
- Subaqueous disposal (deep lake disposal).

Above-ground disposal (tailings dams)
The main disadvantage of this type of disposal is the long-term stability of the containment which may be at risk through erosive forces.

<u>Ring dyke type impoundments</u> comprise a single, enclosing embankment on more or less level ground. Some of these types of facilities are built as water-retaining structures, while others are built similar to agricultural dams. Most of these types of facilities are built as a series of raises, with the walls being increased in height in stages as the dam fills up with tailings.

The materials used for the construction of tailings dams may include waste rock, sub-economic ore or sand fractions of the tailings obtained by cycloning (in the case of an underground mine).

The methods for raises construction depends on site-specific factors and regulatory requirements and may be upstream, downstream or centreline.

Use of sand fractions and / or the sub-economic ore for the construction of tailings dams may create environmental issues such as the possibility of contaminated runoff from the outer wall of the dam and the need for an extended final dry cover over the entire dam, as well as outer walls, to provide long-term stability and reduce radon flux.

Examples of ring dyke type impoundments for uranium mill tailings are Ranger and Olympic Dam, Australia, (Fig. 6.3.2.1) and Key Lake in Canada.

<u>Side hill containment</u> differs from ring dyke type impoundments only by being constructed on planar sloping ground.

Figure 6.3.2.1 Ranger, NT Australia, ring dyke type impoundment for uranium mill tailings. Source: http://www.energy-res.com.au/.

An example of side hill containments is the Cluff Lake Waste Management System, where an embankment was built with a compacted soil / bentonite layer beneath and parallel to the inner wall surface that was keyed into the foundation material.

At the end of the mining and milling activity, above-ground uranium tailings dams require de-watering and permanent dry cover.

Conventional dry cover designs for uranium tailings are multi-layers barriers. Dry covers use a combination of materials including geotextiles liners. Tailings are covered with waste rock or clay to minimize water ingress and reduce gamma radiation and radon emanation levels. An impermeable cap of clay and geotextiles can inhibit rainwater inflow and radon escape. Covering with suitable substrate and local flora will complete rehabilitation of dry capped dams. Vegetation with long roots should be avoided as this may lead to the disturbance of the intact cover.

Long-term stability of tailing dams should be engineered to last at least up to 10,000 years or minimum 200 years as recommended by the U.S. EPA or the recommended time from the Greenland authorities (see Chapter 9).

Below-ground disposal

Below-ground disposal includes disposal of tailings in the mined out pit or backfilling of an underground mine. The numerous advantages of below-ground disposal compared with conventional tailings dam disposal are that it:

- Reduces the amount of land needed for tailings storage.
- Provides high long-term security for the isolation of tailings. It eliminates the potential for catastrophic failure of the containment, provided that the underground or mined out pits have no drainage adits exiting to the surface, or such openings are plugged with high degrees of reliability.
- Reduces significantly the potential for erosion and dispersion of the tailings pile, even in the long term.
- Places the tailings into a geological situation similar to conditions prior to mining.
- Allows thick capping with benign materials ensuring radiation safety (Moldovan et al., 2008) by isolating the tailings from the surface.

Examples of tailings disposal in mined out pits include: Ranger mine, Australia; Nabarlek mine, Australia; Rabbit Lake, Canada; Key Lake, Canada, etc. Many of the mined out pits are located below the water table and prevention of groundwater contamination must be considered. Placing consolidated and reactive waste tailings underwater in a lower oxygen environment remains a preferable option, especially in cases where sulphidic tailings, ARD waste rock, or residual wall rock can become a significant issue.

In fact, placing tailings into pits under 3-5 m of water cover is particularly effective in cold weather climates, as it avoids segregation, consolidates faster, avoids frozen layers of tailings completely, minimizes radon, is perfect shielding for gamma radiation, and speeds up the efficiency of decommissioning the tailings management facility.

Deep lake disposal

Due to environmental and economic issues, this method is no longer a preferred option for uranium mill tailings disposal.

6.3.3 Methods for stabilizing and isolating uranium mill tailings

The containment design for tailings may not suffice to provide a high level of certainty that the tailings will remain isolated from the environment for an undetermined period of time. Thus, a number of processes are needed to ensure the long-term effectiveness of the containment. This may include containment preparation, tailings preparation, tailings discharge and deposition, tailings consolidation, tailings surface treatment, decant water treatment, seepage control and covers.

Tailings containment preparation

Above-ground containment preparation involves work to reduce the permeability of the tailings structure in order to avoid groundwater contamination. Thus, the floor and the walls of a tailings facility have to be sealed with, for example, a low permeability membrane or a clay layer in order to avoid seepage and thus groundwater contamination. Permeability may also be reduced by the addition of more tailings and thus compaction under their own weight. In this case, seepage may remain at the same rate since the head also increases as more tailings are added.

The most common applied techniques to reduce the permeability of below-ground containments are rock grouting into fracture zones, lining of porous faces with impermeable membranes or application of a low permeability layer. Another technique involves the construction of a highly permeable surround placed around the outside of the tailings mass. This allows the groundwater flow to pass preferentially through the surround instead of the much less permeable tailings, thereby reducing the source term to a diffusion-controlled process (Fig. 6.3.3). As an example, Ranger mine has a partial previous gravel blanket at the base of the tailings mass. Water is drawn from the gravel bed via an adit and well pump and is returned to the decant pond above the tailings, thus achieving the settlement density of >1.2 g / cm3 required by Australian regulation (IAEA, 2004).

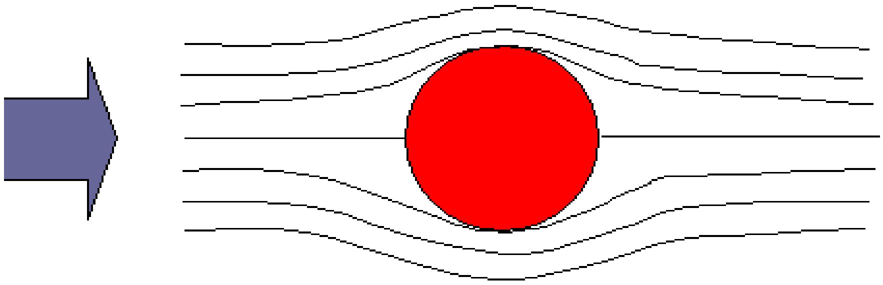


Figure 6.3.3. The concept of 'pervious surround' where groundwater preferentially flows around a tailings mass due to a highly permeable surrounding layer. Source: SENES, ARCADIS, 2014.

Tailings preparation

If the tailings are not treated before final disposal, radium-226, polonium-210, lead-210, thorium and uranium isotopes (if not totally extracted in the hydrometallurgical process) and non-radioactive contaminants are principal constituents of concern of the tailings. It is a common practice to treat the tailings prior to and after disposal with the main aim to remove and / or stabilize radioactive and non-radioactive contaminants within the tailings.

Active and passive treatment methods of the tailings may include but are not limited to segregation, decontamination, containment, volume reduction, chemical adjustment, removal of radionuclides and non-radioactive contaminants from the waste, and change of composition. Neutralization of acidic tailings, removal of radium and lead and non-radioactive contaminants (e.g. heavy metals), and stabilization (by pH adjustment) of thorium, if present in the tailings, are common treatment methods that are widely used at uranium mine sites. Physical treatment methods such as thickening of the tailings under controlled conditions are used to reduce grain-size segregation during disposal.

Tailings discharge and deposition

Physical stability of tailings impoundments and potential tailings flow behaviour in the event of an embankment failure may be determined by the tailings discharge method. The selected method for tailings discharge strongly affects the grain-size segregation and the final tailings density. Denser tailings will: (1) have a lower permeability, reducing the release of contaminants into the surrounding water systems, (2) allow more tailings to fit into the available space and (3) do not require an intensive dewatering process in the rehabilitation phase of a mine project.

Physical stability of the impoundment can be achieved by, for example, isolating the coarse fraction of the tailings. The coarse fraction may be cycloned out or tailings may be discharged from spigots, allowing the tailings to form and then flow down a slope (the coarse fraction settles first, closer to the spigots to form a beach). In the case of above-ground disposal, the spigots are usually placed along the inner top side of the embankment so that the coarser fraction tailings build up adjacent to the embankment, with the slimes settling out in the centre of the dam, thus improving the stability of the impoundment.

Tailings consolidation

The main mechanism to achieve consolidation of tailings is their dewatering. Dewatering can be undertaken prior to and after discharge into the tailings containment. A review of different dewatering techniques, including in situ techniques, is given in IAEA 2004.

For impoundments constructed without an under-drain gravity system, a single-well or a multiple well system with variable pumping positions may be used for tailings dewatering (Wardell, 1984). Dewatering during the operational phase reduces also the need for post closure dewatering prior to placement of a solid cover.

Tailings surface treatment

During the operation phase, treatment of the surface of tailings is required in order to reduce radon flux, reduce gamma radiation, reduce the generation of fugitive dust, improve erosion resistance or reduce water seepage prior to final covering of the tailings.

Examples of treatments of tailings surfaces include but are not limited to: (1) water cover of the tailings or continuous wetting of the tailings surface, (2) application of sealants or stabilizing agents.

For the water cover method, specific requirements have to be put in place in order to avoid possible instability of embankments as a consequence of wave erosion or high phreatic surfaces leading to piping or seepage through the walls.

Decant water treatment

Decant water, for instance water derived from overtopping, breaks in pumping lines or failure of the drainage system, may contain most of the contaminants in the tailings. It may readily escape to the environment and should be collected and either sent to water treatment facilities, and after this released into the environment, or returned to the mill as part of the take-up water, to reduce the draw on uncontaminated water.

Seepage control

The design of tailings impoundments has to include installation of seepage collectors and passive treatment systems. Long-term passive treatment (e.g. permeable reactive liners and barriers) is a committed cost that will be incurred in the future.

At the Key Lake uranium mine in Canada, a seepage collection is engineered into the tailings facility structure through placement of a filter blanket under the tailings pile. Seepage water is expelled into the filter as a result of increasing overburden pressures and hydrostatic head as the tailings pile gets thicker. The seepage is then pumped to the waste treatment circuit for treatment (Clifton, 1984).

Dry cover of tailings facility

Dry covers are designed and applied over the tailings facilities during the rehabilitation phase of the mine and address geotechnical, radiological, hydrological, geochemical, ecological and aesthetic requirements.

In general, covers comprise multiple layers such as, for example, clay layers, coarse materials, vegetative covers, etc. Clay layers are typically used to control radon emanation and water infiltration. Coarse materials are used as drainage layer and to discourage animal and human intrusion. Vegetative covers are used to control wind- and water-induced erosion and moisture infiltration.

The dry cover installed on uranium tailings facilities should minimize radon and dust emission, shield the environment from gamma radiation, minimize water and oxygen infiltration and control erosion.

Factors to be taken into account when designing dry covers include:

- Cover longevity – the dry covers should be engineered to last 200–10,000 years. Erosion can be prevented by use of riprap or cohesive clay layers and development of vegetation covers. Vegetation covers provide good protection against erosion.
- Sealing and shielding:
    - Gamma ray shielding can generally be achieved with a 0.5 m soil layer.
    - Dust can be controlled by applying a vegetative cover based on an adequate soil layer as a plant growth substrate.
    - Potential fugitive dust generation may be eliminated by using a rock cover.
    - Radon emanation is usually controlled by the application of a compacted clay layer and a relatively thin layer of compacted soil. Modelling of radon diffusion may help to select the relevant design parameters and material properties.
    - Freeze / thaw cycle effects on dry cover long-term performance may warrant careful investigation. Multiple layers above the sealing layer (at least 1.5 m thick), acting as a 'sponge' and adapting to weather cycles, may be required. This layer prevents the drying-out of any sealing clay layers. Drying cracks in the sealing layers would compromise their retaining capabilities for gases and infiltrating waters.
- Water and gas infiltration – Infiltration of precipitation (rain and snow) may be prevented by proper design of the sealing layer (sealing material, moisture and density of the material at placement and placement techniques). Usually, saturated hydraulic conductivity specified for sealing layers is of the order 10^{-9} m / s. Prevention of infiltration of oxygen into tailings is required since this will result in oxidation reactions that could lead to acid generation and, hence, mobilization of contaminants.
- Bio-intrusion prevention. Protection of the integrity of the sealing layers against burrowing animals or deep roots that can penetrate the sealing layer, resulting in loss of functional integrity, has to be considered. Covering layers can be made thick enough and layers of riprap introduced to discourage burrowing animals. Such a layer, if sufficiently thick, also discourages humans from digging up the tailings material.
- Potential failure mechanisms. Possible causes of cover failure include differential settlement, desiccation cracks, bioturbation, root penetration, human and animal intrusion, extreme weather events and changes in the design base (e.g. climate changes).

The advantages and disadvantages of the different uranium tailings containments and methods for stabilizing and isolating uranium mill tailings are given in Appendix I.

Tailings monitoring

A waste monitoring programme needs to be implemented at the mine site. The waste monitoring should be carried out by the mining company on a daily basis.

The waste monitoring program may include but should not be limited to:

- Measurements of radon emanation.
- Measurements of contaminants in the water cover and pore water.
- Piezometric measurements of seepage and internal erosion of tailings dams.
- Control of seepage and runoff from waste rock.
- Prevention and detection of leaks from tailings pipelines.
- Monitoring of gamma radiation levels.

6.4 TSF Acute and chronic failure events

For the great majority of uranium mining and milling activities, uranium mill tailings are the greatest potential source of environmental pollution. Potential environmental impacts related to uranium mill tailings are radon emanation, windblown dust dispersal, AMD and leaching of contaminants such as radionuclides and heavy metals into water bodies by acute and chronic failure events. Release of contaminants to water systems and or the environment may be due to acute and chronic failure (Knapp et al., 2002; Gatzweiler, 2000; Pettersson et al., 1988).

Acute events are defined as physical failure of the containment structure. Containment failure can be triggered by:

- Physical weakness of the embankment, leading to breaching.
- Geotechnical instability caused by slope and settlement failure.
- Wind and water erosion (heavy rain or adjacent waterway) mainly affects above-ground tailings containments and waste piles and are less likely to occur in below-ground waste management facilities.
- Spillway caused by heavy overflow of slurry or decants effluent after heavy rain.
- Extreme events such as earthquakes, floods and severe storms, potentially leading to overtopping, etc.

Chronic events may include but are not limited to:

- Radon release and radioactive dust dispersion when the surface of the tailings dries out and dust is dispersed by wind.
- Erosion of tailings from outer surfaces of the containment.
- Effluent discharge as decant leading to draining or overflowing from the tailings containment into the environment. This can be minimized by controlled discharges of treated effluents into the environment (see 7.6 of this report) or recycling of treated effluents to the mine and mill processes and by proper site selection and engineering so as to control the inflow of freshwater to the mine or mill, as well as to the waste management facilities (IAEA, 1992, 1999).
- Seepage through the floor or/and walls of containments with no seal or seepage collection system in the base into surface water or groundwater.
- Spills during the transport of tailings or mine waste. Slurry tailings are transported from the mill to the tailings containment through pipes that may be several kilometres long and leaks may occur from connections and joints. Dry mine waste may be transported by truck or conveyor. If the material transported by truck is not properly covered, it can be released to the environment. Conveyor systems have a potential to lose material from the belts, especially at turns or belt interfaces.

The various causes of tailings dam failures (e.g. acute events and chronic events) for 199 incidents are given in Figure 6.4.1

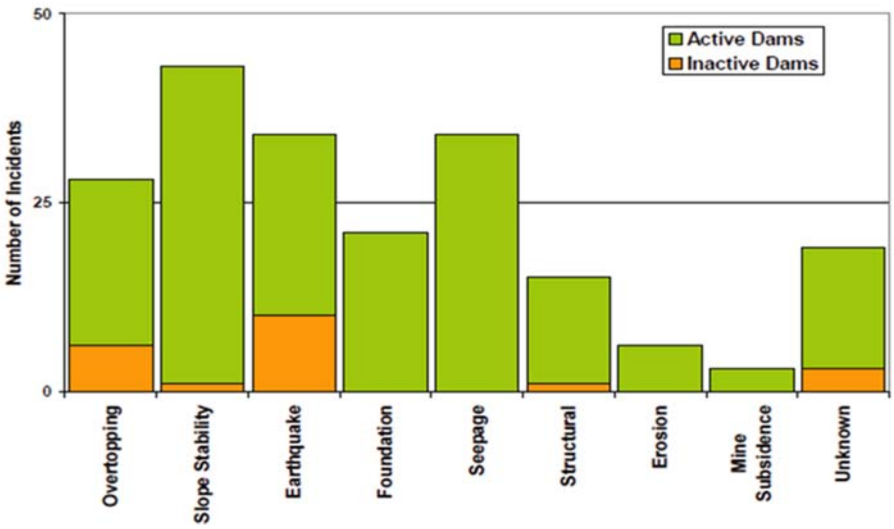


Figure 6.4.1. A total of 199 tailings dam failures classified by cause of failure and active/inactive (closed) facility. Source: IAEA (2004).

6.5 Waste rock or overburden

Rocks enclosing uranium ores possessing no or sub-economic amounts of uranium minerals or other minerals are referred to as waste rock.

Depending on the mineral ore, the waste rock often produced in significant quantities (open-pit mining) can be a valuable byproduct, but it may also be a significant source of pollution (e.g. metals and radionuclides leached and released to environment as acid / alkaline mine drainage).

Clean waste rock, i.e. waste rock which does not contain radioactive or non-radioactive toxic pollutants, can be used for construction of embankments on the mine site, for roads and buildings or as a cement additive.

Some of the waste rock may have variable radionuclide concentrations as well as other non-radioactive pollutants.

Waste rock containing sulphides (even at very low concentrations) can oxidize and release heavy metals and radionuclides. Also waste rock associated with oxide ore (cassiterite, chromite, hematite, ilmenite, magnetite and uraninite deposits) has the potential to release contaminants (IAEA, 2009) to the environment. These materials are typically placed in waste rock piles located close to the mine pit. Properly prepared sites address the risk that using such sites might result in infiltration of rainwater through the rock piles leaching out radioactive chemicals from below-grade ore and potentially resulting in uncontrolled movement of contaminants into the environment. Physical separation of waste from natural topsoil and vegetation can be engineered using constructed bases. The engineered base can also be designed to control the infiltration of water, minerals and chemicals that may otherwise find their way into the surrounding environment. Some of the requirements (liners, seepage collectors systems, etc.) mentioned for tailings management are also applied to waste rock disposal and management.

The waste rock can be either waste that may produce AMD, due to the presence of sulphides, or it may be clean or stable waste that can be placed on the surface without special consideration. AMD waste is commonly stored on an engineered pad to control water drainage and is either returned to the mine as backfill or placed in an open containment pit at the end of mining. Such a containment pit may also have an engineered cover to prevent influx of water and oxygen to reduce the risk of acid mine water runoff.

In the typical situation, the site of the waste piles would have been extensively drilled to confirm that there are no potential mineral resources beneath the site of the waste pile. In Australia, accepted good practice is to cap and grout the drill holes in and beneath the rock pile footprint, to reduce the potential for infiltrated waters into the rock piles entering the ground beneath the pile, or into groundwater (AUA, 2013).

The engineering and rehabilitation standards applied to waste rock piles need to assure their long-term physical stability and low susceptibility to long-term leaching.

6.6 Heap leach residues

Uranium can be removed from low-grade ore using heap leaching. The leaching solution is sprayed on top of the pile. The leaching solution percolates until it reaches a liner below the pile where it is caught and pumped to a processing plant.

Together with waste rock piles, tailings and heap leach piles represent a possible hazard because of potential release of dust, radon and seepage waters. If the waste rock, tailings and heap leach piles are sulphidic, there may be a potential for AMD development in the long term.

6.7 Requirements for the RWMP

The RWMP is an integral part of a project and should be developed at the inception of the project to provide proper management of radioactive waste arising from the operations.

Before the commencement of mining and mineral processing operations, the RWMP must be submitted to the authorities for approval. The plan must be directed towards the best practicable technology and take into account all relevant pathways for dispersion of radionuclides and for radiation exposure of employees and members of the public.

The RWMP should be developed simultaneously with the Radiation Management Plan (Chapter 5) and with the decommissioning plan (Chapter 9).

Optimization of handling, treatment, storage and disposal of radioactive waste should be the outcome of the RWMP. The RWMP should be updated as the project progresses through the various stages of the mine life (including temporary suspension of operation) and be able to cope with any unforeseen emergency.

The RWMP should include:

- An initial impact (safety) assessment.
- An outline of the processes (main components of operation) generating waste, annual rates of generation and volumes that will be generated and health and environmental risk(s) associated with waste management.

Characterization of waste including, for example, chemical composition, physical state (solid, liquid or solid-liquid mixture) and radiological properties (radionuclide composition, activity concentrations and mobility-related parameters such as leaching potential), contaminants and production quantities and rate. Non-radioactive contaminants present in the original ore as well as flotation and processing chemicals to remain with the tailings should also be included.

- A description of the environment (climate, terrain (geomorphology, geohydrology and geochemistry), soils and vegetation, and hydrology) into which the waste will be discharged or disposed, including the baseline radiological characteristics.
- A description of the proposed system for solid and liquid waste management including the facilities (consider also physical location) and procedures involved in the handling, treatment, storage and disposal of radioactive waste.
- Prediction of environmental concentrations of radionuclides, critical group, members of the public and occupational dose assessments, including demonstration that the radiation protection requirements set by the relevant regulatory authority are met.
- Occupational, members of the public, equipment and geotechnical monitoring (including external and internal audit), surveillance and reporting, assessment and review of the integrity of the facility.
- An environmental monitoring programme for radioactive and non-radioactive contaminants and dose assessment for employees and members of the public. The radioactive monitoring programme should include also monitoring of discharges (including seepage) from the mine site (liquid, solid and gaseous) to the receiving environment.
- Contingency plans for dealing with accidental releases such as spills from equipment failures or operational failures and circumstances (natural events) that might lead to uncontrolled release of radioactive waste to the environment.
- Contingency plans to cover the cases of early shutdown or temporary suspension of operations.
- A schedule for reports on waste disposal operations and results of monitoring and assessments.
- A plan for decommissioning and rehabilitation of the site, including proposed decommissioning / rehabilitation outcomes, activities, schedule and cost estimates.
- A system of periodic assessment and review of the adequacy and effectiveness of procedures instituted under the Radioactive Waste Management Plan to ensure currency and to take account of potential improvements consistent with best practicable technology.
- Heritage (social and cultural) and land use (present, potential and future).
- Post-operational practices: temporary suspension of operations, decommissioning, closure, decontamination, rehabilitation, monitoring, (long-term) surveillance and reporting, records management, and institutional control and land use.
- Demonstration that requirements will be met both now and in the future.
- Periodic assessment and review of the activities, including waste management.
- Waste monitoring programme (erosion, seepage control).

The RWMP should be revised if there are significant changes in mine operations or as a result of findings in the monitoring and surveillance programmes. All changes to the RWMP need to be approved by the relevant regulatory authority.

The operator must notify the authorities of:

- Any changes in mine operations that may impact the quantity, chemical, physical and radiological properties of the generated waste.
- Any changes in waste management (change of disposal facility, etc.).
- Any unforeseen events that may affect the approved RWMP.

Best practicable technology is that technology available from time to time, and relevant to the project in question, which produces the minimum occupational doses, member-of-public doses both now and in the future, and the minimum environmental impact that can be reasonably achieved, economic and social factors taken into account. This practice considered in other countries (e.g. Australia, USA) is the best in terms of environmental standards for uranium mining and milling.

Best practicable technology factors when developing the RWMP in order to minimize potential environmental impact include:

- The level of effluent discharges control achieved and the extent to which environmental pollution and degradation are prevented in similar mining, milling and mineral processing operations anywhere in the world.
- The total cost of the application or adoption of that technology relative to the environmental protection (e.g. tailings disposal method, dust suppression technology, water management) to be achieved by its application or adoption, cost of applying the control technology in relation to the waste reduction benefits.
- Evidence of impact, or lack of impact, on the environment after the commencement of the project in question.
- The physical location of the project in question.
- The age of equipment in use on the project site in question and its relative effectiveness in reducing environmental pollution and degradation (intention to periodically review waste management technology).

6.8 Other general requirements for managing mine waste

Waste rock and tailings management shall:

- Maximize the use of mine workings, such as development of former open pits into deposits of tailings and waste rock.
- Maximize the use of engineered and / or natural barriers between the waste materials and the environment.
- Maximize the use of controls designed to minimize release to the environment.
- Take due consideration of the characteristics of the mineralized waste rock or tailings and best management practices.
- Ensure long-term protection of terrestrial, aquatic and marine environments as well as protection of current and future generations.
- Ensure that the design of waste rock and tailings management systems minimizes the active institutional controls post decommissioning.
- Avoid the use of natural water bodies frequented by fish in the long-term management of waste rock and tailings.

6.9 References

Abdelouas, A., Lutze, W., Nuttall, H.E., 1999. Uranium contamination in the subsurface: characterization and remediation. In: Burns P. C., Finch R. (eds) Uranium: mineralogy, geochemistry and the environment, vol. 38. Mineralogical Society of America, Washington, D.C., pp. 433-473 (Reviews in mineralogy and geochemistry).

AUA (Australian Uranium Association), 2013. Uranium Tailings long term management principles.
http://www.aua.org.au/DisplayFile.aspx?FileID=171

Clifton, A.W., Barsi, R.G., Melis, L.A., 1984. Uranium mill tailings management practices in Saskatchewan, Canada. Proceedings, Sixth symposium on uranium mill tailings management, Fort Collins, Colorado, 1–3 February 1984. Colorado State University.

Gatzweiler, R., 2000. Remediation of former uranium mining and milling facilities in Germany – the Wismut experience. Internat. Symp. on Restoration of environments with radioactive residues, Arlington, Virginia, 29 November - 3 December 1999, International Atomic Energy Agency IAEA-SM-359/3D.5, Vienna_477-501.

IAEA, 1992. Current Practices for the Management and Confinement of Uranium Mill Tailings, Technical Reports Series No. 335, IAEA, Vienna.

IAEA, 1999. Technical Options for the Remediation of Contaminated Groundwater, IAEA-TECDOC-1088, Vienna.

IAEA, 2002. The Management of Radioactive Waste from the Mining and Milling of Ores. Safety Standards Series No. WS-G1.2, IAEA, Vienna.

IAEA, 2004. The long term stabilization of uranium mill tailings. IAEA-TECDOC-1403, IAEA, Vienna.

IAEA, 2009. Establishment of uranium mining and processing operations in the context of sustainable development, Nuclear Energy Series No. NF-T1.1, IAEA, Vienna.

Knapp, R.B., Richardson, J.H., Rosenbuerg, N., Smith, D.K., Tompson, A.F.B., Sarnogoev, A., Duisebayev, B., Janecky, D., 2002. Radioactive tailings issues in Kyrgyzstan and Kazakhstan. 9th Internat. Conf. on Tailings and Mine Waste, Fort Collins, Colorado 27-30 January 2002, AA Balkema, Lisse.

Landa, E.R., 1999. Geochemical and biogeochemical controls on element mobility in and around uranium mill tailings. In: Filipek, L.H., Plumlee, G.S. (eds) The environmental geochemistry of mineral deposits. Part B: case studies and research topics, vol 6B. Society of Economic Geologists, Littleton, pp. 527-538 (Reviews in economic geology).

Landa, E.R., Gray J.R., 1995. US Geological Survey research on the environmental fate of uranium mining and milling wastes. Environ. Geol. 26: 19-31.

Lottermoser, B.G., 2010. Radioactive Wastes of Uranium Ores. In Mine Wastes, pp. 263-312. Springer Berlin Heidelberg.

Mahoney, J., Slaughter, M., Langmuir, D., Rowson, J., 2007. Control of As and Ni releases from a uranium mill tailings neutralization circuit: Solution chemistry, mineralogy and geochemical modeling of laboratory study results. Applied Geochemistry 22 (2007) 2758–2776.

Moldovan, B.J., Hendry, M.J., Harrington G.A., 2008. The arsenic source term for an in-pit uranium mine tailings facility and its long-term impact on the regional groundwater. Appl. Geochem. 23: 1437-1450.

OECD (Organization for Economic Cooperation and Development), 1999. Environmental activities in uranium mining and milling. Joint report by the OECD Nuclear Energy Agency and the International Atomic Energy Agency. OECD Publications, Paris.

Pettersson, H.B.L., Hallstadius, R.H., Holm, E., 1988. Radioecology in the vicinity of prospected uranium mining sites in a subarctic environment. J. Environ. Radioact. 6: 25-40.

Pichler, T., Hendry, M.J., Hall, G., 2001. The mineralogy of arsenic in uranium mine tailings at the Rabbit Lake in-pit facility, northern Saskatchewan, Canada. Environ. Geol. 40: 495-506.

SENES Consultants Limited, and Alberta, 2008. Environmental impacts of different uranium mining processes. Edmonton, Alta: Alberta Environment.

SENES, ARCADIS, 2014. Workshop on Uranium Best Practice: The Environment, Safeguards and Security Narsarsuaq and Narsaq, Greenland, 10 – 17 June 2014.

Shaw S.A., Hendry M. J., 2009. Geochemical and mineralogical impacts of H2SO4 on clays between pH 5.0 and -3.0. Appl. Geochem. 24: 333-345.

U.S. EPA (U.S. Environmental Protection Agency), 1995. Extraction and beneficiation of ores and minerals. Volume 5: Uranium. EPA 530-R-94-032 Washington, DC, U.S. EPA, January 1995.

U.S. EPA (U.S. Environmental Protection Agency), 2006. Technologically Enhanced Naturally Occurring Radioactive Materials from Uranium Mining. Volume 1: Mining and Reclamation Background. EPA 402R-05-007 Washington, DC: Revised June 2007.

Wardell, R.E., Nelson, J.D., ABT, S.R., STAUB, W.P., 1984. Review of in situ dewatering and consolidation of uranium mill tailings. 6th symposium on uranium mill tailings management, Fort Collins, Colorado, 1–3 February 1984, Colorado State University.

7 Environmental and radioactive effluents (source) monitoring at uranium mine sites

7.1 Introduction

In order to facilitate the decision-making process at all levels regarding environmental matters, there is a need for development of a clear and reliable environmental and effluent monitoring programme and data and results assessments shall be available and transparent for the public.

The results from the monitoring programme are used, among other purposes, to:

- Establish baseline data to aid in the evaluation of the decommissioning process and site decontamination in case of a release in case of a radiological event.
- Confirm that the preventive and mitigating methods applied at a mine site are suitable,
- Ensure that regulatory requirements (annual effective dose limits, authorized limits on discharges for airborne and liquid discharges and the ‘as low as reasonably achievable’ concept) are met.
- Evaluate the performance of effluent control and effluent treatment.
- Identify possible trends and adverse effects, including also long-term effects on human health and safety, biota and all environmental ecosystems (e.g. land, water and air) as a result of the proposed mining activities, both during operations and decommissioning.
- Provide early warning of any deviations from normal authorized operation.
- Provide information for the public.

Environmental radioactivity monitoring programmes include radiation surveys and radionuclide concentrations in effluents and environmental samples (air, land and water, human and non-human biota). Usually, the environmental monitoring programme comprises an automatic (online) monitoring network system and laboratory-based monitoring of air, land, water and human and non-human biota.

Monitoring activities should include baseline studies (characterization of the environment and baseline monitoring) performed during the exploration activities, environmental monitoring during construction, operation, decommissioning, rehabilitation and long-term surveillance, monitoring of the approved emissions and discharges from mine site and their effects on the receiving environment such as any change that an activity, substance, equipment and facility may have on the environment. Monitoring of the emissions and discharges from a mine site should be performed during exploration, construction, operation decommissioning and rehabilitation.

In relation to monitoring of the environment and effluents and control of discharge practices, the operator should report to the regulatory body any significant changes in releases or increases in environmental radiation fields or contamination that could be attributed to releases from the site. The operator shall report to the regulatory body any changes to the discharge practice (IAEA 2005).

The design of a radiological effluent and environmental monitoring programme at the uranium mine site is based on a site-specific safety assessment and risk analysis and the following factors have to be considered:

- Specific monitoring requirements and limits (authorized discharge limits and discharge rates) established by relevant authorities.
- The existing environment (e.g. receptors such as human and non-human biota, meteorological conditions, design of the facilities, tailings management, the off-site environment, the population distribution, regulatory requirements, etc.).
- Pathways that may contribute to radiological or chemical toxicity exposure. A radioactive inventory of radionuclide composition and non-radiological contaminants at the source.
- Tailings and other mine waste management implemented at the site should consider also an unplanned disaster that results in significant release of contaminants to the environment.
- The annual average doses of the critical group(s) and the environmental radiation levels from planned radioactive releases and possible releases.

The monitoring programme should be conducted both on and outside the site and include:

- Parameters to be monitored (e.g. full assessment of the non-radioactive contaminants and specific radionuclides presented in Table 7.2.1).
- Representative sampling sites and samples.
- Sampling procedures.
- Frequency.
- Sample transport and storage.
- Sample pre-treatment and methods of analysis (radiochemical and radiometric).
- Data assessment and data management (best practice in environmental data management).
- Quality assurance (QA) and Quality Control (QC) (including also quality of samples (representative samples, sampling frequency), the analytical laboratory should be accredited, measurements should be traceable to international standards, inter-comparison of measurements, record keeping, reporting procedures, calibrations of sampling instruments and analysis methods, calibration of measuring instruments, lower limit of detection, precision and accuracy of results, quality of results). Information related to QA is covered in Section 4.5.
- Implementation of QA and QC.
- Procedures for recording and reporting the results (weekly, monthly, quarterly and annual reports).
- Environmental training programmes for employees.

Sampling locations and frequencies

Sampling locations and frequencies of measurements are site and project specific and usually depend on:

- Expected variations and types of release (e.g. aerosols, gases and liquids).
- Stressors such as radionuclides and non-radiological contaminants.
- Dispersion pattern of the discharges, including background areas.
- Pathway monitoring.
- Habits and consumption patterns of the critical group of the population.

- Likelihood that unplanned discharges would require prompt detection and notification.

Monitoring results data permit analysis and evaluation of human and non-human biota radiation and toxicity exposure. Due to this, programmes for monitoring of radionuclides and non-radioactive contaminants in the environment are usually focused on pathways of biota exposure.

An **exposure pathway** defines routes from a source of radionuclides and / or radiation and non-radioactive contaminants to a target individual or a population through media in the environment. There are two main categories of exposure pathways: the external exposure pathway where radiation and / or radionuclides and non-radioactive contaminants remain outside the body and the internal exposure pathway where the radiation and / or radionuclides and non-radiological contaminants are incorporated into the body.

Main external exposure pathways are: (1) direct exposure from a source of ionizing radiation, (2) exposure due to the plume of radionuclides / non-radioactive contaminants in the atmosphere or water, (3) contact exposure from radionuclides / non-radioactive contaminants on the skin and (4) exposure from the radionuclides / non-radioactive contaminants deposited on the ground or on sediments (on the shores of rivers, lakes or the sea) or building surfaces (walls, roofs and floors) or vegetation (trees, bushes and grass).

Main internal exposure pathways are: (1) inhalation of radionuclides / non-radioactive contaminants in the plume, (2) ingestion of radionuclides / non-radioactive contaminants in food or drinks and (3) inhalation of resuspended radionuclides / non-radioactive contaminants.

Environmental pathways by which human and non-human biota may be exposed to radiation may be generalized as:

- Atmospheric pathways that can give rise to doses due to radon and its progeny and airborne radioactive / non-radioactive particles.
- Atmospheric and terrestrial pathways that can give rise to doses resulting from external radiation exposure and / or ingestion (transfer from to) of contaminated soil and food.
- Aquatic pathways that can give rise to doses from ingestion of contaminated water, foods produced using contaminated irrigation water, fish and other aquatic biota and foods derived from animals drinking contaminated water and from external radiation.

The importance of the exposure pathways depends on:

- Radiological properties and chemical toxicity of the material released (e.g. gamma emitters, beta emitters or alpha emitters, physical half-life, toxicity).
- Physical properties (e.g. gas, liquid or solid, particle size).
- Chemical (e.g. organic or inorganic form, oxidation state, speciation, etc.) properties of the material.
- Behaviour such as migration characteristics of radionuclides.
- Environmental factors (e.g. meteorological conditions, type of biota).
- Locations, distances, ages, diets and habits of the exposed individuals or population.

Under conditions of normal discharges (see 7.6), the exposure pathways are usually permanent and well defined.

Environmental sampling locations are site and project specific, usually being selected close to points where the maximum exposure or deposition is expected, preferentially in the main wind direction for airborne discharges or downstream from the release point for aquatic discharges and at the site boundary for direct radiation from the source (effluents release). The sampling should be performed at the same station / location every time. Monitoring locations should also be related to the potential changes in exposure pathways and changes in radionuclides / non-radioactive contaminant levels in the environment. The sampling grid depends also on site conditions. Four transects at 90^0 are often established, one should be established in the predominant wind direction. The spacing between sampling sites is close (a few tens of metres) near the proposed operations and greater (up to 5 km) at the site boundaries and beyond.

A smaller grid, for example 30 m, may be necessary on proposed ore stock piles and waste rock and tailings facilities, processing sites and ore transport routes. Nearby towns may also be sampled on the smaller grid to provide the necessary data and degree of confidence for radiation dose assessment. Additional environmental sampling and / or measurements should be conducted regularly in nearby towns as well as in background areas (upwind or upstream of the source).

Representative samples should be selected and should reflect the conditions in the environment from which they are taken. Specific requirements for taking representative samples have been suggested by the International Commission on Radiation Units and Measurements (ICRU 1996).

The sampling frequency depends on the levels of radionuclides / non-radioactive contaminants in the environment to be monitored, the monitoring precision that is required, the time and space dependence and the variability of the quantity to be measured. Usually, sampling is more frequent in areas where radiation conditions are close to intervention levels or action levels. Sampling should also be more frequent for monitoring with increasing spatial and temporal variability of radionuclides / non-radioactive contaminants concentration, including monitoring of radionuclides with short half-lives.

Monitoring results data have associated uncertainties that arise from technical uncertainties (e.g. spatial and temporal variability of the quantity monitored, uncertainties from procedures for sampling, processing and measurement), the non-representativeness of samples and / or measurements and human errors. Monitoring uncertainties should be determined taking into account uncertainties from sampling and measurement procedures, including the uncertainties in sample processing parameters and equipment calibration, and they should be reported together with the monitoring results.

Environmental monitoring should be performed during all mine phases and should include pre-operational, operational, decommissioning and rehabilitation phases as well as long-term monitoring. A specific monitoring programme for a worst case scenario, such as a radiological event, should also be developed.

The monitoring programme should be reviewed periodically and reflect any change during the lifetime of the mining and milling operations, such as ,for example, changes in waste management practices or environmental conditions, potential receptors and exposure pathways or changes in regulatory requirements. Prior to the mining and milling operations, a baseline programme should be prepared as described in Guidelines for Preparing an Environmental Impact Assessment (EIA) report for mineral exploitation in Greenland (in work) to establish the natural conditions (radioactive and non-radioactive contaminants and different parameters) in the area of concern and enable a subsequent evaluation of the impacts of the mining and milling activities. Baseline studies should include topographical surveys, radiation and radionuclide surveys in all environmental ecosystems, an assessment of soil types on the surface and at depth, biota diversity and distribution.

Records management and reporting

Records for sampling and analysis results should comprise but not be limited to:

- Location of sample.
- Date of sample collection and of sample analysis.
- Type of sample (e.g. air, stack samples, liquid samples (ground and surface water)), other samples such as vegetation, soil, gamma exposures rate, radon, thoron and their progeny flux.
- The concentration of uranium and thorium series radionuclides for all samples, including effluent stack samples, gamma exposure rate radon, thoron and their progeny flux, etc.
- Estimated release rate of natural uranium and thorium and their radionuclide series for stack effluent samples.

As part of the ongoing license coordination, operators are required to submit reports to the appropriate regulatory bodies. Reporting includes but is not limited to: (1) routine and ongoing reports associated with monitoring (quarterly and annually), (2) incidents that trigger legislative requirements and (3) compliance statements. The following information must be included in each environmental monitoring report:

- Name of facility, location and license number.
- Criteria for sampling locations chosen.
- Type of sample.
- Sampling procedure including a description of sampling equipment, sampling frequency and sample volume.
- Dates during which samples are collected.
- Description of applied radio / analytical methods.
- Results assessment.
- Explanation of random and systematic error estimates, including methods of calculation.
- QA and QC.

The reports including the results of the effluents (both liquid and gaseous) monitoring must include:

- Type of sample (gaseous and liquid).
- Sampling location.
- Period or date(s) during which samples are collected.

- Quantities, average concentrations and total estimated analytical uncertainty.
- Estimate of the exposure for the critical group of members of the public.
- Sampling procedure including a description of sampling equipment, sampling frequency and sample volume.
- Description of radio / analytical and radiometric methods used.
- Description of calculation methods (e.g. concentrations of radionuclides, systematic uncertainties, minimum detectable concentration).
- QA and QC.
- Any incidents causing irregular release, including the circumstances of the release and any data available on the quantities of radionuclides released.

The results from environmental and effluents monitoring programs are usually summarized quarterly and reported semi-annually to regulatory bodies.

Quality assurance

Quality assurance (QA) (ISO 14001, ISO 14004, ISO / IEC 17025-2005, ANSI / ASQC E4-1994, ANSI N42.23-2003, EPA QA / G-9S-2006) of the environmental monitoring programme should comprise all planned and systematic actions that are necessary to ensure the quality of monitoring results (e.g. that all radiological and non-radiological measurements supporting the radiological monitoring programme are reasonably valid and of a defined quality) and that random and systematic uncertainties are kept at a minimum. The QA programme of each organization performing radiological effluents and environmental monitoring should be documented by written policies and procedures.

Elements that should be developed and implemented to ensure the quality of data / results for radiological effluent and environmental monitoring programmes are:

- Organizational structure and responsibilities of managerial and operational personnel, levels of authority and interfaces for those managing, performing and assessing the adequacy of work.
- Management measures, including planning, scheduling and resource considerations.
- Qualifications of personnel, education and training.
- Standard operating procedures and instructions.
- QC of the sampling instruments, radio / analytical and radiometric methods, equipment, laboratory tools, internal quality control samples and analysis, inter-laboratory comparisons.
- QC for radioactive effluents monitoring systems, including, for instance, radioactive effluent process monitors, flow monitoring instrumentation and grab sampling of effluent process streams.
- Sampling, sample receipt, storage and disposal, sample analysis, reporting of results.
- Internal quality control samples and analysis.
- Performance evaluation programme (Inter-laboratory Comparison).
- Precision and accuracy of results.
- Records.
- Assessments, audits, and surveillance.
- Preventive and corrective actions.
- Implementation system of QA and QC.

The monitoring programme should include QA (e.g. effluent stack samples, representative environmental samples collected using proper sampling equipment, proper sampling locations, proper sampling procedures, shipment of samples, receipt of samples in the laboratory, preparation of samples, radiological measurements, duplicate analysis of selected samples and periodic inter-comparison test with independent laboratories, data evaluation and reporting of the measurement and monitoring results). QA procedures should ensure that the handling and storage of samples are not changed prior to analysis and measurement.

QC should be an integral part of QA and comprises all QA actions to measure and control the characteristics of measurement equipment and radio / analytical and radiometric methods to meet established standards. The QC may include but is not limited to employee training programmes, written procedures for calibration of used sampling and measuring equipment in order to ensure that the equipment will operate with adequate accuracy. Frequency of calibrations depends on the stability of the system and / or the manufacturer's suggested interval. Recalibration is needed after equipment maintenance and whenever it is suspected that the equipment does not meet the required parameters, is damaged and does not operate properly. Periodic routine tests should be conducted in order to demonstrate that the equipment meets the required parameters.

Available analysis methods of radionuclides in different media are listed and discussed in detail in the references in the following subchapters. Please note that the listed references should be used as sources of information and that we do not endorse all the methods described.

7.2 Air

Parameters to be monitored

Atmospheric emissions from uranium mining, milling activities and uranium tailings sites are the radioactive gases radon (^{222}Rn) and thoron (^{220}Rn), airborne radioactive dust particles and non-radioactive contaminants (e.g. airborne trace metals, NO_x, SO_2, fluoride). Only monitoring of radioactive gases and radioactive dust is considered in detail in this chapter. Monitoring of non-radioactive contaminants should be done at the same stations as the monitoring of radioactive contaminants, and environmental guideline values are given in Guidelines for Preparing an EIA Report for Mineral Exploitation in Greenland (2015).

Atmospheric radioactive monitoring programmes at uranium mine sites are focused on airborne radioactive dust, radon, thoron and their progeny (specific decay products). Gamma radiation surveys are conducted 1 m above the ground. Specific radionuclides included in the environmental and effluent monitoring programme at uranium mine sites are given in Table 7.2.1.

Both radiological parameters (e.g. uranium and thorium series radionuclides as listed in Table 7.2.1) and other parameters (e.g. average of the annual precipitation including rain and snow, duration of snow cover, closeness of open sea, monthly, seasonal or annual frequencies of wind speed and direction, diurnal and monthly averages and extremes of temperature and humidity, air temperature, temperature inversions, frequency of occurrence and effects of storms, total particulate matter (dust) and particle size, inhalable and non-inhalable particles, element composition of particulate matter) should be taken into account when the monitoring programme is designed. Non-radiological parameters are site specific and thus not all the above-mentioned parameters need to be monitored at every site.

Table 7.2.1. Radionuclides included in an environmental and effluent radioactive monitoring programme (uranium production for the nuclear fuel cycle). The listed radionuclides have to be monitored in effluents and environmental samples (land, water and air).

Radon, thoron and their progeny*	^{222}Rn; ^{218}Po; ^{214}Pb; ^{214}Bi; ^{214}Po ^{220}Rn,^{216}Po, ^{212}Pb, ^{212}Bi, ^{212}Po and ^{208}Tl
Airborne radioactive dust or airborne radioactive particulate matter**	^{238}U; ^{235}U; ^{234}U; ^{230}Th; ^{232}Th; ^{228}Th; ^{228}Ra; ^{226}Ra; ^{210}Po; ^{210}Pb; ^{227}Ac

*Radon and thoron progeny are defined as specific radioactive decay products of ^{222}Rn and ^{220}Rn that are short-lived alpha- and beta-emitting radionuclides.
**Airborne radioactive dust (particulate matter) is a mixture of small-sized particles and liquid droplets, which present a potential radioactive inhalation or ingestion hazard to all of the organs and tissues of the body.

Sampling locations

Sampling locations at fixed positions (e.g. upstream / downstream, near field / far field) should be determined according to the project site. Sampling locations should provide a representative picture of the medium to be sampled. Environmental sampling locations should be selected close to points where maximum exposure or deposition is expected, preferentially along the dominant annual or seasonal wind directions, downwind of the site. Sampling should be performed at the same location every year. Monitoring locations should also be related to the potential migration pathways, changes in human exposure pathways and radionuclide levels of exposure. Additional environmental measurements should be conducted regularly in nearby towns as well as in background areas (upwind or upstream of the source). Generally, radon / thoron and their progeny are sampled at the same locations as those where particulate sampling is performed.

The following factors should be considered in determining the sampling locations:

- Average meteorological conditions (wind speed, prevailing wind direction, atmospheric stability, barometric pressure, rainfall and temperature).
- Site boundaries nearest to mill, ore piles and tailings site.
- Human exposure pathways and radionuclide levels of exposure.
- Direction and distance of nearest sensitive receptors such as local communities.
- Location of estimated maximum concentrations of radioactive materials.

Gamma survey points may be chosen on the basis of a site's importance, such as tailings, mine waste piles, active working areas (mine and milling facilities), residential sites or sites near the mine which are of environmental or cultural significance. The distance between measurement points could increase with, for example, the distance from the tailings facility. Atmospheric dispersion modelling systems showing the fate and transport of airborne radionuclides are also useful when selecting monitoring / sampling locations.

Sampling frequency

Airborne monitoring/sampling frequency and the number and distribution of sites and samples should be set based on dose rates and concentrations of contaminants, their fluctuations over time and, in the case of radioactive dust, the potential for its inhalation and ingestion. Sampling frequency (e.g. continuously, weekly to monthly, quarterly) and the number and distribution of sites should be established by the relevant Greenland authorities. Airborne radon and thoron may be measured continuously or quarterly. Monitoring of radon and thoron progeny is conducted continuously. The ambient gamma radiation dose rate is monitored quarterly at uranium mine sites. Radionuclides in PM10 are monitored continuously.

Results from the baseline monitoring programme and from the background level monitoring stations located far from the mine should be used as basis for comparison.

Radiometric/radio-analytical methods

Samples of airborne particulate matter (dust) at the uranium mine sites are collected using portable or fixed air sampling systems. Air sampling systems usually consist of a pump drawing air through a filter that collects the airborne particulates and a flow meter to record the volume of air passing through the collection filter during the sampling period. Grab samples collected over a few minutes are useful for detecting rapidly changing concentrations or obtaining multiple samples from several locations quickly. Long-term, integrated samples are taken continuously over periods of up to several weeks using high volume samplers. At the mine site airborne particulate matter is usually continuously monitored by using a high-volume air sampler. Permanent sampling stations should be protected from the weather but must still allow representative samples to be collected. Usually, filters for continuous airborne particulate matter samples are changed weekly or as required by dust loading. If the results are used for estimating radiation doses from radioactive contaminants, the respirable dust particle size should be determined using, for example, a cascade impact or a similar system. The results on concentrations of radionuclides from passive dust monitoring are reported in Bq/g and for the total uranium in mg/g.

Airborne radon and thoron are usually measured by using active (continuously) or passive (quarterly) environmental monitors or grab sampling. Radon and thoron grab sampling or passive monitoring measures the average ambient concentrations over several weeks or a month. Active monitoring can be used to measure short-lived alpha-mitting radon progeny directly. Radon and thoron progeny are monitored continuously employing active environmental monitors, and the data from those monitors are correlated with wind direction data collected applying, for instance, a wind direction sensor. The results may be used, for instance, to quantify the health risk to critical receptors due to their decay progeny. Generally, decay products of radon and thoron gases are continuously monitored at the mine site.

Data on radon exhalation from bare surfaces of the waste management facility are used as input for a risk assessment through pathway modelling. The results from radon exhalation are used also to assess the need for remedial action and the type of remedial action necessary to minimize the radon release from the site in the long term. Furthermore, the radon exhalation data can provide the basis for evaluating the effectiveness of reclamation techniques used during closure. The exhalation rate can be measured by inverting a cylindrical container with one open end on the surface and measuring the increase in the concentration of radon inside it. Parameters such as moisture content and temperature of the waste material are important considerations in radon exhalation. Seasonal and other variations in the radon exhalation rates, for instance weather conditions, need to be included in the monitoring programme.

Radiometric / radio-analytical methods for detecting, measuring and monitoring air contaminants concentrations are described in NCRP (1988), IAEA (1992, 2011, 2013), IEC (2006, 2014) and CNSC (2003). Concentrations of radon and thoron decay products should be reported in $\mu J/m^3$. Concentrations of passive radon / thoron and radionuclides in particulate matter are usually reported in Bq/m^3.

Monitoring of gamma radiation levels (usually monitored quarterly at uranium mine sites) about 1 m above the ground in the area surrounding the mine and associated facilities permits detection of any spread of radioactive material. Any increase in gamma levels may be an indication of dispersal of materials at the mine site, such as tailings or other mine waste and mined ore, outside the controlled areas. Surveys of gamma radiation may also be used to determine the effectiveness of tailings or waste pile covers. The baseline gamma radiation levels will be used as basis for comparison. Measurements of environmental terrestrial gamma radiation dose rates are typically performed using a variety of different types of active and passive detectors.

Passive detectors include:

- Thermo-luminescence dosimeters (TLD).
- Photo-luminescence detectors (PLD).
- Optically stimulated luminescent detectors (OSLD).

Active detectors for environmental monitoring of gamma radiation levels include:

- High pressurized ionization chambers.
- Properly calibrated (IEC, 1991, 1994) portable dose meters such as Geiger-Müller counters (GM).
- Scintillation detectors.
- Proportional counters.
- Electronic dose meters usually equipped with Geiger-Müller detectors.

Generally, radiation level surveys are performed 1 m above ground level using a low level environmental monitoring meter or a sodium iodide detector calibrated against a pressurized ionization chamber. An integrated record of external radiation levels over several months is typically obtained by using thermo-luminescence dosimeters. Gamma radiation measurements must be made in dry weather and not during periods following precipitations (rainfall and snow cover). The results of environmental radiation levels should be reported in S.I. units of nGy / h. If the results from gamma surveys are used to obtain an indication of whether levels from anthropogenic (man-made) sources are acceptable within the limits specified for exposure of people, the µSv / h unit should be used.

Instrumentations used to measure dose rates and airborne radioactive concentrations should be regularly calibrated and traceable to recognized national standards.

7.3 Fresh and seawater (including drinking water)

Water monitoring is performed in order to assess the potential for short- and long-term contamination from mining and milling activities, especially from tailings and other mine waste.

Samples and parameters to be monitored

Environmental monitoring of water quality should include assessment (flow and quality) of groundwater, fresh and seawater potentially affected by the mining and milling activities. Freshwater samples should include water from lakes, ponds, rivers and streams near the mine site. Precipitation samples such as of snow and rain water need also to be included in the monitoring programme. Additionally, pore water samples should periodically be analyzed and the results used to assess whether geochemical changes occur within the waste / tailings. The pore water monitoring results may also be used to model the release and migration of radionuclides and non-radioactive contaminants from the tailings and or other mine waste facilities into the environment.

Water samples are taken by, for example, collecting water directly in clean sampling containers or by use of a small peristaltic pump. The sample is usually passed through a filter directly into a sample container. Any material collected on the filter is analyzed for radioactive and non-radioactive contaminants.

The parameters to be measured are site specific and depend, for example, on the geochemical characteristics of the waste and the employed chemistry processes. The parameters measured in fresh and seawater should include uranium and thorium series radionuclides (see previous chapter on air sampling). Especially important is radium-226 which is soluble in water and originates from the decay of uranium-238. Gross alpha activity of the water samples is usually also determined. Relevant non-radiological contaminants, such as heavy metals, fluoride, major ions such as carbonate, ammonium, sulphate, chloride and nitrate, should be measured as part of the monitoring programme at the same sampling stations, but these will not be treated in detail in this chapter.

Guideline values for non-radiological contaminants are described in Guidelines for preparing an EIA report for Mineral Exploitation in Greenland (2015). Parameters to be monitored are, for instance, turbidity, pH, Eh, alkalinity, conductivity, dissolved oxygen content, temperature, flow rate and current, infiltration, percolation and seepage from tailings and waste rock facilities into the water systems, hydrology and hydro-biological characteristics, precipitation and evaporation. Local fresh and surface waters and their connections should be measured as part of the water sampling as they influence the behaviour of the radionuclides and other contaminants in the water.

Sampling locations and frequency

The number and location of sampling sites and sampling frequency should be decided for each specific mining and milling project as it will vary with the nature and scale of the project (ore type, production size, proximity to towns or settlements, pathways to receptors, concentrations of radionuclides and non-radioactive elements in waste and tailings, climatic factors, occurrence of flora and fauna, etc.).

Sampling locations should be selected taking into account local hydrological conditions, location of tailings and other waste facilities and points where the maximum exposure or deposition is expected. Samples should be collected both upstream (to provide background levels) and downstream of potential sources of contamination such as, for example, release points for aquatic discharges. The maximum distance from the tailings and other mine waste disposal facilities at which the water sample should be collected depends on the downstream water usage and the likelihood of the water bodies receiving contaminants (e.g. erosion, drainage, seepage from, for instance, tailings facilities, etc.). The sampling should be performed at the same location every year. Pore water may be sampled via wells (extending into the tailings facility without passing through its base), use of suction plate apparatus or the compression of core samples of waste material to extract the moisture or lysimeters.

Monitoring locations should also be related to the potential migration pathways, changes in human exposure pathways and levels of exposure to radionuclides.

Monitoring is usually directed towards waters bodies that pass near or through waste facilities that could be subjected to seepage or affected by waste facilities failure events.

For both freshwater and seawater sampling, it is important to include reference samples from areas outside the impacted areas as well as baseline samples taken prior to the mining and milling activities for comparison.

Drinking water (in Greenland: streams and lakes) supplies should be regularly monitored (e.g. at least through monthly samples during the first year of operation and quarterly thereafter). Freshwater samples are usually collected at least quarterly from each on-site water source (pond, lake and stream) and any offsite water source that may be subject to runoff / seepage from potentially contaminated areas, tailings or drainage due to tailings dam failure. Freshwater samples should be collected upstream and downstream of the site. During the operational phase of the mine, any unusual water release (runoff, seepage) should be sampled. Sea water sampling should be done near potential pollution sources such as mine pits, processing plants and ports.

Radio-analytical/radiometric methods

Methods for analyses of radionuclides in water include both gross alpha and beta activity measurements and radionuclide-specific measurements for the individual radionuclides (EPA, 2014).

Drinking water, guideline values

With regard to drinking water, guideline values have been developed by the World Health Organization for gross alpha and beta activity and for natural radionuclides. The present (2014) guideline values are listed in Table 7.3.1. The concentrations of individual radionuclides should be determined and compared with the guidance levels. The relevant Greenland authorities will have to develop guideline values for radioactive contaminants in both fresh and seawater (see 7.6).

Table 7.3.1. Drinking water quality guidelines for radionuclides developed by the World Health Organization (WHO, 2011).

Radionuclide	(Bq L^{-1})
Screening level	
Gross alpha activity	0.5
Gross beta activity	1
Guidance level	
Pb-210	0.1
Po-210	0.1
Ra-226	1
Ra-228	0.1
Th-228	1
Th-230	1
Th-232	1
U-234	1
U-238	10

Radiological quality of drinking water

Recommended values for maximum acceptable concentrations (MACs) or guidance levels for natural radionuclides in drinking water are listed in Table 7.3.2. The recommended guidance levels for radionuclides correspond to a reference dose level (RDL) equal to 0.1 mSv (for each radionuclide listed) from one year's consumption of drinking water. A guideline for radon in drinking water is not deemed necessary, but the recommendations given by the EU and Nordic countries are included in the table.

Table 7.3.2. Recommended MAC for radionuclides in Greenland drinking water.

Radionuclide	Half-life	Decay mode	Adult dose co-efficient (DC) for ingestion (mSv/Bq)	MAC (Bq/L) due to radiation	MAC µg/L due to chemical toxicity
Total uranium (U-238, U-235 and U-234)			-	10	15
Th-228	1.91 years	alpha (100%)	7.20E-05	2	
Th-230	75,400 years	alpha (100%)	2.10E-04	0.6	
Th-232	14 billion years	alpha (100%)	2.30E-04	0.6	
Ra-226	1600 years	alpha (100%)	2.80E-04	0.5	
Po-210	138.4 days	alpha (100%)	1.20E-03	0.1	
Pb-210	22.3 years	beta (100%)	6.90E-04	0.2	
Rn-222	3.824 days	alpha (100%)		100	

Natural uranium isotopes (238, 235 and 234) have half-lives ranging from hundreds of millions to billions of years. The specific activity of uranium isotopes is low; thus, the MAC for uranium in drinking water owes to its chemical toxicity rather than its radiological properties. Lead-210, like radium, is a bone-seeking radionuclide. The radiological MAC for Pb-210 should not be confused with the chemical MAC for Pb of 0.01 mg/L. A Pb-210 concentration at a radiological MAC of 0.2 Bq/L would correspond to a total lead concentration of only 7×10^{-8} µg/L.

7.4 Biota

Samples and parameters to be monitored

A radioactive monitoring programme should include typical types of Reference Animals and Plants (RAPs) (ICRP, 2014). Definitions of RAPs and criteria for RAPs selection for a monitoring programme can be found in ICRP (2008). Potential food sources such as sheep and caribou (flesh and entire liver), dairy products, vegetables, fruits and freshwater and marine fish (arctic charr), shrimp and crabs should be sampled. The samples should be collected from the area that may provide food and drink sources for humans either in the field or at the local market. Local conditions should be taken into consideration when selecting the food and drink samples to be included in the radioactive monitoring programme. Forage vegetation, droppings samples (e.g. sheep / caribou droppings) should also be taken into account. Moreover, marine and terrestrial samples such as seaweed, marine mussels, seals and whales (if possible), lichens, arctic hare, leaves and twigs of bushes and grass should be considered.

Both radiological parameters (all listed in Table 7.2.1) and relevant non-radiological parameters such as dust concentration and deposition should be monitored.

Sampling locations and frequency

Biota sampling locations should be selected close to points where maximum exposure or deposition is expected. Biota sampling should not be limited to on-site areas, samples from downwind and downstream locations and areas where potentially contaminated water is used for beneficial purposes (e.g. farm, irrigation of crops) should also be included in the monitoring programme. The sampling should be performed at the same location every year. Monitoring locations should also be related to the potential migration pathways, changes in human exposure pathways and levels of radionuclide. Additional environmental sampling and / or measurements should be conducted regularly in nearby towns as well as in background areas (upwind or upstream of the source).

Representative samples should be selected and reflect the conditions in the environment from which they are taken. Specific requirements for sampling of representative samples have been suggested by the International Commission on Radiation Units and Measurements (ICRU, 1996).

The frequency of sampling (e.g. semi-annually, quarterly or annually) and the scale of the monitoring depend on the concentrations of contaminants and their fluctuations over time. The grazing season of animals may be selected as sampling period. This period is region / country dependent. As the indicator species to be sampled in the marine and intertidal environment are slow growing, the sampling should be carried out once a year in August-September (end of growing season). Usually, fish samples are collected semiannually from any bodies of water that may be subjected to seepage or surface drainage from potentially contaminated areas. Forage vegetation, if any, should be collected during the grazing season. Information considered of interest for interpreting the results obtained on the sampling sites should include site and place, geographical coordinates, date of sampling, grazing area, grazing period, number of grazing animals, type of breed and type of farm, if any.

Results from the baseline monitoring programme and from the background level monitoring stations (reference stations) located far from the mine should be used as basis for comparison.

In planned exposure situations, such as uranium mining and associated activities, the lower end of the Derived Consideration Reference Levels (DCRLs) can be used as points of reference for decision making / protection of different types of biota (ICRP, 2008). DCRLs are reference values relevant to different RAPs (ICRP, 2008).

Radio-analytical/radiometric methods

Available methods for analysis of uranium and thorium series radionuclides in biota samples are mentioned in Chen et al. (2001). Radio / analytical and radiometric methods used to measure the radioactive concentrations of uranium and thorium series radionuclides in biota samples should be regularly calibrated and traceable to recognized national standards.

7.5 Other samples

Samples and parameters to be monitored

Samples such as of surface soil, marine and freshwater sediments as well as blood, hair and urine of the mine workers and the most exposed members of the public have to be collected and the radioactive concentration of uranium and thorium series radionuclides should be determined. Parameters such as soil type, bulk density, particle density, total porosity and soil moisture must also be considered (Blake and Hartge, 1986).

Sampling locations and frequency

Soil and marine and freshwater sediments are usually collected annually from locations around the mine facilities. Soil is usually sampled at a depth of 15 cm, with gamma radiation measurements being taken at the same locations, both at the ground surface and 1 m above the surface. Blood, urine and hair samples should be collected regularly. The frequency of sampling (e.g. monthly, semi-annually, quarterly or annually) and the scale of the monitoring depend on contaminant concentrations and their fluctuations over time.

Background level monitoring stations far from the mine facilities should also be included in the monitoring programme.

Radio-analytical/radiometric methods

Available radio / analytical and radiometric methods for analysis of uranium and thorium series radionuclides in the above-mentioned types of samples are given in Colmenero et al. (2004), and Chen et al. (2001). Analytical methods and equipment used to measure contaminant concentrations should be regularly calibrated and traceable to recognized national standards.

7.6 Radioactive effluents monitoring

This subchapter provides a description of the monitoring of controlled discharges of radionuclides in the form of airborne (gases and particulate matter emission through a building ventilation system) and liquid effluents to the environment from all facilities at the mine site. A detailed description of the monitoring of effects of discharges of radioactive effluents into the environment should be further developed. Releases of radionuclides arising from radiological events are not considered.

For both airborne and liquid discharges to the environment, three types of measurements are possible:

- Online monitoring.
- Continuous sampling and laboratory analysis.
- Batch sampling and laboratory analysis.
- Discontinuous monitoring.

Choice of sampling and measurement type depends on:

- Characteristics and amounts of discharged radionuclides.
- The expected variation with time in the discharge rates of the radionuclides.
- Likelihood of unplanned discharges requiring prompt detection and notification.

Accurate determination of the volume of material discharged as a function of time so that the total activity discharged over a given time period can be computed on the basis of measurements of activity concentrations.

Regarding effluent discharge, the following information has to be provided by the operator to the appropriate regulatory body:

- Routes of discharge and discharge points, expected time pattern of discharge.
- Climatological conditions, meteorological dispersion data.
- Radionuclide(s) listed in Table 7.2.1 in discharged effluents (gas, particulate matter and liquid).
- The proposed maximum quantities and concentrations of radionuclide(s): expected total amount of radionuclides to be discharged per year.
- Physical and chemical form and radiological characteristics of the radioactive and non-radioactive constituents in the effluent discharged, particularly if this is important in terms of environmental or metabolic behaviour.
- Particle size distribution of airborne discharges.
- pH of the liquid discharged.
- Hydrological characteristics of the aquatic environment into which liquid effluents are released (e.g. variations in water fluxes and characteristics of effluent mixing), hydrodynamic characteristics (e.g. water currents, characteristics of general circulation, thermocline evolution and mixing conditions) of the aquatic environment.
- Estimated effective dose to members of the public from releases.
- Other regulatory requirements.

Discharges limits
Discharge limits for shorter periods or annual emission limits of radionuclides to the environment from uranium mining and associated activities should be set by the appropriate regulatory body in Greenland in order to protect humans and prevent and control environmental pollution.

The authorized discharge limits shall satisfy the requirements for optimization of protection and the condition that doses to the critical group shall not exceed the appropriate dose constraints.

Authorized discharge limits can be set based on limiting either dose or quantity of radioactive material discharged from the facility. The dose is viewed as a more fundamental quantity and underlies the system of limitation of discharges. Limits in terms of quantities of radionuclides to be discharged reflect the quantity that is to be controlled and measured and are therefore connected to the actions that the registrant or licensee must take to control discharges.

Dose and quantities of radionuclides are directly proportional for any given site, and one can be converted to the other without difficulty, thus expressing limits in terms of dose or quantity of radioactive material discharged does not represent a fundamental difference. The quantities of radionuclides in the effluent to be discharged are a measurable magnitude, while the doses to members of the public are based on assessments.

Discharge limits are regulatory established limits for controlled release of radionuclides to the environment in the form of airborne and liquid effluents from mine sites. Those limits should represent the upper limit quantity of radionuclides that a member of the public should be exposed to. The annual effective dose limit for members of the public resulting from controlled releases should not exceed the regulatory effective dose limit established for members of the public (e.g. 1 mSv / y). Persistence, toxicity and bio-accumulative properties of released radionuclides also need to be considered when establishing the discharge limits.

Discharge limits set as doses

Discharge limits expressed in terms of dose are generally based on the limitation of individual doses.

Radiation dose generally refers to the amount of energy left by radiation in the target material per unit weight. The unit of effective dose is sievert (Sv). In practice, thousandth of sievert, millisieverts (mSv), or millionth of sievert, microsievert (µSv), are used. If a person receives 1 mSv from any source of radiation, she / he has approximately 0.005% probability of developing cancer in their lifetime.

A single limit based on the effective dose to the critical group of the members of the public and to any member of the public and one or more equivalent organ doses may be set by the relevant regulatory bodies (Table 7.6.1). In general, setting limits in terms of a single dose value will be appropriate only for those facilities that discharge few radionuclides.

The location of the critical group and any member of the public at which the dose is to be specified must be defined. The disadvantage when using the effective dose to the critical group of members of the public is that it will be subject to changes in the group, or their habits. Therefore, it is better to specify the dose limits at the site boundary, which is the boundary within which the licensee exerts complete access control, and from which the public is normally excluded.

Limits on effective dose

Occupational and members of the public dose limits apply to the sum of exposures from sources related to practices that are already justified in normal conditions Table 7.6.1. ‘For occupational exposure, a limit on effective dose of 20 mSv per year, averaged over 5 years (100 mSv in 5 years), with the further provision that the effective dose should not exceed 50 mSv in any single year’ (ICRP 1991). ‘For public exposure, the limit should be expressed as an effective dose of 1 mSv in a year’.

Table 7.6.1. Radiation dose limits (Source ICRP, 1991).

Annual Effective Dose Limit (mSv/y)	**Occupationally Exposed employees**	**Members of the public**
	20	**1**
Five year Cumulative Dose limit (mSv)	100	5
Annual Equivalent Dose		
Lens of the eye	150 mSv	15 mSv
Skin [1,2]	500 mSv	50 mSv
Hands and feet	500 mSv	-

[1] The limitation on effective dose provides sufficient protection for the skin against stochastic effects. An additional limit is needed for localized exposures in order to prevent tissue reactions.

[2] Averaged over 1 cm^2 area of skin regardless of the area exposed.

Effective doses to members of the public from all exposure pathways and all discharges of radionuclides into the environment, both in water and air, from uranium facilities as recommended by ICRP (1991) are limited to 1mSv/y. In the recommendation, it is stated that the total discharges of all radionuclides to the receiving environment (atmosphere, surface waters bodies and any other emissions) from activities involving radioactive materials, in this case uranium mining and associated activities, shall not exceed those amounts that will cause any member of the public to receive in any year an effective dose higher than 1mSv/y.

When establishing the discharge limits for both airborne and liquid effluents from all facilities at the mine site to the environment, an ALARA dose constraint should be used. The choice of a dose constraint should ensure, for any source (including radioactive waste management facilities) that can release radioactive effluents (gases, particulate matter and liquid) to the environment, that the cumulative effects of each annual release from the source be restricted so that the effective dose in any year to any members of the public, including people distant from the source and people of future generations, is unlikely to exceed any relevant dose limit (e.g. 1 mSv/y).

Limits set to the quantity of the radioactive material discharged

The limits on quantities of radionuclides discharged are usually specified at the point of discharge, such as the stack for airborne discharges and the discharge pipe for liquid discharges. This choice of location is usually the point at which measuring or sampling equipment is located. If the discharges are made in batches, rather than continuously, then analysis of samples from each batch before discharge will be necessary. The operator has to collect and analyze an undiluted, unfiltered sample.

Radionuclide quantity limits

When discharge limits are specified in terms of quantity of radioactive material discharged, separate limits are usually specified for different radionuclides.

The regulatory body should set a dose constraint which will be used when establishing the discharge limits for individual radionuclides from all the facilities from the mine site to the environment. The dose constraint should be set below the annual effective dose limit for members of the public. Usually, a dose constraint of 0.1 mSv / y to the critical group and members of the public associated with discharges from all the facilities at the mine site is used. A dose constraint is an upper bound on the annual dose that members of the public should receive from a planned operation. To ensure that radiation exposure to members of the public does not exceed the annual limit of 1 mSv, the ICRP suggest the use of a dose constraint. ICRP recommended recently a dose constraint value of 0.3 mSv in a year for the control of public exposure to radiation.

Critical groups of members of the public are individuals receiving the highest effective dose or equivalent dose (as applicable) from the given source because of their location, consumption of food and water and other lifestyle habits. Recommendations related to the determination of critical group of members of the public can be found in ICRP (1985). The group should be relatively homogenous with respect to age, diet, living and environmental conditions and specific aspects of behaviour that affect the doses received. Exposure pathways, food consumption rates and other characteristics are assumed site specific. Dose constraints and dose limits established by the regulatory body generally apply to the mean dose to this critical group. Some countries have placed dose constraints on effluent releases that are source specific (e.g. for a given site or facility) and specific to discharge mode (e.g. for airborne or liquid discharges), for ease of application.

Discharge limits of individual radionuclides to the environment, in the form of airborne (gases, particulate matter) and liquid effluents from all facilities at the mine site, may be established as mean values of dose assessment models (IAEA, 2000). Dose modelling can be done by using computer software (e.g. EPA models to assess risk and dose - COMPLY and COMPLY - R).

Assessment should be made of the dose to individuals of the critical group (the sum of the doses via all discharge routes and pathways) for each of the discharge options considered and it should be verified that this dose does not exceed the appropriate dose constraint.

Modelling should be done by both the appropriate regulatory body in Greenland and by the mining company or its consultants using a computer software model approved by the authorities. All parameters of and information on the model used by the mining company should be submitted to the regulatory bodies prior to commencement of the operations in order to enable an evaluation of the results. Parameters and information include:

- Radionuclides for release to the environment, characteristics and activity (including, for instance, physical (e.g. gas, liquid or solid), chemical and radiological (e.g. alpha, beta or gamma emitters, physical half-life) properties, total amount of various radionuclides expected to be discharged per year, expected time pattern of discharge).
- All discharge points, routes and main exposure pathways by which discharged radionuclides can deliver public exposure.
- Magnitude and likelihood (estimation) of associated radiation doses to critical groups and members of the public attributed to the discharges.
- Optimization of radiation protection (e.g. ensure that the dose to critical group(s) and members of the public due to the anticipated discharges comply with the regulatory requirements, etc.).

Persistence, toxicity and bioaccumulation properties of released radionuclides and the dose modelling should result in proposals for discharge limits in the form of, radionuclide concentrations in air and water at key outlet points. The numerical values of the authorized discharge limits should never exceed the discharge level corresponding to the dose constraints.

A license should be accompanied by specific requirements and conditions to be complied with by the operator. For discharges to the environment, these conditions could take the form of annual and shorter term limits on the discharges of particular radionuclides. Shorter term levels can be set in order to: (1) trigger investigations and (2) ensure that the procedure used and the associated conditions and assumptions applied to estimate doses remain valid (prevent significantly higher doses being received owing to higher than normal discharges under conditions of poor dispersal in the environment). As example, shorter term levels could be set to 50% of the annual limit for a calendar quarter, 20% of the annual limit for a calendar month, as considered appropriate, with account taken of the nature and operation of the source. The operator should notify the regulatory body if the shorter term levels are exceeded, state the reason for this and propose mitigation measures.

In order to ensure that discharges are in compliance with the established limits, airborne (gaseous and particulate matter) and liquid effluent releases from all mine facilities should be continuously monitored. Similarly, in order to check the assumptions used to evaluate dose to critical group, environmental monitoring is required. Environmental monitoring will also lead to identification of any unexpected release of radionuclides. A non-compliance programme for the case when the radionuclides discharged into the environment are above the authorized discharge limits should be developed.

Site- or facility-specific limits

Discharge limits, whether specified in terms of dose or quantity of radioactive material released, may be specified either for the whole site, for each unit within the site or even for each discharge point, such as stack or pipe. A unit in this context means an identifiable entity that generates airborne or liquid wastes. For example, at a uranium mine site, there may be a mill facility, a waste treatment facility, each of which has its own discharge points and each of which may be considered as a separate and independent unit on which discharge limits may be imposed. In nearly all cases, regulatory bodies impose a site limit. When a site limit alone is used, without limits on individual units, the discharge from each unit is still expected to be optimized. The site limit in such cases serves as a cap on the future development at the site. An additional new unit will add to the overall discharge from the site, but the total would be expected to remain within the site limit. Site limits alone, as well as site plus unit limits, are used.

Emission control devices

Particulate matter bearing uranium and thorium series radionuclides and radioactive gases (e.g. radon and thoron and their progeny) is generated from fixed points and fugitive sources and may be released to the atmosphere. Operation areas include: (1) ore stockpile, handling and crushing, (2) ore grinding and chemical processing (including leaching, precipitation, etc.), (3) yellowcake drying and packaging (only a dust generation source since the sources of radon and thoron were removed in the previous steps of the hydrometallurgical process employed), (4) other mill facilities such as laboratories, storage areas and maintenance store and (5) waste rock and tailings management facilities.

Proper mill operations (procedures and engineering controls) have to be conducted to ensure that all airborne effluent releases to the environment are reduced to levels as low as reasonable achievable (ALARA). The primary means of accomplishing this is the control of emissions at the source. Thus, emission control devices (e.g. bag or fiber filters, orifice or baffle scrubbers, wet impingement scrubbers, venturi scrubbers and water spray systems, etc.) have to be installed in the ventilation systems of all uranium mill facilities (Task CE 309-4, RG 3.56, 1986).

The most significant sources of radioactive particulate matter are handling and crushing, yellowcake drying and packaging areas. These are usually controlled by separate ventilation systems that remove the radioactive particulate matter through, for instance, local hoods, hooded conveyor belts, etc., into emission control devices where they are removed from the air streams. The cleaned air is then discharged by fans into the atmosphere through local exhaust stacks.

Samples, frequency and parameters to be monitored

Airborne effluents

Effluents from the yellowcake dryer and packaging exhaust stacks and from other stack facilities at the mine site are usually sampled at least quarterly (from yellowcake dryer and packaging stack) and semi-annually (other and non-radiological stacks) during normal operations. The sampling must be carried out in isokinetic conditions and should provide representative samples for determination of the release rates and concentrations of uranium and thorium series radionuclides in the discharged effluents. Samples from the yellowcake dryer and packaging stack should be analyzed for natural uranium and thorium. Samples should also be analyzed for uranium and thorium series radionuclides if data on these cannot be obtained from other sources such as isotopic analysis of yellowcake products. Samples from other stacks should be analyzed for uranium and thorium series radionuclides.

Flow rates (cubic metres per second (m^3/s) or total stack flow (m^3, if stack is not in continuous use)) should be measured at the time of sampling at all stack locations (processes or area). Radon and thoron progeny can be continuously monitored by placing a detector directly in or adjacent to the effluent stream (EPA, 1989).

Liquid effluents and water quality monitoring

Liquid effluents and water quality monitoring studies consist of effluent characterization, toxicity testing and water quality monitoring.

Effluent characterization

Representative samples of liquid effluents should be collected at each outlet point and the quantities and average concentrations of uranium and thorium series radionuclides discharged in any liquid effluents that could reach an unrestricted or restricted area should be determined. The concentrations of non-radioactive contaminants and other parameters such as effluent hardness, pH, alkalinity, electrical conductivity and temperature must also be determined. The liquid effluent for discharge must be analyzed unfiltered and undiluted.

The effluent samples must be collected prior to release. The volume of collected sample should be sufficient to allow all required analyses and tests plus associated quality control samples (e.g. field duplicates, laboratory replicates and spiked samples).

Water quality monitoring

Water quality should be regularly monitored at each key liquid release point (e.g. outflow from a tailings dam, pipeline of process water) and related reference areas to ensure that the regulation complies with the approved discharge limits set by the authorities. Uranium and thorium series radionuclides and the concentration of non-radioactive contaminants must be determined for the collected water samples. Additionally, parameters such as pH, alkalinity, electrical conductivity, hardness and temperature must be measured. The operator has to implement quality assurance and quality control measures that will ensure the accuracy of liquid effluents and water quality monitoring data.

For continuous release, the operator should continuously collect representative samples at each release point. For batch releases, a representative sample of each batch should be collected and supplemental information documenting that these samples are representative of actual release should be provided. The operator must provide information on volume of liquid effluents, quantities and activities of radionuclides discharged per year, routes, points and methods of discharge, significant exposure pathways by which discharged radionuclides can cause public exposure, expected time pattern of discharge and dose estimation of potential exposure to members of the public and critical groups due to the planned discharges.

Toxicity testing

Toxicity testing should include: a fish species, an invertebrate species, a plant species and an algal species in the case of effluent discharge into freshwaters and a fish species, an invertebrate species and an algal species in the case of effluent discharge into marine and estuarine waters. The toxicity tests shall be conducted on the aliquots of effluent samples collected from the mine's final discharge point that potentially has the most adverse environmental impact on the environment
(http://laws-lois.justice.gc.ca/eng/regulations/sor-2002-222/index.html).

Radio-analytical/radiometric methods

The concentration and quantity of all uranium and thorium series radionuclides in effluents (liquids, particulate matter and gases) released from mine operations to unrestricted or controlled areas have to be determined. Analysis methods of uranium and thorium series radionuclides in effluent samples are provided in the reference of subchapters 7.1 and 7.2. Minimum detectable concentrations (MDCs) or lower limit of detection (LLD) for radionuclides in liquid and gaseous effluent samples should also be established. The quantity of each radionuclide released should be reported by the operator semi-annually.

The results from liquid and gaseous effluents monitoring programmes will be used to:

- Assess the environmental impact of radionuclides in effluents.

- Demonstrate compliance with the annual effective dose limits (1mSv / y) for members of the public.
- Demonstrate compliance with regulatory requirements, for instance that concentrations of radionuclides in liquid and gaseous effluents are kept ALARA.
- Assess the adequacy of effluent controls.

Operator responsibilities

During the entire life of the project licensees should:

- Keep all radioactive discharges as far below authorized limits as is reasonably achievable and report to the regulatory body any releases exceeding any reporting levels or authorized discharge limits.
- Review discharges and their associated control measures at regular intervals in the light of operating experience. Any changes in exposure pathways and any changes in the composition of critical groups potentially affecting the calculated doses should also be kept under review and taken into account whenever the discharge authorization is reviewed.
- Establish and carry out monitoring programmes for effluents and environmental radiation.
- The operators should routinely compare the monitoring results to the EIA predictions, the companies' commitments, the regulatory expectations, and any Identified Action Levels. These action levels are concentrations where action is to be taken, and may include: additional monitoring, further studies, corrective actions, public notification, etc.

Non-compliance with the authorized discharge limits

Unforeseen situations may arise that necessitate the release of effluents exceeding the limits specified in the authorization. In such a case, the licensee has to make an application providing details of the circumstances leading to the situation and justification for the need for this special release. The regulatory body may grant a special authorization for the discharge provided that the resulting maximum future critical group dose does not exceed 5 mSv in one year and that the average annual dose in a five-year period is limited to 1 mSv, including doses from all other controlled sources.

In a situation where authorized discharge limits have been exceeded, the licensee should:

- Investigate the violation and its causes, circumstances and consequences.
- Undertake appropriate actions to remedy the circumstances that led to the breach and to prevent a recurrence of a similar situation.
- Communicate to the regulatory body the causes of the breach and the corrective and / or preventive actions taken or to be taken.
- Undertake all other actions required by the regulatory body.

Communication of a breach of the authorized discharge limits should be prompt and immediate whenever an exposure emergency has developed or is developing. Failure to take corrective or preventive actions within a reasonable time in accordance with national regulations should be grounds for modifying, suspending or withdrawing any authorization that was granted by the regulatory body.

Non-compliance with authorized effluent discharge limits or other regulatory requirements concerning control of radioactive discharges is subject to the provisions laid down in relevant national legislation or by the regulatory body.

7.7 References

ANSI / ASQC E4-1994. Specifications and Guidelines for Quality Systems for Environmental Data Collection and Environmental Technology Programs. American National Standards Institute / American Society for Quality Control, New York, NY, 1994.

ANSI N42.23-2003. Measurement and Associated Instrumentation Quality Assurance for Radioassay Laboratories. American National Standards Institute, New York, NY, 2003.

Blake G.R., Hartge K.H., 1986. Bulk Density, 'in: Methods of Soil Analysis, Part 1: Physical and Mineralogical Methods, 2nd ed., (Klute A., ed.), American Society of Agronomy, Inc., and Soil Science Society of America, Madison, Wis., pp. 363-376.

Chen, Q., Aarkrog, A., Nielsen, S.P., Dahlgaard, H., Lind, B., Kolstad, A.K., Yu, Y., 2001. Procedures for determination of 239, 240Pu, 241Am, 237Np, 234, 238U, 228, 230, 232Th, 99Tc and 210Pb and 210Po in Environmental Materials. Risø National Laboratory, Risø, Denmark.

CNSC, 2003. Measuring Airborne radon progeny at Uranium Mines and Mills. Canadian Nuclear Safety Commission. 19 p. (Available at: www.nuclearsafety.gc.ca / pubs... / 44019-G4E.pdf; accessed 20 May 2014)

Colmenero Sujo, L. et al., 2004. Uranium-238 and thorium-232 series concentrations in soil, radon-222 indoor and drinking water concentrations and dose assessment in the city of Aldama, Chihuahua, Mexico. J. Environ. Radioactivity 77 (2004) 205–219, http://ac.els-cdn.com/S0265931X04001067/1-s2.0-S0265931X04001067-main.pdf?_tid=e40fb53c-3419-11e4-b859-00000aab0f26&acdnat=1409824833_025b0d36305337919917028c6d70272a

EPA QA / G-9S-2006. Data Quality Assessment: Statistical Tools for Practitioners. U.S. Environmental Protection Agency, Washington, DC, EPA / 240 / B-06 / 003, February 2006.

EPA, 2014. Analytical Methods Approved for Drinking Water Compliance Monitoring of Radionuclides. United States Environmental Protection Agency. 17 p. (Available at http://water.epa.gov/scitech/drinkingwater/labcert/upload/815b14002.pdf, accessed 14 April 2014)

Guidelines for preparing an Environmental Impact Assessment (EIA) Report for mineral exploitation in Greenland (in preparation, 2014)

IAEA, 1992. Measurement and Calculation of Radon Releases from Uranium Mill Tailings. International Atomic Energy Agency. Technical Reports Series No. 333. (Available at: http://www-pub.iaea.org/books/IAEABooks/1437/Measurement-and-Calculation-of-Radon-Releases-from-Uranium-Mill-Tailings, accessed 20 May 2014)

IAEA 2000. International Atomic Energy Agency. Regulatory control of radioactive discharges to the environment. Safety Standards Series No. WS-G-2.3.

IAEA, 2011. Radioactive particles in the environment: Sources, particle characterization and analytical techniques. International Atomic Energy Agency. TECDOC-1663. (Available at: http://www-pub.iaea.org/MTCD/publications/PDF/TE_1663_web.pdf, accessed 20 May 2014.

IAEA, 2013. Measurement and calculation of radon releases from NORM residues. International Atomic Energy Agency. Technical Reports Series No. 474. (Available at: http://www-pub.iaea.org/books/IAEABooks/10369/Measurement-and-Calculation-of-Radon-Releases-from-NORM-Residues, accessed 20 May 2014)

ICRP, 1985. Principles of Monitoring for the Radiation Protection of the Population, Publication 43, Pergamon Press, Oxford and New York.

ICRP, 1991. Recommendations of the International Commission on Radiological Protection. ICRP Publication 60. Ann ICRP, 21, 1-3.

ICRP, 2008. Environmental Protection - the Concept and Use of Reference Animals and Plants. ICRP Publication 108, Ann. ICRP 38, 4-6.

ICRP, 2014. Protection of the environment under different exposure situations. ICRP Publication 124, Ann. ICRP 43(1).

IEC, 1991. Radiation protection instrumentation - Portable, transportable or installed equipment to measure X or gamma radiation for environmental monitoring. Part 1: Ratemeters. International Electrotechnical Commission (IEC). 1017-1 © IEC
http://webstore.iec.ch/webstore/webstore.nsf/artnum/000065!opendocument

IEC, 1994. Radiation protection instrumentation - Portable, transportable or installed equipment to measure X or gamma radiation for environmental monitoring. Part 2: Integrating assemblies. International Electrotechnical Commission (IEC). 1017-2 © I EC: 1994
http://webstore.iec.ch/webstore/webstore.nsf/artnum/000066!opendocument

IEC, 2006. Radiation protection instrumentation – Radon and radon decay product measuring instruments – International Part 1: General requirements. International Electrotechnical Commission (IEC). 61577-1 □ IEC: 2006 – 3 – CONTENTS
http://www.iec.ch/dyn/www/f?p=103:91:0::::FSP_LANG_ID:25?q=radon

IEC, 2014. Radiation protection instrumentation – Radon and radon decay product measuring instruments – International. Part 2: Specific requirements for 222Rn and 220Rn measuring instruments. International Electrotechnical Commission IEC 61577-2:2014 © IEC 2014
http://webstore.iec.ch/webstore/webstore.nsf/artnum/049873!opendocument

ICRU, 1996. International Commission on Radiation Units & Measurements (ICRU), 1996. Sampling of Radionuclides in the Environment.

ISO/IEC 17025-2005, General Requirements for the Competence of Testing and Calibration Laboratories. International Standards Organization/International Electrotechnical Commission, Geneva, Switzerland, May 2005, Correction 1, August 2006.

NCRP, 1988. Measurement of Radon and Radon Daughters in Air. National Council on Radiation Protection and Measurements, Bethesda, MD, NCRP Report No. 97. (Available at:
http://www.ncrponline.org/Publications/Press_Releases/97press.html, accessed 20 May 2014)

Task CE 309-4, RG 3.56, 1986, U.S. Nuclear Regulatory Commission, General Guidance for Designing, Testing, Operating, and Maintaining Emission Control Devices at Uranium Mills, Regulatory GUIDE 3.56.

U.S. EPA, 1989. Environmental protection agency, Indoor radon and radon decay product measurement protocols, EPA 520/1-89-009, US EPA, Washington, DC.

WHO, 2011. Guidelines for drinking-water quality. World Health Organization. Fourth edition. 564 p. (Available at
http://whqlibdoc.who.int/publications/2011/9789241548151_eng.pdf?ua=, accessed 5 May 2014)

8 Yellowcake Packaging and Transport

Yellowcake is produced from uranium ore in the uranium milling process. The material can be a mixture of uranium oxides: UO4, U3O8, ADU, MgDU, uranyl peroxide, etc. Yellowcake may be colored reddish, orange to yellow naturally or dark green to grey or almost black when calcined (in a furnace).

International packing and packaging recommendations for the transport of yellowcake are made so to limit the radiation exposure from yellowcake during the shipment. When transported properly, the radiation exposure of the workers involved and the environment should be insignificant.

8.1 Yellowcake packaging

Yellowcake is packed in sealed 200-litre steel drums (Fig. 8.1.1) meeting IP-1 (industrial package) standards (IAEA, 2012). Before packing the drums, the operators have to follow validated procedures to sample each batch of the product for QC analysis. The samples are sent to the QC laboratory, and customer samples are also collected and sent along with the drums to verify the operator´s analysis. The operator may collect a third sample and send it to a reference laboratory in case the customer´s analysis disagrees with the QC results analysis of the batch.

Figure 8.1.1. Drums of yellowcake being filled. Source: Guide to Safe Transport of Uranium Oxide Concentrate, Australia (2012).

Each drum has a tight-fitting lid which is secured to the drum with a steel locking ring that is clamped by a locking ring bolt. Drums filled with yellowcake are recommended to be stowed securely within 20-foot International Organization for Standardization (ISO) sea freight containers (or cargo transport units (CTUs)) to international standards using a webbed Kevlarbased strapping system to withstand the G-forces expected during road, rail and sea transportation and associated handling operations (Fig. 8.1.2). This greatly reduces the likelihood of there being an incident involving a spillage of the material. This is the preferred packaging method and complies with the requirement of the International Maritime Dangerous Goods (IMDG) Code and relevant United Nations (UN) guidelines for packaging of CTUs. About 36 standard 200-litre drums (able to withstand routine and normal conditions of transport, including thermal resistance) fit into a standard transport container.

Figure 8.1.2. Yellowcake packaging. Source: Guide to Safe Transport of Uranium Oxide Concentrate, Australia (2012).

The process of packing yellowcake in drums involves use of remote, automated handling techniques; the packaging system enables loading of granular yellowcake into a custom-designed drum contained in a lead-shielded overpack through the following steps:

- A powered conveyer moves the drum and overpack through an airlock and within the drum loading area.
- The drum's outer lid is removed once inside confinement and the drum is then translated into the shielded loading station.
- The drum is raised to create a 'bagless transfer' seal with the loading station.
- After the drum is raised and mated to the underside of the loading station, the drum's inner cover is removed.
- Once this inner cover is removed, the contaminated product transfer equipment will communicate directly with the interior of the drum, but not the external surfaces of the drum.
- Product transfer equipment is positioned to load the drum, a product transfer valve is opened and the product is transferred (by gravity) into the drum.
- Once fully loaded, the transfer equipment is retracted, the drum's inner cover is replaced, the drum is lowered and the drum is swiped and translated back to reattach the outer lid.

Yellowcake drums should be washed down to remove any surface contamination. Surveys of external surfaces of yellowcake drums prepared for shipment should be carried out before shipment. The surveys conducted should be adequate to ensure that the wash-downs reduce surface contamination levels to less than the regulatory limits. The bottoms of all drums should also be surveyed to determine the effectiveness of the wash-downs. The licensee should ensure the accuracy of survey measurements by having a quality assurance (QA) programme (see Chapter 4 and 7).

Contamination on drums (packages) should not exceed the regulatory limits. The average measured removable alpha contamination determined by wiping the external surface of the package with an absorbent material should be below 0.3666 Bq/cm^2 if a non-exclusive-use vehicle is to be used and or 3.666 Bq/cm^2 if an exclusive-use vehicle is to be used. Packages having higher contamination levels should be cleaned and resurveyed prior to shipment.

Labeling

All steel drums and containers containing yellowcake must bear labels, placards, etc.

Transport workers need to be aware of the contents of the packages, overpacks, tanks and freight containers that they are handling.

It is necessary to be able to identify the precise radiological hazard associated with the content of the cargo unit and the storage and stowage provisions which may be applicable. In the event of an accident in which a package is damaged, the radioactive content and activity information marked on the label is useful to emergency response personnel.

Because of the low level of radiation per unit mass, the yellowcake is classified as 'Low Specific Activity' LSA-1 and is treated as a Class 7 Dangerous Good for transportation with the assigned UN number 'UN 2912'.

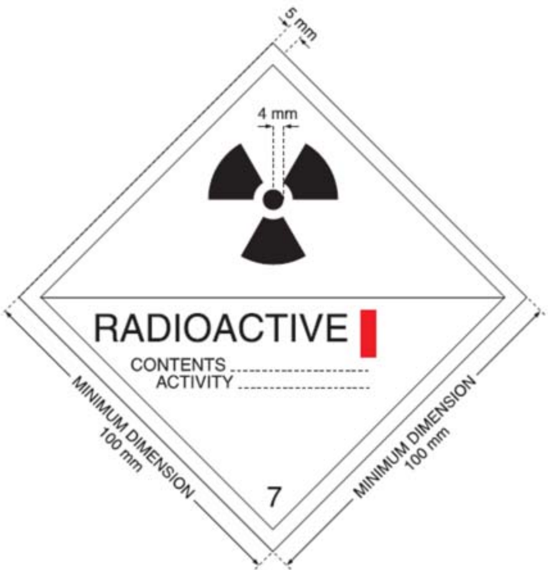
In terms of the radiation levels which may be encountered on the surface of the package, and in terms of transport index, packages are classified according to one of three categories. There is a different label for each category of package to simplify recognition and facilitate control by workers when handling packages.

The labels are either white or yellow. The yellow labels indicate that limitations are placed upon how these packages can be stowed or stored to ensure radiation safety and guard against criticality.

The packaging categories and labels are as follows:

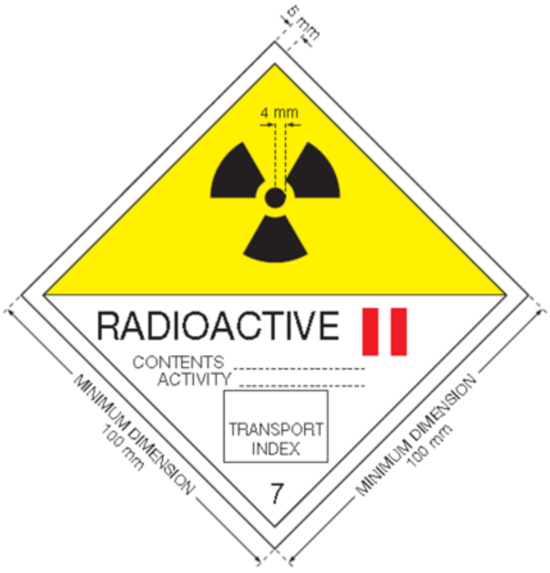
Category I - White, in which the maximum radiation level at the surface is not more than 0.005 mSv / h and the transport index does not exceed 0 (Fig. 8.1.3).

Figure 8.1.3. Category I – White label. Source IAEA (2012).



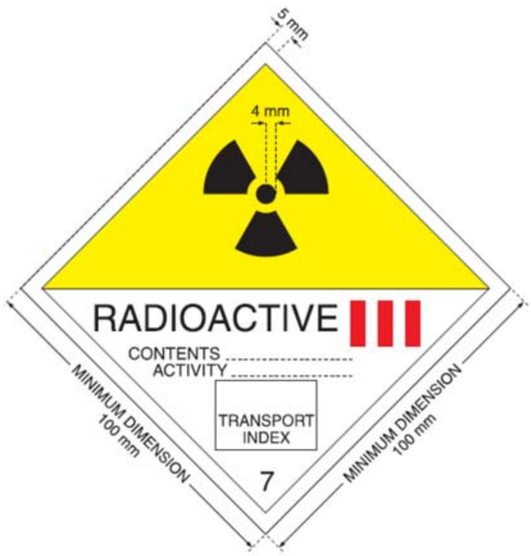
Category II - Yellow, in which the radiation level at the surface does not exceed 0.5 mSv / h and the transport index does not exceed 1 (Fig. 8.1.4).

Figure 8.1.4. Category II – Yellow label. Source IAEA (2012).



Category III - Yellow, is usually for packages with a surface radiation level of not more than 2 mSv / h and a transport index of not more than 10 (Fig. 8.1.5).

Figure 8.1.5. Category III – Yellow label. Source IAEA (2012).



Transport Index (TI)

The TI is a number which is assigned to a package (or overpack, tank, freight container or consignment) and used to provide control over groups of packages for the purpose of minimizing nuclear criticality and radiation exposure risks.

The transport index is the maximum radiation level in μSv / h at one metre from the external surface of the package divided by 10:

Example: 1 μSv / h (0.1 mrem / h) at 1 m equals a TI = 0.1.

Labels

The radioactive material labels constitute part of a set of labels implemented by the UN Recommendations on the Transport of Dangerous Goods, which is used internationally to identify the various classes of dangerous goods. This set of labels has been established with the aim of making dangerous goods easily recognizable from a distance by means of symbols.

Moreover, the number ‘7’, corresponding to the number of the UN hazard class for radioactive material, the consignor name, the UN2912 number, the proper shipping name ‘RADIOACTIVE MATERIAL, LOW SPECIFIC ACTIVITY (LSA-1)’, the type of package, for instance IP-1, the activity and the weight of the drum, the Marine Pollutant labelling should also appear on the label (Fig. 8.1.6).

The quantity of LSA material in a single Type IP-1 package shall be so restricted that the external radiation level 3 m from the unshielded material or object or collection of objects does not exceed 10 mSv / h.

Figure 8.1.6. Information required for the radioactive material labels.

The yellowcake producer should label each drum with a unique identification number which can be referred to the specific batch analysis. Each drum must be weighed using calibrated scales. The scales must have a calibration and maintenance programme to ensure the required accuracy.

Each applied seal must have a unique identification number that can be tied back to the production batch.

In accordance with national regulations and international recommendations, the containers should be marked, labelled, placarded and weighed. The containers are then inspected and sealed with bolt seals fixed to the door of each container. The container doors remain sealed throughout the entire shipment from mine site to receiver. The container seals are checked for integrity at all trans-shipment and discharge points.

An example of placarding required for containers carrying UOC in Australia is given in Figure 8.1.7.

Figure 8.1.7. Placarding required for containers carrying UOC in Australia. Source: Guide to Safe Transport of Uranium Oxide Concentrate, Australia (2012).

All information associated with the shipment must be kept in a system that tracks the batch number, net weight, QC results listing all the impurities for each batch and the results from the radiological surveys required to meet international transport regulations. This information is necessary for the authorities to approve the shipment.

8.2 Transport of yellowcake

The IAEA Transport Safety Regulations (2005, 2012) recommend that a Radiation Protection Programme, which includes an emergency response plan, shall be established for the transport of radioactive materials. The nature and extent of the measures to be employed in the programme shall be related to the magnitude and likelihood of radiation exposures.

IAEA (2012) has set recommendations for the safe transport of radioactive materials (including also yellowcake) in the document 'Regulations for the Safe Transport of Radioactive Material SSR-6'. The requirements of SSR-6 have been taken up by the modal organizations in their regulations (Table 8.2.1).

Table 8.2.1. Safety regulations for the transport of radioactive material. Source: http://www.wnti.co.uk/nuclear-transport-facts/regulations.aspx.

Mode of transport	Regulation/code
Sea	International Maritime Dangerous Goods Code (IMDG Code) International Code for the Safe Carriage of Packaged Irradiated Nuclear Fuel Plutonium and High-Level Radioactive Wastes on Board Ships (INF Code)
Road and rail	European Agreement concerning the International Carriage of Dangerous Goods by Road (ADR) Convention concerning International Carriage by Rail (COTIF) Appendix C – Regulations concerning the International Carriage of Dangerous Goods by Rail (RID) 2013 Edition Agreement of Partial Reach to Facilitate the Transport of Dangerous Goods MERCOSUR
Air	Technical Instructions for the Safe Transport of Dangerous Goods by Air (ICAO - TI) Dangerous Goods Regulations (IATA - DGR)
All	Recommendations on the Transport of Dangerous Goods (UN)
Inland waterways	European Agreement concerning the International Carriage of Dangerous Goods by Inland Waterways (ADN)

Different packaging standards have been developed by IAEA (2009b) according to the chemical, physical and radiological characteristics and potential hazards posed by the different types of radioactive material, and regardless of the mode of transport.

Packages must contain and prevent the release of the contents and shield ionizing radiation. The packages should have safe lifting attachments, be easy to clean and decontaminate, prevent the collection or retention of moisture, dust or other contaminants and should comply with the requirements within the agreements. The requirements of the industrial packages can be seen in Table 8.2.2.

Table 8.2.2. Industrial packages (IP) requirements. Modified from: http://www.wnti.co.uk/media/31649/IP7_EN_MAR13_V1.pdf.

	IP-1	**IP-2**	**IP-3**
Design requirements	General requirements: Relation to its mass, volume and shape. Can be properly secured in/on conveyance. Proper lifting attachments (snatch lifting). External surface easily decontaminated and free of protruding features. Outer layer should prevent collection and retention of water. Should withstand the effects of any acceleration, vibration or vibration resonance which may arise under routine conditions of transport. Material should be physically and chemically compatible with the radioactive contents. All valves should be protected against unauthorized operation. Take into account ambient temperatures and pressures that are likely to be encountered. Additional pressure and temperature requirements, if transported by air (Temp -40°C to 55°C and pressure no less than maximum normal operation pressure plus 95kPa). Requirement concerning smallest overall external dimension.	Same as general requirements for IP-1. Additional tests: Free drop (from 0.3 to 1.2 metres, depending on the mass of the package). Stacking or compression (24 hours/ equivalent to the greater of the equivalent of 5 times the mass of the actual package or the equivalent of 13 kPa multiplied by the vertically projected area of the package).	Same as general requirements for IP-1. Type A additional requirements (smallest overall external dimension, seals, tie-downs, temperature, containment, reduced pressure, valves). Additional tests: Each of the following tests must be preceded by a water spray test (approximately 5 cm per hour for at least one hour): Free drop (from 0.3 to 1.2 metres, depending on the mass of the package). Stacking or compression (24 hours/ equivalent to the greater of the equivalent of 5 times the mass of the actual package or the equivalent of 13 kPa multiplied by the vertically projected area of the package). Penetration (6 kg bar dropped from 1 metre).

All consignor producers have an obligation to ensure that the product is packaged correctly and stowed securely within shipping containers that comply with national and international standards as required by IAEA, IMO and European and North American authorities.

An additional requirement for each Consignor producer is to ensure and certify that both the drums and the shipping containers are clean and free of any radioactive residue or associated surface contamination. The limits for surface contamination should be specified in the regulations, and consignors are responsible for observing them.

Carriers have to take into account potential contamination of conveyances. The IAEA recommendations specify that: 'A conveyance and equipment used regularly for the transport of radioactive material shall be periodically checked to determine the level of contamination (IAEA, 2012). The frequency of such checks shall be related to the likelihood of contamination and the extent to which radioactive material is transported' (IAEA, 2012).

The IAEA recommendations include appropriate test procedures (e.g. tests that simulate normal transport conditions such as a fall from a vehicle, exposure to rain, being struck by a sharp object, having other cargo stacked on top, free drop and compression) for the various package types. For yellowcake, requirements stipulate that packages maintain their integrity during normal transport conditions. Yellowcake is packed in sealed 200-litre steel drums meeting IP-1 industrial package requirements. Each drum has a tight-fitting lid which is secured to the drum by means of a steel locking ring and then clamped by a locking ring bolt.

In the unlikely event of a spill, management of the clean-up is described by the Emergency Preparedness and Response Plan. The emergency plans for transport of yellowcake should be established by the operator, transport company, regulatory body, transport authority and public security agencies (GWADMP, 2013).

A spill of yellowcake must be treated in the same way as an incident involving any other dangerous good / heavy metal concentrate. The most important thing to remember is to remain upwind and avoid inhalation. In the event of spill, the following may be required: particulate respirator, dust-proof goggles, coveralls and PVC, rubber or cotton gloves. Other than the inhalation hazard, spilled yellowcake does not pose any immediate danger.

IAEA Transport Regulations and supplementary guidance documents are listed in Table 8.2.3.

Table 8.2.3. IAEA Transport guidance documents.

Title	Guide
Advisory Material for the IAEA Regulations for the Safe Transport of Radioactive Material (2012 Edition)	SSG 26
Planning and Preparing for Emergency Response to Transport Accidents Involving Radioactive Material Safety Guide	TSG 1.2
Radiation Protection Programmes for the Transport of Radioactive Material Safety Guide	TSG 1.3
The Management System for the Safe Transport of Radioactive Material Safety Guide	TSG 1.4
Compliance Assurance for the Safe Transport of Radioactive Material Safety Guide	TSG 1.5

Storage

Yellowcake storage on-site and off-site should be undertaken in accordance with the relevant national and international regulations and recommendations.

Where regular storage occurs, it is good practice to always use the same area within the shipping terminal for the storage of yellowcake containers to assist personnel to identify, familiarize themselves with and remember storage locations.

If the drums are stored for some time before transportation, the area should be secured and gamma radiation should be monitored.

Accidental dispersal of radioactive material via dust or mud on equipment (vehicle) leaving the site should be prevented by passing a contamination clearance process.

The selected storage location prior to shipping must be away from offices, accommodation camps, workshops and regular and highly trafficked areas.

Final check prior to transportation

An important requirement is that the radioactive surface contamination levels on any external part of the package must not exceed 4 Bq/cm^2 for beta and gamma emitters and low toxicity alpha emitters and 0.4 Bq/cm^2 for all other alpha emitters. This can be achieved by ensuring that all external and internal packaging has not been in contact with radioactive material. A 'wipe test' is used to determine the radioactive contamination on the surface of a package.

The potential for occupational exposure to the yellowcake product will primarily occur during the drying and packaging processes. These processes will be undertaken in a controlled access area.

All workers entering the area are required to wear the following and follow the recommendations:

- Use disposable overalls with hood (tyvek or similar), disposable latex or similar gloves, disposable overshoes, a correctly fitted dust mask, safety glasses or full face shield as appropriate.
- Prohibit drinking, smoking and eating in the filtration and packaging areas and adjacent areas.
- Inspect the external surface after sealing a drum of yellowcake to confirm the absence of dirt, product or other contaminants. A wipe test of the lid, rim and upper external wall of the drum will be taken to confirm that the alpha activity is less than the authorized level.
- Visually inspect for drum pressurizations.
- Be familiar with the Emergency Response Plan.

Consignor producers empty shipping container inspection checklist

There is a requirement for all consignors to comply with the 'Convention for Safe Containers (CSC)' and (if members) to conform to the shipping container packing requirements of the United States Customs and Border Protection, Customs-Trade Partnership against Terrorism (C-TPAT).

External checks:

- Record shipping container number details, name of person undertaking the inspection and the date of inspection.
- Record the Approved Continuous Examination Program (ACEP) and CSC approval details, shipping container type, date of manufacture, maximum gross, stack and shipping container tare weight details for the shipping container indemnity and cleanliness certification.
- Check that the ACEP identification label or the validity of the CSC container safety approval plate and re-inspection date has not expired.
- Check the undercarriage to ensure there is no damage to the under floor timber, the shipping container floor rails or the box Tyne channels, etc. Extreme care must be taken to ensure worker safety when performing these checks. The worker should never stand underneath the shipping container when performing these checks.
- Check that all exterior surfaces have minimal surface and no major structural rust. The shipping container should been in good condition and have a visually pleasing appearance.

- Undertake visual checks to ensure there is no obvious damage, holes or cracking of the external wall, roof panelling or corner joints. Minor cracks in joints can be filled with silicon if required.
- Ensure that any bowing or warping of the roof or wall surfaces fall within the stated Institute of International Container Lessors (IICL) limits.
- Check both doors to ensure they are not distorted and close tightly; that all door fittings, locking mechanisms, door gaskets and seals are in serviceable order.
- Remove any previously applied placards, markings and associated warning or advisory labels.
- Check the top and bottom mounted corner fitting locking structures for serious damage.
- Always feel free to record and document any issues irrespective of them being considered good or bad as photographic evidence is irrefutable and in the modern age of the digital camera is a cheap form of insurance.

Internal checks:

- Check that the shipping container has been cleaned free of any previous cargo residue material. Check that there is no dirt or debris left on the floor or the door of the shipping container.
- Undertake a survey of the shipping container prior to packing to ensure that no form of contamination is present.
- Check that all interior surfaces have minimal surface and no major structural rust.
- Undertake visual checks to ensure there is no obvious damage, holes or cracking of the internal wall, roof paneling or corner joints. Minor cracks in joints can be filled with silicon if required.
- Ensure that any bowing or warping of roof or wall surfaces fall within the stated IICL limits.
- Check that there is no damage or evidence of fresh staining to the shipping container flooring.
- Ensure that the top and bottom securing lugs are both appropriate and fit for use.
- Undertake a water proof test** to ensure the integrity of the overall sealing capability of the shipping container to effectively prevent the entry or discharge of material or moisture.

**Water proof test: This is best done by entering inside the shipping container and having someone close both of the shipping container doors. Due to the extremes of temperature experienced at many if not most mine sites, consideration as to the total time spent 'shut' inside the shipping container must be given. Additionally caution should be taken as there is always the possibility that residual potent gases from the fumigation of previous cargoes could also be present. Should any indication of daylight be seen through the door seals or from elsewhere within the shipping container it must be assumed that water could gain entry and therefore the shipping container should be deemed unfit for purpose.

Consignor (producer senders) packed shipping container inspection checklist

After the shipping container has been packed and well prior to preparing the shipping documentation, each packed shipping container should once again be inspected.

Good practice suggests that wherever possible a person independent of those specifically involved in the packing of the shipping container conducts a final external and internal check addressing the requirements above applying to empty shipping containers also addressing the additional items below:

- Confirm with those involved in the packing of the shipping container that no incidents occurred during packing of the shipping container that may have resulted in shipping container contamination.
- If a possible contamination incident did occur, confirm that the shipping container was emptied, cleaned and resurveyed.
- If resurveyed, confirm that survey results were documented and acceptable.
- Ensure that all drums are adequately secured.
- Check that locking seals on each drum lid are tight and that each drum has the applicable Radioactive Category label and Marine Pollutant labelling.
- Check that the drum details match the drum, batch and lot details against the shipping container packing log sheet.
- Conduct wipe tests on the external surface of all drums. When using a well-established and reliable drum cleaning station, a random selection of drums can be wipe tested based on statically sampling techniques.
- Ensure that there are no obvious signs of residual or extraneous packaging or securing material.
- Close and lock the shipping container doors applying the designated seal numbers as per the shipping container log sheet.
- Clean and wash the external surfaces and undercarriage of the shipping container to remove residual surface dust or soil that could contain or support any form of contamination.
- Clean, prepare and affix a UN2912. Cat III Yellow and Marine Pollutant labels to the four sidewalls of the shipping container.
- In order to eliminate the possibility of contaminated soil becoming caught up in the undercarriage of the shipping container, store the packed and inspected shipping container on a clean area of bituminous or concrete covered hardstand area ready awaiting transport from the mine site.
- File and store copies of the final inspection report in line with internal operating procedures.
- Always feel free to record and document any issues irrespective of them being considered good or bad as photographic evidence is irrefutable and in the modern age of the digital camera is a cheap form of insurance.

Consignor's responsibilities

- Yellowcake is a chemical concentrate of uranium ore and it is defined as being a low specific activity (LSA-I) material.
- The regulatory requirements for packaging LSA-I material allow for the consignment to be shipped in bulk or in most types of IP-1 packaging.
- As both road and sea transport modes are to be used (e.g. in Greenland), the shipment should satisfy the requirements of the Transport Code and International Maritime Dangerous Goods Code, including the local authority. Although the requirements of the two Codes may be highly similar, it would be advisable to check for possible variations.
- The steel drums should be loaded into freight containers.
- Labeling and marking: Each package should
    - Be marked with:
        - The consignor's and consignee's names.

- UN2912 and the proper shipping name 'RADIOACTIVE MATERIAL, LOW SPECIFIC ACTIVITY (LSA-1), non-fissile or fissile-excepted, Category, TI'.
    - Marine pollutant Mark.
    - The type of package (e.g. IP-1).
    - Unique ID number.
    - Weight and total activity.
- Have completed WHITE or YELLOW labels on opposite sides.

For LSA-I material, the documentation shall include the information specified on the labelling as well as information on the physical and chemical form of the material and maximum activity of the radioactive content during transport expressed in units of Becquerel (Bq) (IAEA, 2012).

Suggested specification for shipping containers to be used for the transportation of yellowcake

- Ideally all shipping containers used to transport yellowcake should be rated to 30 (30.4) tonnes load capacity.
- The Container Safety Convention (CSC) plate on each shipping container must indicate a valid re-inspection date or Approved Continuous Examination Program (ACEP) identification.
- All shipping containers must be ISO 1496-1 compliant having an adequate number of top and bottom anchor points.
- Shipping containers are to be free of dents in walls, doors and roof.
- Shipping containers need to have under floor box channelling for fork lift tynes.
- Shipping containers are to be clean inside and outside having minimal surface and no major structural rust.
- Shipping containers should be totally free of any holes or cracks that may allow the entry or discharge of material or moisture into or from within the shipping container.
- Shipping containers must have adequate door seals that provide effective dust proof seals preventing the entry or discharge of material or moisture into or from within the shipping container.
- At least one of the locking handles on each shipping container door must have a hole capable of allowing the placement of a shipping container bolt seal.

For further information refer to the Institute of International Container Lessors (IICL) Guide for Container Equipment Inspection 5th Edition (IICL-5) https://www.iicl.org/education/publications.cfm

Compliance – transport of radioactive materials

The relevant competent authority shall arrange for periodic assessments of the radiation levels and radiation doses to persons due to the transport of radioactive material (yellowcake) in order to ensure that the system of protection and safety complies with the regulatory requirements.

Compliance with transport regulations should include an inspection team trained for transport of radioactive materials, reporting requirements for inspectors, standards of conduct of inspectors, methods of inspection to be used (such as in transit, packaging – photos, interviews), methods for selection of inspection samples (sampling, preparation, analysis and duplicate), standard procedures and practices for enforcement policy (illegal shipments), security verification, transboundary issues, relevant technical information and questionnaires, previous inspection result follow-ups.

Non-compliance

In the event of non-compliance with any limit in regulatory requirements applicable to radiation level or contamination:

The consignor, consignee, carrier and any organization involved during transport that may be affected shall be informed of the non-compliance by:

- The carrier if the non-compliance is identified during transport.
- The consignee if the non-compliance is identified at receipt.

The carrier, consignor or consignee, as appropriate, shall:

- Take immediate steps to mitigate the consequences of the non-compliance.
- Investigate the non-compliance and its causes, circumstances and consequences.
- Take appropriate action to remedy the causes and circumstances that led to the non-compliance and to prevent a recurrence of circumstances similar to those that led to the non-compliance.
- Communicate to the relevant competent authority on the causes of the non-compliance and on corrective or preventive actions taken or to be taken. The communication of the non-compliance to the consignor and the relevant competent authority shall be made as soon as practicable.

8.3 Radiation protection during the production of yellowcake

The occupational and public monitoring, dose assessment and radiation protection programmes should be developed in detail by relevant authorities.

Since the ore processing steps reject nearly all the radium to the tailings, very little radon is generated and released during the production of yellowcake. Yellowcake drying and packaging activities present a potential for particulate matter release and are therefore of concern. The potential for particulate release during yellowcake production depends on the degree to which the product is dried or calcined and on the effectiveness of off-gas filtration. The drying process should be performed under negative pressure with exhaust gases passing through dust collection systems to avoid yellowcake losses. Off-gases are scrubbed or filtered prior to release via a stack.

In the precipitation circuit and the yellowcake drying and barreling areas, surface contamination can be a problem. The IAEA recommends a limit for alpha contamination on such areas as walls, floors, benches and clothing of 37 Bq/cm^2. Based on experience, the IAEA concluded that if surface contamination levels are kept below this value, the contribution to airborne radioactivity from surface contamination will be well below applicable limits.

Yellowcake contamination on surfaces is visible (NRC 2002). It is recommended that surfaces where yellowcake may accumulate be painted in contrasting colours because surveys for surface contamination in work areas are visual. In yellowcake areas, daily visual inspections should be made for locating yellowcake contamination on surfaces. Visible yellowcake should be cleaned up promptly, especially where contamination will be disturbed and re-suspended on walkways, railings, tools, vibrating machinery and similar surfaces. Spills should be cleaned up before the yellowcake dries so that re-suspension during clean-up will be lessened.

Although yellowcake is only weakly radioactive, radiation protection remains of importance. In most cases, radiation doses associated with yellowcake transport are well below all relevant international limits and guidance levels and are low in comparison with natural background radiation doses. The radiation characteristics of yellowcake are presented in more detail below and are based on the Guide to the Safe Transport of UOC (uranium oxide concentrate - yellowcake) from the Government of Australia.

There are two ways in which yellowcake can contribute to a radiation dose during packaging and transportation: alpha emissions (if inhaled or ingested) and gamma radiation.

Yellowcake is mainly an alpha emitter and if the material remains in its container it poses no potential alpha dose risk. The only time the environment may be exposed to alpha radiation from yellowcake would be in the event of a spill of the material. In this case, the risk to the personnel involved and the environment can be controlled by using personal protective equipment (PPE such as respiratory protection) and by controlling dust dispersion. If yellowcake is not inhaled or ingested, in all normal transport scenarios, the contribution of alpha radiation to dose levels would be zero.

Yellowcake is also a weak, low-energy gamma emitter. When in proximity to containers and drums of yellowcake, there will be an increase in the gamma dose rate. The radiation dose rates of gamma radiation from drums and containers are well known, and a conservative approach is used to provide a high level of protection during transport. Table 8.3.1 shows the typical radiation dose rates 1 m from a drum and a container of yellowcake when shipped.

Due to the radioactive nature of yellowcake, the gamma radiation dose rates increase over time after it is produced. The increase in the gamma dose rate is due to the decay of the uranium-238 to thorium-234 which is a gamma emitter. The thorium-234 comes into equilibrium with uranium-238 after about two to three months, so the gamma dose rate ceases to increase after this time. To account for this increase in gamma dose rates, yellowcake producers often use a conservative maximum upper dose rate in their delivery (production) documentation. This dose rate is reported in shipping documents and is also used to calculate the TI, which is used to designate the degree of control that needs to be exercised by the carrier during transportation.

Table 8.3.1. Typical radiation dose rates for yellowcake (this is just an example). Modified from http://www.industry.gov.au/resource/Documents/Mining/uranium/Guide-to-Safe-Transport-of-UOC.pdf.

Description	Contained activity of U_{238} (GBq)	Gamma dose rate at 1 metre (µSv/h)	Max Gamma dose rate at surface (µSv/h)	Transport Index
Drum	10	4#	20	0.4#
Container	440	20	60	2

Measured maximum values from actual drums.

To put these dose rates in context, they can be compared with both statutory limits and natural background radiation. The occupational and public effective dose limits for exposure to radiation recommended by ICRP are 20 mSv/year and 1 mSv/year, respectively. This means that a person would have to spend approximately 1,000 hours within one metre from a container of yellowcake to reach the occupational limit. During typical transport operations (including loading, trucking and shipping), doses typically remain well under the public dose limit.

The level of exposure received from transporting yellowcake is similar to that received from natural background radiation. The average person worldwide is exposed to 2.4 mSv/year of background radiation from natural sources (UNSCEAR, 2008). The dose range in nature is between 1 and 10 mSv/year, the exact annual dose being dependent on location, climate and lifestyle (Holm, 2000). The highest known level of background radiation affecting a substantial population is in Kerala and Madras states in India where some 140,000 people receive doses which average over 15 mSv per year (WNA, 2012). Dose rates received standing near a container are similar to those received in a modern aircraft (because there is less atmospheric shielding from cosmic rays). For this reason, personnel involved in the transport of yellowcake will typically receive a lower dose than that received by international aircrew and some frequent flyers.

The most significant potential environmental impact not related to the radioactivity of the yellowcake production is contamination of the aquatic environment by organic solvents and other reagents used in the milling process. Release of, for example, ammonia to the environment may occur through co-disposal of ammonium sulphate bleed streams and tailings slurries.

Yellowcake can be produced when the ADU is decomposing at approx. 800 °C in a hearth calciner and can also be produced from uranyl peroxide using a strong acid strip/hydrogen peroxide precipitation process. The last process uses less energy (40% to 50% less) for drying and has significantly less solids discharge (IAEA, 2009a). The transport, storage and use of liquid ammonia and hydrogen peroxide also pose potential significant environmental risks. A specific ammonia or hydrogen peroxide disaster plan should be available in the event of a spill or leakage from the tanks.

Milling processes generate solid and liquid wastes containing radionuclides and non-radioactive contaminants. If those wastes are not properly managed they may lead to environmental contamination of air, water and land (Chapter 6).

8.4 Examples of radiological risks resulting from failures in the yellowcake production

The radiological risk resulting from equipment failures during yellowcake production is mainly for occupational and members of the public. Some examples will be described, but it should be taken into consideration that the consequences of failures are site specific and depend on the radiological event, the extent of radioactive contamination, climatic conditions, prompt actions undertaken by emergency preparedness and response team, etc. The examples below do not cover all potential radiological events at a uranium mine site.

Thickener tank failure

The thickener tank stores leached solution before it is sent to liquid-solid separation, purification and concentration and precipitation and drying into yellowcake. Thickener tank failure can pose an inhalation risk to workers and groundwater, air (dust dispersion) contamination if spills are not cleaned up before the contaminants are allowed to dry. If the yellowcake slurry is allowed to dry in case of a spill incident, it would pose a significant risk of uranium inhalation. The thickener tank itself does not pose any external exposure risk, as most of the uranium progeny have been removed and the alpha component would be significantly attenuated by the slurry. Annual external exposures have been calculated to be 1.2 mSv for the limiting case of a worker standing directly next to the thickener tank for an entire 2,000 hour work year (Mackin et al., 2001).

Exposure to pregnant lixiviant

Pregnant lixiviant (the liquid in which the uranium has been dissolved) and loaded uranium resin (ion exchange resin used in uranium extraction) may pose a radiological hazard as an external exposure source and an internal exposure source by the possibility of inhaling radon-222 and thoron-220, in case the deposit contains also thorium-232. The most likely indoor exposure incident would occur if the pregnant lixiviant / resin were released due to a pipe or valve failure during the ion exchange process, at which point the solution would drain from the ion exchange column and the radon gas would be released to the air. In addition to the inhalation hazard from radon, the pregnant lixiviant contains some other radioisotopes of interest (natural uranium, Po-218, Po-214, thorium isotopes, Pb-210, Po-210 and Ac-227) that may also cause a significant exposure (Mackin et al., 2001).

Yellowcake dryer accidents

Yellowcake remains stable under all conditions of storage, handling and transport. If proper procedures are followed, there is little risk to handlers.

The dried yellowcake can pose a significant inhalation hazard to the on-site worker if spilled and allowed to dry. Failure of the dryer cake systems includes fire / explosion (worst case), spillover of dryer contents due to a faulty discharge valve and failure of off-gas treatment systems causing the gases to release into the dryer area.

Drum pressurization events has happened in the past, resulting in inhalation of yellowcake by workers. To avoid such accidents, the U.S. NRC states that for facilities utilizing hydrogen peroxide precipitation and drying temperatures below 800°C, a cooling and venting period of at least 12 hours is necessary to prevent oxygen gas build-up in yellowcake drums. Shorter periods may be ineffective. Many operators have elected to implement a cooling and venting time of 24 hours.

To prevent drum pressurization, some operators have implemented two basic corrective actions: increasing the cooling / venting time before the lid is sealed and conducting visual inspections of the drums for signs of pressurization prior to shipment.

Facility operators should also develop protocols to minimize the potential for organics, including oils and greases, to enter into yellowcake process circuits.

8.5 References

Guide to the Safe Transport of Uranium Oxide Concentrate, Australia, 2012, available online at http://www.ret.gov.au/uranium.council

Government of Western Australia, Department of Mines and Petroleum (GWADMP), 2013. Guide to Uranium in Western Australia. East Perth, Western Australia.

Holm, L.E., 2000. UNSCEAR: present and future activities from IRPA-10. Proceedings of the 10th international congress of the International Radiation Protection Association on harmonization of radiation, human life and the ecosystem United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), Vienna, Austria.

IAEA, 2005. Regulations for the Safe Transport of Radioactive Material Safety Requirements No. TS-R-1, IAEA, Vienna.

IAEA, 2009a. Establishment of uranium mining and processing operations in the context of sustainable development, Nuclear Energy Series No. NF-T1.1, IAEA, Vienna.

IAEA, 2009b. Regulations for the Safe Transport of Radioactive Material, Safety Standards Series No. TS-R-1, IAEA, Vienna.

IAEA, 2012. Regulations for the Safe Transport of Radioactive Material – 2012 Edition Specific Safety Requirements IAEA Safety Standards Series SSR-6, IAEA, Vienna.

Mackin, P., Daruwalla, D., Winterle, J., Smith, M., Pickett, D., 2001. A Baseline Risk-Informed Performance Approach for In Situ Leach Uranium Extraction Licensees, NUREG/CR-6733, Nuclear Regulatory Commission, Washington, DC. September 2001.

NRC-RG 8.30, 2002, Health physics surveys in uranium recovery facilities, Regulatory guide 8.30, U.S. Nuclear Regulatory Commission

UNSCEAR (United Nations Scientific Committee on the Effects of Atomic Radiation), 2008. Sources and effects of ionizing radiation available online http://www.unscear.org/docs/reports/2008/09-86753_Report_2008_Annex_B.pdf

WNA, 2012.
http://www.world-nuclear.org/info/Safety-and-Security/Radiation-and-Health/Radiation-and-Life/

9 Decommissioning and Rehabilitation of uranium facilities

This chapter provides a description of specific requirements for decommissioning and rehabilitation of uranium facilities and surrounding areas.

At the completion of a mine project, the mine, mill and tailings facilities have to be decommissioned and, if possible, returned to the state existing prior to the commencement of mining.

The mine project should be designed with the end state in mind. Decommissioning, rehabilitation and long-term care and monitoring costs should be accounted for, and the following factors should be taken into consideration: lessons learnt, successes achieved elsewhere over the last 30 years (IAEA, 2014), minimization of long-term adverse effects with the aim to protect the environment and humans, including also non-humans, and future generations (the site should be safe for people and wildlife, if any, the mine site should be chemically, radiologically and physically stable, etc.), minimization of restrictions on future land use and reclaimed landscape (stable and self-sustaining), when possible.

Decommissioning is undertaken on the basis of planning and assessment to ensure safety, protection of employees, members of the public and the environment.

Planning for decommissioning, rehabilitation and long-term care should commence at the design stage of the project with progressive improvements and rehabilitation work throughout the lifetime of the facility. During the operational phase, any activity that impacts mine closure should be considered (for example dispersal of radioactive materials during processing and transport, storage of concentrates and disposal of tailings and waste, location of wastes used as land).

9.1 Decommissioning and rehabilitation plan

In the early phase of the project, the operator has to prepare an initial decommissioning and rehabilitation plan and submit it to the appropriate authorities for review and approval (as part of the license application or renewal).

The initial decommissioning and rehabilitation plan should be progressively updated throughout the life of the facility, and each separate application for authorization (construction, operation and decommissioning) should include a decommissioning plan. As required by the authorities, the closure (decommissioning and rehabilitation) plan should be periodically (e.g. every five years) updated by the operator and should be submitted to the authorities for review. Updates of the closure plan shall be made as necessary, concerning, for example, changes in the operational process, relevant operational experience gained, recent experience derived from international developments in closure practices of similar facilities, new or revised safety requirements / technologies relevant to the adopted closure strategy and incidents that may occur at the mine site and have an impact on the closure process.

The operator has to prepare and submit a final closure plan and supporting documents for review and approval by the regulatory body, in accordance with national regulations, in order to obtain an authorization to conduct closure activities.

The final closure plan shall be supported by a safety assessment addressing the planned decommissioning and rehabilitation activities and incidents, including accidents that may occur or situations that may arise during decommissioning.

The appropriate authority should conduct the inspections and review of the closure actions to ensure that they are being carried out in accordance with the authorization for closure and the specific requirements (e.g. safety requirements). The appropriate authority should determine when the decommissioning activities have been ended and the rehabilitation of the site may commence.

The operator should plan and conduct the decommissioning and rehabilitation actions in compliance with the authorization for closure and with requirements derived from the national legal and regulatory framework. The operator should be responsible for all aspects of safety, radiation protection and protection of the environment during closure.

The selected closure techniques should ensure the following requirements:

- Radiation protection and safety of workers, members of the public and the environment.
- Minimization of waste generation during the decommissioning.
- Minimization of potential negative environmental impacts.

When determining the appropriate closure strategy, the following aspects should be considered, with due regard to regulatory requirements:

- Public input.
- Forms and characteristics of radioactive and non-radioactive hazardous contamination.
- Potential environmental impacts.
- Occupational and public radiological doses.
- The integrity of tailings facility containment and other structures over time.
- The potential for recycling of equipment and materials.
- Availability of decontamination and dismantling technologies.
- Availability of knowledgeable staff.
- Proposed end-state of the site.
- Costs and available funding.
- Other requirements (political, social and economic considerations).

The initial decommissioning and rehabilitation plan should be based on the applicable requirements derived from the national legal and regulatory framework and should include but not be limited to the following:

- Decommissioning and rehabilitation timeliness of actions. Environmental impact assessment (site characterization including groundwater modelling, seepage load balance, waste rock and tailings characterization, site contamination survey, water balance, assessment of the environmental values in the environment, flora and fauna investigations, etc.).

- Baseline data, environmental monitoring results during the construction and operational phases, environmental and effluent monitoring programme during decommissioning and long-term surveillance programme.
- Decommissioning strategy (e.g. radiological surveys for determining levels of contamination at the facility, decontamination of facilities including buildings, areas and equipment clean-up to the extent practicable, recycling of salvageable equipment and materials, removal and / or disposal of radioactively contaminated materials, building dismantling, approved waste disposal site, water treatment (if necessary) and disposal of water treatment plant sludge, disposal of domestic and industrial wastes, disposal / or recycling of hazardous materials such as explosives, fuels and chemical reagents).
- Management of waste, including radioactive waste generated during decommissioning. Potential waste generated during decommissioning may include but is not limited to: residual liquids from mill components, solid and liquid decontamination residues, residues generated from the water treatment plant, building materials that may be contaminated, contaminated materials from processing plant and machinery, unprocessed ore or lower grade rock materials, etc.
- Map and extent of contaminated site and areas at the mine sites that have to be rehabilitated. Investigations that may be performed prior to rehabilitation of the site may include but are not limited to: environmental monitoring, water balance, groundwater assessment (modelling), waste rock and tailings characterization, seepage load balance, flora and fauna investigations, etc.
- Description of the rehabilitation measures / methods to be applied (stability period).
- Reclaiming the tailings site(s) (long-term stabilization of tailings).
- Rehabilitation of waste rock dumps (re-shape and cover).
- Rehabilitation of contaminated soil (if any). Factors to be considered: geotechnical properties assessment, detailed geochemistry, depth of contamination, refinement of volumes, etc.
- Restoring groundwater (and other water sources if impacted by the mining activities) to acceptable conditions by reducing levels of contaminants (e.g. AMD mitigation methods).
- Management of the waste generated during the course of the rehabilitation programme.
- Long-term surveillance and care: details on monitoring and surveillance programmes that will be conducted after completion of the rehabilitation programme, plans for remediation of possible upset events occurring during the rehabilitation programme.
- Predicting the final state of the rehabilitated areas, including site surveys of radiological and non-radioactive parameters for soil, water and air. Demonstrating that the facility meets the final state (end state) criteria specified in the approved final plan. Verifying that the end state criteria have been met by performing a final radiological survey. Gamma radiation levels and radon emanation rates from the rehabilitated site should not exceed the regulatory limits established by the regulatory body. Similarly, the levels of non-radioactive parameters should not exceed the regulatory limits established by the regulatory body.
- Appropriate safety procedures, implementation programme and emergency plans.

- Provision for properly trained, qualified and competent staff to conduct the decommissioning activities.
- Keeping and retaining records and submitting reports as required by the regulatory body.
- The proposed end state of the decommissioned and rehabilitated facilities and surrounding areas, supported by radiological surveys to demonstrate that the end state has been achieved. Proposed end state includes also general controls after decommissioning, land characterization (radiological parameters), water treatment, when necessary, groundwater protection and, if necessary, clean-up. Verifying that end state criteria have been met by performing a final radiological survey.
- Inspection and enforcement plan.
- Estimating the cost of decommissioning and rehabilitation actions and providing financial assurances and resources to cover the costs associated with safe decommissioning, including management of the resulting radioactive waste.
- Establishing and implementing an integrated management system. If the licensee changes during the lifetime of the facility, procedures shall be put in place to ensure transfer of responsibilities for decommissioning to the new licensee.
- Public involvement.
- Other aspects.

Before abandoning a uranium mine site, a final decommissioning / rehabilitation report should be submitted to the appropriate authority. The final report shall ensure that the end state of the facility specified in the final decommissioning / rehabilitation plans has been reached. The final report should include but not be limited to the following:

- Final version of the radioactive waste management plan (RWMP), including the locations (geographical coordinates) in which radioactive waste is buried, depth of waste deposition and the types of waste, radiological parameters and quantities of waste (including also equipment / machines / materials buried).
- Description of performance for the liner material (clay, plastic, concrete) and for the cover top, including its thickness and the surface gamma dose rate of the rehabilitated site.
- Location of reshaped and rehabilitated areas showing surface contours and re-vegetation.
- Reports on all environmental monitoring results of radioactive and non-radioactive contaminants.
- Dose assessment records of employees and members of the public.
- Records of measurements that confirm compliance with clean-up criteria.
- Quality assurance audits and inspections.
- List of buildings, roads and harbour constructions that will remain on site and have been taken over by other persons or institutions (approved by relevant authorities).
- A commitment to inspect, monitor and maintain the abandoned site for a certain period of time (to be set by the relevant authority).
- Recommendations for improvements that could be incorporated into future similar mining operations.
- Other issues / items.

On the basis of this review and the evaluation of the end state of the mine site, the authority may release the site from regulatory control with / or without restrictions on the future use. If the mine site is released from regulatory control with restrictions on future use, appropriate controls and programmes for environmental monitoring and surveillance, including responsibility for implementation, should be put in place.

When the work (decommissioning, rehabilitation, monitoring and care) to be carried out by operator is completed, the responsibility for long-term surveillance, monitoring and maintenance of the site is transferred to the appropriate authorities.

9.2 Financial Assurances

In order to provide the necessary confidence that the resources will be available to maintain radiation and environmental protection during all project activities, provision for allocating resources should be established early in the planning of the uranium facility.

According to the international recommendations/legal framework, such a mechanism should be established prior to operation to secure the funds needed for decommissioning. This mechanism should be sufficiently robust to provide for decommissioning needs in the event of a premature shutdown of the uranium facility, i.e., at any time from exploration through to decommissioning. Irrespective of the type of financial mechanism used, provision for premature decommissioning must be in place should it be needed. The funding mechanisms must be put in place, to ensure that adequate funds will be made available to enable completion of the decommissioning activities on a timescale commensurate with the decommissioning plan. A summary of the measures that will be employed to manage project risks and prevent or mitigate cost escalation must be provided by the operator and approved by the regulator.

Closure costs can be distributed into the following categories:

- Decontamination and dismantling of facilities at the mine site.
- Reclamation activities including partial or complete backfilling of pits, stabilization of tailings, installation of covers, stabilization of waste rock piles, appropriate contouring of disturbed land surface, and re-vegetation.
- Water treatment facility.
- Restoration of groundwater, if necessary.
- Rehabilitation of the landscape and surroundings.
- Long-term surveillance, care and control of the reclaimed areas.
- Indirect costs such as contingency, overhead and profit.

The cost estimate for closure shall be updated periodically.

9.3 Radiation protection standards for clean-up of buildings and their associated land and equipment at the mine site. Waste clearance levels

At the time of mine closure, decommissioning and rehabilitation activities may involve but are not limited to the dismantling of processing plants, demolition of buildings, water treatment, stabilization and sealing of tailings and waste rock piles and other required site rehabilitation activities.

Clearance levels in terms of maximum gamma levels and maximum concentration limits for radioactive and non-radioactive contaminants, for clean-up of soil, water and facilities and waste clearance levels have to be established by relevant regulatory bodies prior to the initiation of decommissioning and rehabilitation activities. Direct gamma exposure from the tailings or wastes should be reduced to background levels.

The IAEA Safety Guide (2004) gives guidance for the application of the principles of exclusion, exemption and clearance and sets radionuclide specific clearance levels for bulk solid materials intended for unrestricted disposal.

‘Exclusion means the deliberate exclusion of a particular category of exposure from the scope of an instrument of regulatory control on the grounds that it is not considered amenable to control through the regulatory instrument in question. Such exposure is termed excluded exposure’ (IAEA 2004). Examples of excluded types of exposure include exposure from ‘unmodified concentrations of radionuclides in most raw materials’.

‘Exemption means the determination by a regulatory body that a source or practice need not be subject to some or all aspects of regulatory control on the basis that the exposure (including potential exposure) due to the source or practice is too small to warrant the application of those aspects’ (IAEA 2004). The quantitative guidance for exemption levels is limited to moderate quantities of material, namely amounts ‘at most of the order of a tonne’.

Clearance is similar with exemptions but relate specifically to the removal of radioactive sources, including substances, materials and objects within authorized practices from any further control by relevant authorities. According to IAEA (2004), ‘clearance‘ means the removal of radioactive materials or radioactive objects within authorized practices from any further regulatory control by the regulatory body. Removal from control in this context refers to control applied for ‘radiation protection purposes’. To ensure that material, once cleared from regulatory control, does not immediately become liable for regulation again, the clearance levels shall not be higher than the exemption levels defined by the regulatory body.

The values of activity concentrations for radionuclides of natural origin recommended by IAEA (2004) that may be used, applying a graded approach for exclusion, exemption and clearance, are given in Table 9.3.1. The values are derived using the exclusion concept and are valid for the natural decay chains in secular equilibrium and individually for each decay product in the chains or for the head of subsets of the chains. For mixtures of radionuclides of natural origin, the concentration of individual radionuclides should be lower than the value of the activity concentration given in Table 9.3.1.

Table 9.3.1. Values of activity concentration for radionuclides of natural origin.

Radionuclide	Activity concentration (Bq/g)
^{40}K	10
All other radionuclides of natural origin	1

Effective doses to individuals as a consequence of these activity concentrations would be unlikely to exceed about 1 mSv in a year, excluding the contribution of emanation of radon. The values of activity concentration for radionuclides given in Table 9.3.1 do not apply to foodstuff, drinking water, animal feed, radon in air, potassium-40 in the body, material in transport, etc.

It is usually not necessary to regulate materials (waste) of which radionuclide activity concentrations are below the values given in Table 9.3.1. In other words, these may be used to determine whether material within a practice can be released from regulatory control. However, exposure to materials with activity concentrations below those given in Table 9.3.1 may in some instances require regulatory control, for instance buildings materials.

If radionuclide activity concentrations exceed the values in Table 9.3.1., a graded approach, and values of activity concentrations derived using the exemption and clearance concept, may be applied by regulatory bodies (IAEA 2004).

According to IAEA (2004), the primary radiological criterion for establishing values of activity concentrations for radionuclides of natural origin for the exemption and clearance of radioactive sources is that the effective doses to individuals should be of the order of 10 μSv or less in a year. The second radiological criterion is that the collective effective dose committed by one year of performance of the practice is no more than about 1 man Sv (the SI unit for collective dose is man-sievert).

Radionuclide specific levels for the exemption and clearance of solid materials should be derived taking into account typical exposure scenarios for all materials, for instance external irradiation, dust inhalation and ingestion (direct and indirect). Effective doses to individuals as a consequence of these activity concentrations are unlikely to exceed about 1 mSv in a year.

Verification of the values may include direct measurements on the material (homogenous), laboratory analysis of representative samples, use of properly derived radionuclide relationships, adequate traceability of materials, including its origin, etc.

9.4 Decontamination and/or dismantling of facilities

Equipment and buildings and their associated land at the uranium mine sites must be decontaminated and / or demolished. If possible, the buildings at the mine site should be decontaminated to a level that permits release from regulatory control in the future.

Demolished building material is usually disposed of in the open-pit or underground mines together with other types of waste such as, for example, waste rock.

Equipment associated with the conventional mining and milling is generally decontaminated by thorough washing with water or other mild cleaning agents. Following the decontamination, the equipment can be transported to another site for reuse, depending on its residual radioactivity level and regulatory requirements. Old and radioactive contaminated equipment is usually buried with waste rock or other mine waste. The resulting waste and equipment disposed of in, for instance, mined-out pits are reclaimed by installing a dry cover.

The following factors should be taken into consideration:

- Identifying the need for decontamination based on detailed investigations of buildings, associated land and equipment.

- Decontamination techniques, if needed, include chemical and physical methods such as vacuuming, scrubbing, high pressure water, spraying or steam jetting and sandblasting (sandblasting may disperse radioactive material and lead to surface contamination embedded in the surface of the equipment). Also, disposal of clean-up fluids resulting from this operation should be taken into consideration.
- Decontamination to the largest possible extent of plant surfaces, interior structures, machinery and equipment is required prior to demolition / dismantling.
- The equipment to be removed from the buildings during the clean-up process may be potentially salvageable for unrestricted use following radiation checks and required decontamination, possibly contaminated but potentially saleable to other uranium operations and contaminated equipment requiring safe disposal. Salvageable equipment usually derives from the crushing and grinding operations.
- Slightly contaminated equipment and materials, and equipment and materials that cannot be decontaminated to a level below that required, must be safely disposed of (after consultation with the appropriate authority).
- Demolition methods should avoid release of dust into the environment. Prior to demolition, walls and ceilings may require washing or painting to suppress contaminated dust particles.
- For easy handling, processes such as cutting up of building materials and pieces of equipment, cutting, crushing and flattening of pipes, tanks and similar structures can be selected.
- During the decommissioning, a person competent in radiation monitoring should conduct all the radiation monitoring, interpret the results and sign all radiation clearance documentation for release of materials.
- Exposure limits and protection measures (health and safety) for the employees, members of the public and the environment should be established.
- During the decommissioning, a programme should be established to control the movements of waste and potentially contaminated equipment and materials. All vehicles and equipment leaving controlled areas should be decontaminated (if needed) to the required limits in order to prevent the spread of contamination to the environment.
- Clean-up of areas, debris and soil (e.g. roads and parking lots) that have become contaminated at the mine site during the operation of a facility has to be performed, and re-soiling, fertilizing and re-seeding, necessary to re-establish vegetation, may be undertaken. The vegetation selected should be similar to native types at the mine site.
- Treatment of generated contaminated water.
- Other relevant factors to safe decommissioning of buildings and facilities.

During the decommissioning, there may be other types of waste, such as hydrocarbon spills from storage tanks or vehicle fueling, polychlorinated biphenyls (PCBs) from old electrical transformers, laboratory waste, explosives and refuse. Those wastes must be cleaned up in accordance with established regulatory requirements for hazardous wastes.

9.5 Rehabilitation of the mine and tailings facilities

Rehabilitation will, to some extent, reduce on-site and off-site inhalation of radon, thoron and contaminated dust, external exposure and consumption of contaminated food or water. Rehabilitation of uranium mining and processing sites covers issues associated with soil remediation, liquid effluents treatment, application of permeable barriers and cover systems for the tailings facilities and waste rock dumps.

Cover systems

Cover systems for tailings and waste rock minimize impacts on groundwater, surface water and air quality, as well as the uptake of radionuclides by plants (if the covered facility is re-vegetated). Cover systems for tailings disposal facilities and waste rock dumps should resist long-term erosion, promote run-off, limit water and oxygen infiltration, minimize radon and dust emission, shield the environment from gamma radiation, reduce long-term maintenance, minimize animal and human intrusion and reduce risks to human health and the environment.

Tailings and waste rock dump cover design and construction are site specific and should take into account the local climate, availability of construction materials, nature of the tailings impoundment, regulatory requirements as well as public acceptance.

The design criteria of covers address geotechnical, radiological, hydrological and geochemical requirements.

Cover systems comprise multiple layers of earthen material, layers of different material types, including native soils, non-reactive waste materials, geosynthetic materials, oxygen-consuming organic materials and a vegetative layer. Each layer has a specific function. By way of example, clay layers are used to control radon emanation and water infiltration. Vegetative layers are used to control wind- and water-induced erosion and moisture infiltration. Coarser material is used as drainage layer and to prevent animal and human intrusion.

A dry-cover system requires the following steps:

1) Removal of tailings water and stabilization of the surface.
2) Recontouring and landscaping of tailings facilities (if possible).
3) Capping.
4) Re-vegetation (if possible) and maintenance.

The cover system should be designed and constructed with respect to the key factors that will control long-term performance:

- **Longevity**. Covers need to be engineered for life spans of the order 200 to 10,000 years or more. Long-term erosion resistance, weathering and evolution of the cover system are the key factors to be considered.
- **Sealing and shielding requirements**. Gamma ray shielding, dust control, radon emanation and resistance to damage in freeze / thaw cycles. Gamma ray shielding can be achieved with a soil layer of, for instance, 0.5 m. Dust can be controlled by applying a vegetative cover or rock cover for fugitive dust. A compacted clay and thin compacted soil layer are usually used to control radon emanation.
- **Water infiltration**. Limitation of infiltration of atmospheric precipitation can be avoided by proper design of the sealing layer.
- Geotechnical, hydrological and durability properties of cover materials.
- **Gas infiltration**. Prevent infiltration of oxygen into tailings. The methods used for limitation of water infiltration and minimizing radon emanation are also effective to limit or control the inflow of gases.

- **Erosion prevention**. Riprap or cohesive clay layers and development of vegetation cover are used to prevent long-term erosion. Riprap is loose stones produced by crushing hard rock.
- Water storage layers consist of multiple layers above the sealing layer that act as a 'sponge', adapting to water cycles. Drying cracks in the sealing layers would compromise their retaining capacities for gases and infiltrating waters.
- **Biointrusion**. Protection of the integrity of the sealing layer against burrowing animals and/or penetration of deep roots is usually achieved by using a thick riprap layer.
- **Climatic conditions** at the site. Information on mean annual precipitation or temperature, short, intense rainfall events and peak precipitation events is necessary to properly predict the water balance in cover systems.
- Specific physical and chemical processes such as freeze/thaw and wet/dry cycling, implications of waste geochemistry, upward migration of radionuclides, salts and metals from the waste material into the cover system and, subsequently, into the vegetation cover. This issue is generally addressed by either increasing the thickness of the cover system or incorporating a capillary break layer near the base of the cover system.
- Hydrogeological setting of the waste storage facility.
- Potential failure mechanisms.

Soil remediation

Soil remediation techniques can be used to extract radionuclides, metals and some types of organic waste from saturated or unsaturated soils, slurries and sediments.

The key factors considered in soil remediation are site status, range of contaminants treated and other site-specific considerations.

Before soil remediation is undertaken at a site, a number of different field and laboratory screening tests must be conducted to determine whether the particular site is amenable to a specific or a combination of treatment techniques. Field and laboratory screening tests may include field conductivity surveys, geochemical analysis of soil, chemical analysis of water, determination of soil pH values, etc.

Soil remediation methods may include but are not limited to soil flushing, electrokinetics, phytoremediation, solidification and stabilization techniques, etc.

Soil flushing techniques promote mobility and migration of metals by solubilizing the contaminants via application of flushing fluid (water as flushing fluid or chemical reagents) to the surface of the site, and the resulting leachate is then typically recovered. The drawbacks of soil flushing remediation techniques are that there is a: (1) potential risk of aquifer contamination by the residual flushing solution at the site and that they are (2) currently applicable only to a limited range of metals.

Electrokinetics remediation is most efficient at sites where the soil is homogeneous and the moisture level relatively high. It employs electrical potential differences or a low intensity direct current between two electrodes inserted in the soil.

Phytoremediation uses plants to remove, contain or render environmental contaminants harmless. This remediation technique requires longer treatment times and may be applied at sites where contaminant concentrations are relatively low.

Solidification and stabilization techniques are used to change the physical characteristics and leaching potential of waste to improve its handling and to reduce the mobility of the contaminants through chemical or thermal interactions. Solidification and stabilization techniques are limited by lack of data on the long-term integrity of the treated material. The technology is most effective at sites where little or no debris is present.

Liquid effluents treatment

Water draining from abandoned mine sites is a major cause of freshwater and land pollution in many regions of the world. Such drainage is often enriched in toxic heavy metals and radionuclides, which may lead to ecological problems. Usually, uranium and radium-226 are not the main contaminants and can even be of secondary importance compared with other contaminants of greater eco-toxicological significance.

Acidification of water as a result of sulphide oxidation can lead to a long-term requirement for water treatment or the implementation of passive strategies for water clean-up.

Apart from the well-known AMD problems associated with some mining sites, other sites are characterized by carbonate rich waters. Treatment strategies of carbonate waters must take into account that uranium occurs in uranyl-carbonate complexes and thus must be hydrolyzed before uranium can be effectively precipitated from aqueous solution.

Remediation strategies include treatment techniques to be applied to contaminated liquid effluents and in situ treatment applied to the contamination source. Treatment methods of liquid effluents are described in detail in subchapter 4.2.2 of this report.

Avoidance of environmental pollution is a best practice technique; thus, the operator has to close the site in a way that will minimize or exclude potential drainage of contaminated water from the abandoned mine site.

Rehabilitation work

The options for reclaiming the mine and tailings facilities depend on the physical stability of the tailings facility, the walls of the mined-out pits and tunnels, existing drainage patterns and future land use.

General steps involved in rehabilitation of mine and tailings facilities are as follows:

- Site characterization.
- Reassessment of the waste facility in terms of physical structure and chemical stability of disposed waste. When the options are found to be unsatisfactory, measures such as reinforcement of the physical structure of the tailings disposal site, reprocessing and or mixing the tailings with other materials for final disposal and, if necessary, relocation of the tailings have to be considered.
- The pit may need to be reworked to achieve flatter slopes for possible future use.

- Reshaping of the edges of the tailings sites, if needed, to minimize erosion hazards from surface runoff.
- Remediation actions (land (soil) and buildings clean up) shall be selected and conducted so that, after the mine closure, gamma radiation levels and radon emanation to the atmosphere from the mine and tailings facilities should not exceed background levels by more than the established regulatory limits established by the appropriate authority.
- Long-term protection of ground and surface waters from contamination. Engineering measures to minimize or eliminate post-closure migration of radioactive material from the tailings sites to the groundwater or surface waters (e.g. radioactive material should remain in a depositional / low oxygen environment, any seepage should be minimized / controlled and no catastrophic failures should be possible).
- Isolation / removal of material from contact with the public and stabilization of contaminated materials, for instance treatment of waste (including liquid effluents) during the mining operation and, if necessary, during decommissioning to ensure the stability of radionuclides and non-radioactive contaminants, thus inhibiting their release to the environment.
- Passive long-term waste treatment should also be considered.
- Drainage in the vicinity of the tailings facilities should be redirected, if necessary. This may require establishment of new drainage routes or diversions such as wing dams. Consideration must be given to the maximum possible magnitude of floodwater over the design life of the tailings pile, which should be minimum 200 years (decided by the appropriate authorities) and up to 10,000 years.
- Measures should be taken to avoid hydro-geological effects such as erosion.
- Reshaping, slope stabilization, covering of waste rock dumps and, if necessary, relocation to a safe site.
- Co-disposal (dewater tailings, combine with other types of waste, e.g. waste rock) and in-pit disposal of tailings and / or waste rock.
- Tailings dewatering, covering the tailings site(s).
- The cover(s) for the tailings disposal facilities should resist erosion, promote runoff, limit infiltration, minimize radon emanation rates, reduce long-term maintenance, minimize animal and human intrusion and reduce risks to human health and the environment. To verify its suitability, the material used for covering the tailings facilities must be tested for some characteristics such as acidity, impermeability, radiation and radon emanation and other characteristics taking into consideration the disposal of heavy metal contaminants. The thickness of the cover varies with the nature of the tailings facility and with the material used and can be estimated using computer models that must be approved by authorities.
- Dry cover of tailings facilities with radon barrier material and various types of rocks and earth material, compacted clay-soil mixture or, if feasible, vegetative cover must be established in order to reduce wind and water erosion and thus diminish the rate of dissolution of soluble components to negligible levels. For erosion protection, ‘rip rap’ is the preferred cover material.
- To minimize the erosion potential and to provide conservative safety factors for long-term stability, embankment and cover slopes should be relatively flat after the final stabilization.
- Due to possible changes in the surrounding environment, covers may not behave as designed. Incorporating vegetation in combination with dry covers (rock materials) may create a self-sustaining cover that can prevent infiltration while providing erosion resistance. The re-vegetation of covers

must be as close as possible to the species and plant communities growing naturally in the area.

- The owner or operator must close the facility in a manner that minimizes the need for further maintenance or repair to preserve isolation. Examples of planned maintenance (e.g. vegetation control, grass mowing and removal of weeds or debris), unplanned maintenance (e.g. removal of deep-rooted or other unwanted vegetation from the disposal cover) and repair (e.g. repair of damage to disposal cover, fence or locks, surveillance features).
- The owner or operator must close the facility in a manner that minimizes the need for long-term institutional controls and minimizes or eliminates post-closure escape of hazardous materials to ground or surface waters or to the atmosphere.
- If possible, the whole area should be re-vegetated with vegetation without root systems that may reach the radioactive tailings through the topsoil (dry cover of the tailings facility). If re-vegetation is planned, soil amendments, such as lime, may be needed. The site must be monitored for growth of the vegetation and erosion of the soil.
- Control and monitoring of groundwater contamination (groundwater restoration / clean-up) and atmospheric radionuclides release. Control of radioactive materials shall provide reasonable assurance that the radionuclide release and emanation rates will not exceed the established concentration limits in the uppermost aquifer and in the atmosphere.
- Control of radioactive and non-radioactive materials must be effective for up to 10,000 years or at least 200 years (decided by the appropriate authorities).
- Prevention of unauthorized removal of tailings.
- Measures to ensure that tailings from the disposal facility are not brought back to the surface by burrowing animals.
- Emergency measures should be in place in case of subsidence, cracking, sliding or slope instability of the disposal cover, observed seepage, deterioration in drainage ditches or of erosion protection material, or natural phenomena such as floods, windstorms, glaciation and fire.
- Restricted areas (if such exist according to the appropriate authorities) at the mine site should be surrounded / enclosed by a fence.
- Other relevant options required by the authorities.

Each rehabilitation project is unique, and it must be born in mind that there is no single solution that can solve all cases.

9.6 Groundwater remediation

Groundwater rehabilitation (if necessary) must be conducted to eliminate / restrict generation of additional contaminated groundwater, to prevent or minimize the movement of such water from the site and to collect it for treatment (e.g. pump and treat technology, reverse osmosis, groundwater sweep, etc.) and recycling. Groundwater remediation is a very important step for ISL.

The groundwater restoration process comprises:

- Sampling and monitoring of groundwater around the site.
- Identification of contamination sources if the groundwater has been impacted by the mining activities. A risk assessment of the impact must be used to assess necessary remediation methods. If necessary, cut-off ditches and drains to bedrock can be placed where drainage from the site may occur.

- Collection wells to prevent groundwater from moving through geological formations and off the site.
- Reduction of the groundwater flow by limiting the amount of surface water entering the site.
- Evaporation ponds for disposal of collected contaminated groundwater.
- Other processes.

9.7 Monitoring programme during decommissioning and rehabilitation

Occupational and members of the public monitoring programs and dose assessment and radiation protection programmes for implementation during decommissioning of uranium mine sites should be developed by the operator with support from relevant authorities. Non-human biota radiation risk assessment should be performed (see Chapter 10).

Environmental and effluent monitoring during the decommissioning of a facility should be similar to that for the operational stage (see Chapter 7). However, the operational monitoring programme should be reviewed and possibly adapted to the decommissioning phase to ensure that it still enables verification of compliance with the authorized limits.

The choice of procedures for sampling and measurement during decommissioning depends on:

- Sources, stressors, pathways, receptors and radiological, chemical and physical characteristics of the released radionuclides.
- Sensitivity of the measurement system.
- Expected variations.
- The likelihood of unplanned discharges requiring prompt detection and notification.

As for the operational stage, monitoring during decommissioning of a facility includes:

- Atmospheric radon / thoron and their progeny, radionuclides in dust, total dust and gamma surveys.
- Radon emissions from the dry covered tailings and waste rock facilities.
- Radionuclide monitoring in surface water and groundwater.
- Radionuclide and radioactive dust monitoring in foodstuffs, non-human biota, soil and sediment samples.
- Monitoring of discharges of radionuclides in the form of gases, aerosols and liquid effluents (see Chapter 7).
- Monitoring of non-radioactive hazardous materials.

Once discharges of radioactive liquid effluents have been eliminated, it may be possible to reduce and eliminate the need for liquid effluents monitoring. The programme for collecting and measuring aerosols and gases that was established for the operational stage should be continued during decommissioning.

The operator should, for a number of years (e.g. at least five years in Canada and Australia) after completion of decommissioning and rehabilitation, demonstrate that the levels of contaminants at the closed site are below the regulatory limits.

9.8 Long-term stewardship (LTS) and surveillance

Radiation from closed uranium sites remains a potential risk concern for thousands of years due to the long half-lives of uranium and thorium isotopes and their progeny.

In order to demonstrate the radiological-physical-chemical stability of the closed facility, the operator has to perform environmental monitoring for a number of years (e.g. 5 to 30 years in Canada and Australia) after completion of decommissioning and rehabilitation of the site. Based on the environmental results such as radiation levels, radionuclides in surface water and non-radiological contaminants, it can be decided if there is a need for further rehabilitation of the site.

When the work involved in decommissioning, rehabilitation and monitoring and care for a number of years has been completed by the operator, the responsibility for long-term surveillance, monitoring and maintenance of the site is transferred to the appropriate authorities.

The engineering methods used during the closure activities to prevent human exposure to contaminants may degrade over time. Sometimes the closed facility may even not obtain the conditions deemed acceptable for unrestricted use. Therefore, long-term stewardship (LTS) or long-term surveillance and maintenance or long-term monitoring and surveillance have to be implemented after the closure of facilities.

Stewardship may refer to the institutional controls (ownership or governmental) which have to be put in place to ensure that a specific site meets its closure goals.

Institutional controls can be:

1) Active, requiring continuous or intermittent human activity to maintain the condition of the site.
2) Passive, not requiring human intervention and with on-site preventive measures to prevent disturbance of the remediated site.

Examples of active controls are air, surface and groundwater monitoring, site inspections, ground radiation surveys and aerial gamma surveys. Examples of passive controls are land use restrictions, fences and signs. Installation of passive controls does not exclude the need for active institutional controls.

Potential emissions of radionuclides to the atmosphere and to the surrounding environment from the closed facility should be considered; thus, monitoring of radioactive waste disposal facilities and environmental monitoring after closure should be carried out.

The main objectives of the monitoring program are to:

1) Demonstrate compliance with reference environmental levels established by the regulatory body and
2) Provide indications of any malfunctioning of the waste containment, leading to unpredicted release of radionuclides (e.g. waste containment erosion, wind erosion, seepage of water and subsequent contamination of groundwater and surface water, re-vegetation and other remedial measures).

Monitoring will allow for the assessment of the effectiveness of the decommissioning and rehabilitation work:

- Site inspections will confirm that the integrity of the site has not been disturbed.
- Geotechnical monitoring will identify any settling, erosion or movement that have occurred.
- Surface water monitoring will detect changes in the quality or quantity of surface water and reveal movement of radioactive (uranium) and non-radioactive contaminants into waterways.
- Air monitoring will identify increases in radon and other emissions from the site.
- Ecological monitoring will determine if biota is affected by potential bioaccumulation of heavy metals and radionuclides.
- Gamma levels.
- The post-closure monitoring programme should include measurements of environmental radiation levels and of radionuclide concentrations in environmental samples of air (radon emissions from rehabilitated waste sites), soil, water and groundwater, surface water, sediments, biota and foodstuffs.

Monitoring locations should be related to the potential migration pathways, changes in human exposure pathways and radionuclide exposure levels. Although the surface of a sealed facility (waste) cover will prevent or minimize atmospheric release of radionuclides, subsurface leakage into the ground through the engineered barriers may still occur. This may result in a change of human exposure pathways and exposure levels in comparison with the operational period.

Frequencies of sampling and measurements should be specified with a view to timely detection of significant changes in the release rates and concentrations of radionuclides and the associated levels of human exposure.

Radionuclide levels in all relevant environmental samples in the surroundings of the closed waste disposal facility should be compared with monitoring data collected during the operational phase and with baseline data to provide a basis for determining whether any significant changes or impacts have occurred or are likely to occur.

Monitoring should be continued after closure of the waste disposal facility for as long as the facility is deemed to remain a potential hazard. The regulatory body should determine the time period, taking into account the physical decay of the radionuclide content, non-radioactive contaminant levels in the waste and the results of the safety assessment and monitoring.

Long-term monitoring of radioactive waste disposal facilities should be carried out within the framework of the programme of active institutional control. The monitoring programme should be developed by the organization responsible for the institutional control and should be approved and reviewed as necessary by the regulatory body. The environmental monitoring programme for a closed waste facility site should be reviewed and factors to be taken into account include any changes in climatic and environmental conditions as well as societal changes, for instance altered land use possibly causing changes in human exposure pathways.

The time period requiring monitoring depends on a number of factors, one of which is funding availability. Current remediation plans are projected for minimum 200 to 10,000 years ahead (plans for uranium tailings sites must be designed for 10,000 years of control).

Initially, on-site monitoring should be conducted every year, if little change is recorded the frequency may be reduced to every second year or even once every five years. Generally, if the monitoring results show that the levels of radionuclide or pollutant discharge do not increase, sites may be released for unrestricted use.

Some examples of closed uranium mine sites, post closure monitoring, maintenance and institutional control of mine sites from Canada, Australia and the U.S. are provided in Appendix G.

A long-term surveillance plan should include:

- Description of final site conditions, including groundwater characterization.
- Description of the surveillance programme.
- Inspection procedures, personnel qualifications and report frequency (an inspection shall be conducted at least annually at disposal sites, an inspection team shall consist of at least two inspectors with appropriate technical experience, the inspectors should observe, for instance, erosion features such as gullies or rills, sediment accumulation, vandalism, animal intrusion and plant growth, perform and collect monitoring data as required, take and record photographs to document conditions at the disposal site and provide a continuous record for changing conditions over time).
- Constituent limits for groundwater (surface water), gamma radiation limits.
- Record keeping and reporting.
- Criteria for follow-up inspections.
- Maintenance as necessary / Criteria for instituting maintenance (examples of maintenance: grass mowing, road maintenance, removal of weeds or debris, vegetation control or replacement of signs, removal of deep-rooted or other unwanted vegetation on the disposal cover, repair damage to disposal cover, fence, gate or locks, surveillance features, wells or roads).
- Emergency measures should be in place in case of need (e.g. surface rupture of the disposal cover through subsidence, cracking, sliding or slope instability, deterioration of the erosion protection rock on the disposal cover, monitored or observed seepage).

9.9 References

IAEA, 1992. International Atomic Energy Agency, Current practices for the management and confinement of uranium mill tailings, Technical Reports Series No. 335, IAEA, Vienna.

IAEA, 1994. International Atomic Energy Agency, Classification of Radioactive Waste, Safety Series No. 111-G-1.1, IAEA, Vienna.

IAEA, 2002. International Atomic Energy Agency, Monitoring and Surveillance of Residues from the Mining and Milling of Uranium and Thorium, IAEA Safety Report Series No. 27, IAEA, Vienna.

IAEA, 2004. International Atomic Energy Agency, The Long Term Stabilization and Isolation of Uranium Mill Tailings, IAEA-TECDOC-1403, Vienna.

IAEA, 2004. Application of the Concepts of Exclusion, Exemption and Clearance, IAEA Safety Guide, No. RS-G-1.7

IAEA, 2014. Lessons Learned from Environmental Remediation Programmes, IAEA Nuclear Energy Series, 2014.

ICRP, 2014. Protection of the Environment under Different Exposure Situations. ICRP Publication 124. Ann. ICRP 43(1).

10 Sources, receptors, stressors, exposure pathways and biota radiation risk assessment

This chapter provides a general description of radiation sources into the environment, receptors, stressors, sources at the mine site, exposure pathways and biota radiation risk assessment with emphasis on the activities associated with uranium production.

10.1 Radiation sources

Ionizing radiation (high energy radiation such as, for example, alpha, beta, gamma radiation, X-ray and neutron radiation) in the environment includes natural (background) and man-made sources.

Natural radiation sources

Natural radiation has always been present and is everywhere. All living organisms are continuously exposed to external and internal ionizing radiation. The UNSCEAR has identified four major natural radiation sources: (1) high-energy cosmic ray particles that come from outer space and from the surface of the sun (exposure at ground level and aircraft altitudes), (2) terrestrial radiation from natural radioisotopes that occur in the Earth’s crust and in building materials, (3) radon and thoron gases in air produced by, respectively, the decay of uranium and thorium and (4) trace amounts of radioactive minerals naturally found in the contents of water and food and in the human body itself (UNSCEAR, 2008).

Natural radiation varies with location, cosmic rays are, for instance, more intense at higher altitudes, and concentrations of natural radionuclides such as uranium, thorium, potassium-40 and radon-222 are elevated in soils in some specific areas. Worldwide, the annual effective dose to the members of the public from natural radiation sources is 2.4 mSv (UNSCEAR, 2008).

Man-made radiation sources

The main man-made source of radiation to the environment originates from the nuclear weapons testing from 1945 to 1980. ‘Each nuclear test resulted in unrestrained release into the environment of substantial quantities of radioactive materials (called fallout), which were widely dispersed in the atmosphere and deposited everywhere on the Earth’s surface’ (UNSCEAR, 2008). Much of the fallout had short half-lives and no longer exists, but some continues to decay to this day; thus, the environment receives smaller and smaller doses from the fallout every year.

Other man-made radiation sources include: (1) nuclear power plant accidents, (2) marine, freshwater and atmospheric controlled discharges from reprocessing facilities, nuclear power plants (OSPAR) and uranium production activities, (3) agriculture, (4) oil and natural gas activities, (5) medical uses of radiation and (6) coal mines and coal burning and mine projects including rare earth elements and phosphates.

Worldwide, the average effective dose to members of the public varies greatly depending on location and habits. Figures 10.1 and 10.2 show the average annual effective dose from natural and man-made radiation sources received by members of the public in the U.S. and Denmark, respectively.

According to the figures, background radiation contributed about 50% to the annual effective dose for an average individual in the U.S and about 75% to the effective dose for an average individual in Denmark. Background radiation includes terrestrial sources such as natural deposits of uranium, potassium and thorium, cosmic radiation, radon and thoron gas seeping into homes and other buildings, and trace amounts of radioactive minerals that are naturally found in the contents of food, in drinking water and the human body. The contribution from uranium production (including all the mine phases) is included in the industrial and occupational section.

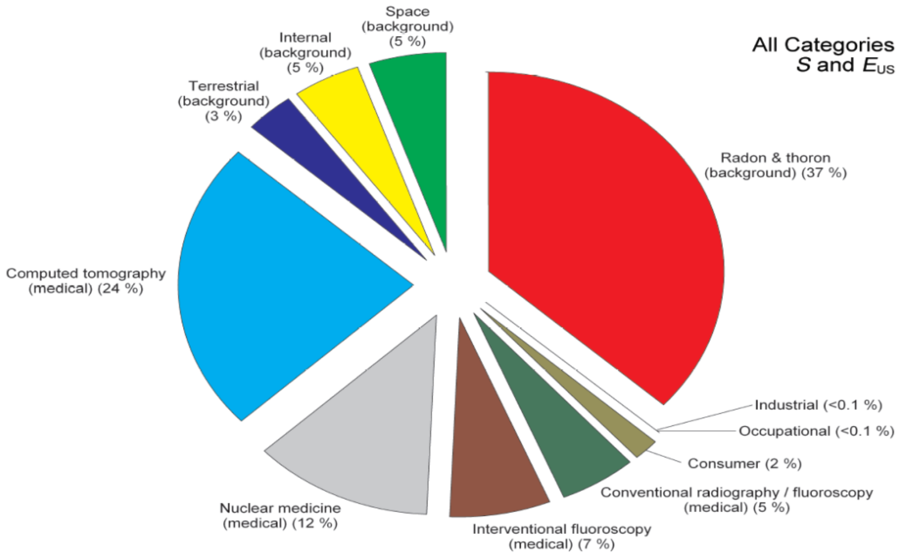


Figure 10.1. Relative contribution of various sources of exposure to the average annual effective dose per individual in the U.S. population (6.2 mSv) for 2006. Reprinted with permission of the National Council on Radiation Protection and Measurements http://www.epa.gov/radiation/radiation-sources-and-doses

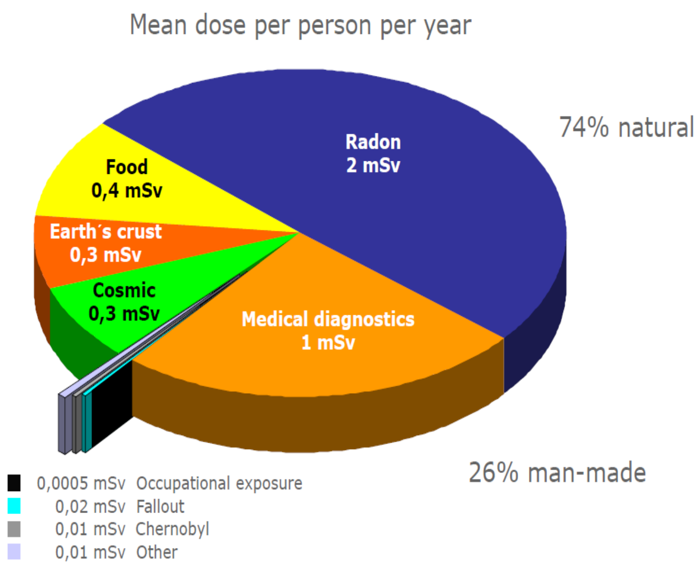


Figure 10.2. Average annual effective dose per individual in Denmark (in mSv). Source: www.sis.dk.

10.2 Receptors, stressors, sources and pathways of exposure

Chemical stressors can be transported through the environment and contribute to exposure of *receptors* (humans and non-human biota (NHB)) via the terrestrial, atmospheric and aquatic environment. Human and NBH (flora and fauna) are referred to as receptors and are site specific. If the main sources from the mining operations are not controlled, contamination of different primary media like the atmosphere and the aquatic environment may occur and from there they may be transported by different mechanisms to secondary ecosystems (Fig. 10.2.1). As a result, receptors can be exposed to chemical and physical stressors through ingestion (food or water), inhalation, cell membrane-mediated uptake, cutaneous absorption and biotic uptake / trophic transfer (Table 10.2.1.).

Chemical stressors include radioactive and non-radioactive contaminants which are site and project specific. Radioactive stressors include external gamma radiation, uranium and thorium and their decay products such as radium-226, radium-228, thorium-230, actinium-227, radon-222, thoron-220, lead-210, polonium-210, etc. Non-radioactive stressors usually include inorganic (e.g. metals, metalloids, non-metals and salts) and organic (e.g. used in and / or generated by mining and milling processes) contaminants. *Physical stressors* may include but are not limited to pit wall stability, tailings integrity (dam stability), particulate matter (PM 10, PM 2.5), exhaust gas / fumes (engines and blast), total suspended solids (TSD) to the aquatic environment, water and wind erosion, erosion due to animal intrusion, freezing / thawing processes, infrastructure development, noise from construction / operation, etc.

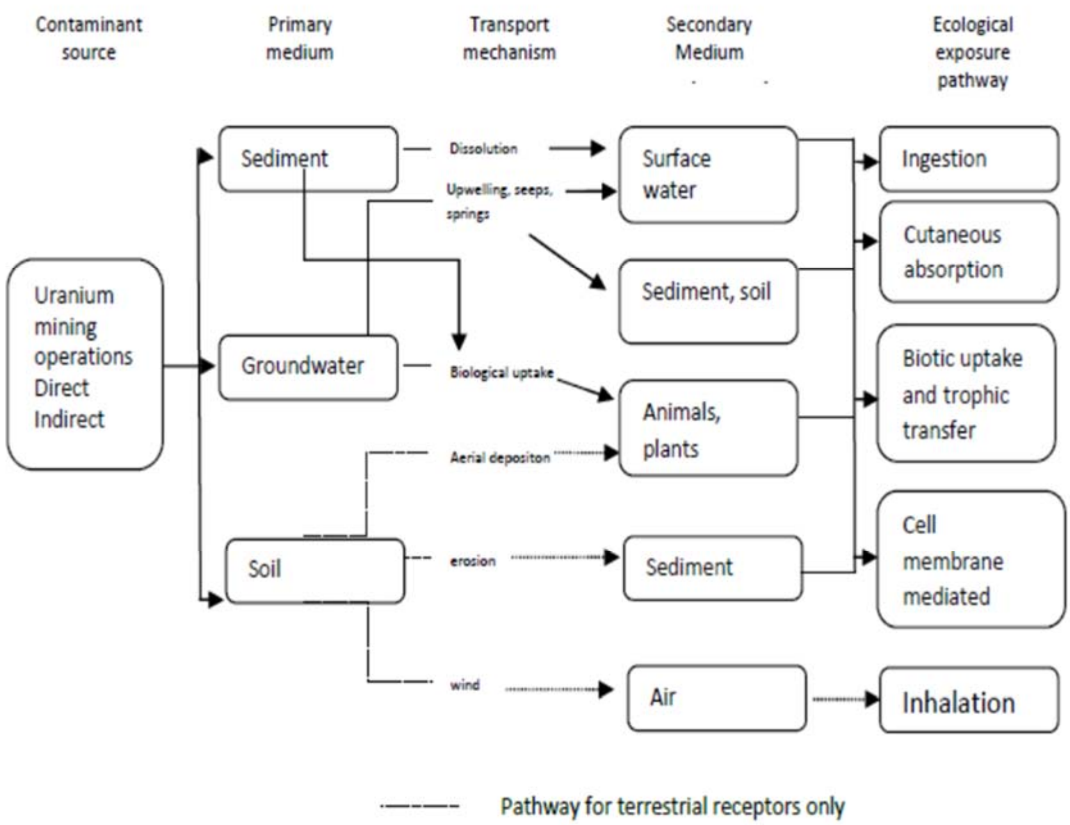


Figure 10.2.1. Pathways of radiation exposure (modified from Hink et al., 2010).

Table10.2.1. Pathways of radiation exposure, matrix for aquatic and terrestrial biological receptors (modified from Hink et al., 2010).

Receptor	Ingestion	Inhalation	Cell membrane-mediated uptake	Cutaneous absorption	Biotic uptake or trophic transfer
Aquatic habitats					
Algae, cyanobacteria and microorganisms			*		*
Vascular plants			*	*	*
Invertebrates	*		*	*	*
Fish	*		*	*	*
Terrestrial habitats					
Soil microorganisms			*	*	*
Plants			*	*	*
Invertebrates	*	*	*	*	*
Birds	*	*	*	*	*
Mammals	*	*	*	*	*

Mining, milling and waste management are potential *sources* for release of radionuclides to the environment.

Exposure of humans and NHB to different stressors may occur when a pathway of exposure exists, i.e. a route between, for example, the radioactive material and the exposed humans and NHB (flora and fauna). Contaminant transport routes / exposure pathways from a specific source at the mine site are: (1) atmospheric, (2) aquatic and (3) terrestrial (soil, sediment, humans and NHB).

The atmospheric pathways include release of radon, thoron, non-radioactive gases (NO_2, SO_2), particulate matter PM10, PM2.5 µm (dust containing radioactive and non-radioactive contaminants) and external gamma radiation.

Release to water or soils usually involve: (1) liquid effluents after chemical treatment, (2) pit dewatering and (3) seepage from stockpiles. If no minimization / prevention methods are established, uncontrolled release of contaminated liquid effluents to aquatic and terrestrial ecosystems may occur in the form of, for example, seepage, drainage and overflow from tailings and waste rock, leaks or spills from conveyors during transfer of tailings (pipelines), dewatering pipes, catastrophic failure of tailings management facility, etc. These contaminants may be transported further to the terrestrial and aquatic environment as a result of dry or wet deposition (including also resuspension and further dry or wet deposition).

The dominant pathway of contaminant release is site specific, but the main pathways in the Arctic environment (long and cold winter period, strong winds and high rainfall) are generally aquatic and atmospheric.

For a given uranium project, the pathways for radon release derive from drilling, blasting, excavation, loading, transport of the ore, ore storing and tailings management. In yellowcake drying and packaging, only small amounts of thorium and radium are contained and no significant radon release occurs since only 0.1% of the original radium-226 in the ore is found in the yellowcake. The amount of radon released through each pathway depends on ore type, ore storage procedures, crushing or grinding operations and tailings disposal practices. Methods to reduce the release of radon to the environment from the different sources at the mine site have to be implemented. Significant release may occur via a radiological event at the mine site; thus, the operator, and relevant authorities, have to develop and implement an emergency preparedness and response plan.

Some factors affecting radon pathways are: (1) radium content of the ore, (2) barometric pressure (e.g. falling pressure tends to draw soil gas out of the ground, increasing radon concentrations in the near-surface layers whereas high barometric pressure cause an increase in radon exhalation) (Bigu 1985, Mudd, 2004), (3) precipitation and moisture content; for example, radon exhalation practically ceases at complete water saturation of soil.

Particulate matter (PM10, PM2.5 (dust)), typically contains both non-radioactive contaminants (heavy metals and silicates) and uranium and thorium series radionuclides (mainly thorium-230 and radium-226) and may be released, if not controlled, from mine workings, ore stockpiles, drilling, blasting, excavation, transport, crushing and grinding ventilation systems, mill stacks, yellowcake drying and packaging operations and tailings management.

Direct gamma exposure to ore bodies and / or stockpiles (high ore grade) and tailings management represent a relatively low risk, except to employees working adjacent to ore bodies and / or stockpiles. Members of the public are not allowed access to the mine site. As gamma exposure decreases with distance, this is generally a negligible exposure pathway for members of the public and even for employees at the mine site, if properly controlled.

In uranium mines, occupational radiation exposure originates from external gamma radiation, inhaled radon and thoron decay products and radioactive dust. The external gamma radiation exposure ceases as soon as the source is removed or the receptor moves away from the source. Internal exposure occurs when the radioactive material enters the body by inhalation and ingestion and through wounds and skin absorption.

The dominant sources of internal exposure are radon / thoron and their decay products and long-life alpha radionuclides such as uranium and thorium series radionuclides contained in dust and in contaminated food and water. The occupational health risk increases if the radioactive dust is released as small-sized particles (e.g. $\leq 10\mu m$), especially in insoluble form. The internal exposure depends on the half-life of the radionuclide inhaled or ingested, the chemical form in which it is inhaled and or ingested and on particle size.

Employees at uranium mines can be exposed to radiation via four principal exposure pathways:

Direct external radiation from ores, tailings and waste rock. Employees will mainly be exposed to external gamma radiation.

Ingestion of contaminated water and food. Transport of radionuclides into the environment from mine sites via different pathways may occur if these are not properly controlled. Thus, ground water, surface water and food items within or near the mine site can contain elevated levels of radionuclides and should not be used as drinking water or food.

Inhalation of radon, thoron and their progeny. Radon, thoron and their decay products may emanate from different sources at the mine site (if not properly controlled) and may be inhaled by employees.

Inhalation and ingestion of dust-containing radioactive isotopes. Mining and associated activities produce dust, which can be inhalable or non-inhalable and may contain radioactive or non-radioactive contaminants.

One should bear in the mind that radiation sources and pathways are site and project specific. Potential radiation sources and exposure pathways for members of the public during the operational phase of an open-pit uranium mine project may include long-lived alpha radionuclides in dust and inhalation of radon and thoron decay products. Depending on the status of the mine site at closure, the main post closure exposure may include direct gamma radiation from the mine site, direct or indirect inhalation of radon and thoron decay products and ingestion of long-lived alpha radionuclides. Consequently, the requirements for decommissioning and rehabilitation of the mine and mine facilities must take these factors into account (see also Chapter 9).

10.3 Behaviour of radionuclides in the environment

In the environment, a given element can have different isotopic compositions, oxidation states and different chemical forms (e.g. organic / inorganic).

It is well-known that the biogeochemical cycle of radionuclides in the environment is determined by their physical and chemical (especially chemical speciation) properties and different environmental key factors such as soil pH, water chemistry and climate (Hinck et al., 2010; Hansen, 2011). Short growing seasons, prolonged freezing of soil and effects of low temperatures are some of the factors influencing the radionuclide biogeochemical cycle in arctic and sub-arctic ecosystems (Beresford, 2002 and 2005, Sheppard, 1994; Butler, 1996). Furthermore, low temperatures, lack of nutrient and, extreme seasonal variations in light cause environmental stress, rendering arctic and sub-arctic biota vulnerable to contaminants (AMAP, 1998).

Information on the biogeochemical cycle of radionuclides (Fig. 10.3.1.) can be used when undertaking risks assessments in connection with radiological events, developing countermeasures, designing the tailings disposal method, etc.

Uranium, a naturally occurring radioactive element is widely distributed in the Earth’s crust, rivers and oceans. Traces of uranium are also found in food and the human body.

Naturally occurring uranium is a mixture of three radionuclides, namely U-234, U-235 and U-238. Natural uranium consists of the U-238 isotope (99.3%), with the U-235 and U-234 isotopes constituting about 0.71% and 0.0057%, respectively (Berlin and Rudell, 1986). Uranium decays primarily by alpha decay but also by beta and gamma decay.

The bioavailability and toxicity of uranium depend on its speciation and several environmental key factors. Uranium occurs naturally in the +2, +3, +4, +5 or +6 valence states but is most common in hexavalent form (Lide, 1992; Cothern and Lappenbusch, 1983).

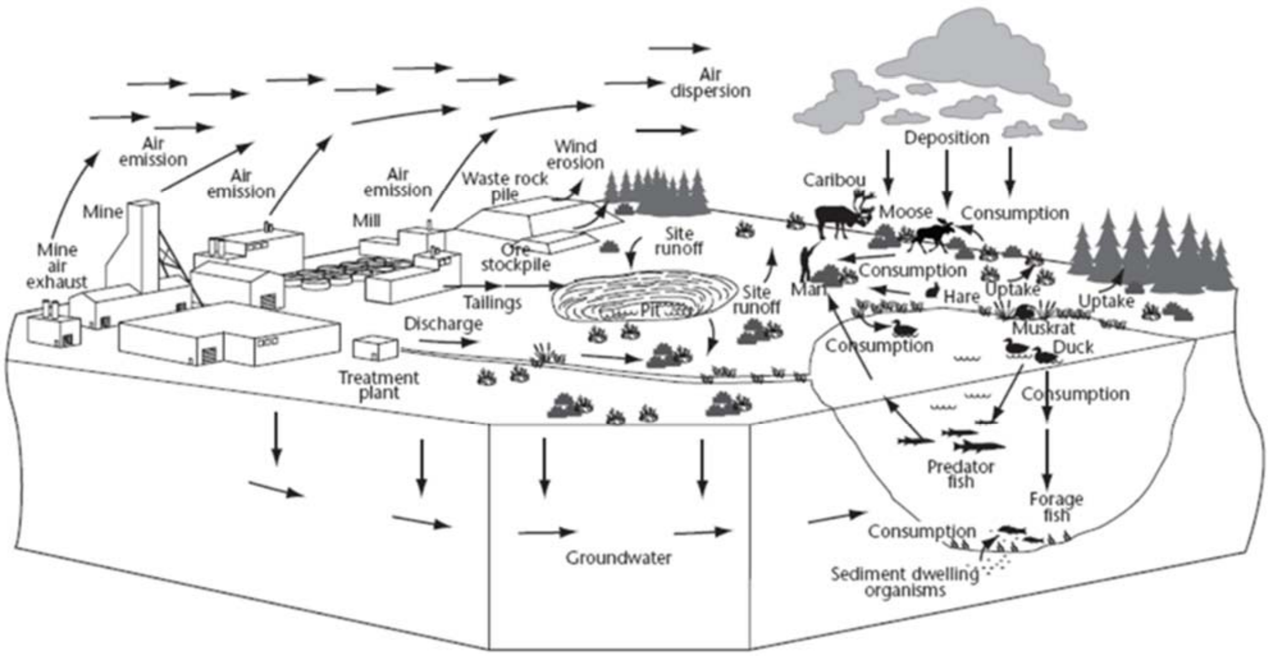


Figure 10.3.1. Pathways of radiation exposure. Source: *CSA N288.4-10(R2015)*.

Uranium is a relatively mobile element in the near surface zone owing to the stability of uranium (VI) aqueous complexes. However, it may be precipitated by reduction of uranium (VI) to uranium (IV) or in the form of uranium minerals, principally phosphates, silicates, arsenates, vanadates and oxyhydroxides (Závodská et al., 2008). The amount of uranium released to ground water or surface waters from these secondary sources will depend on the solubility and dissolution rate from these minerals, which is also influenced by site-specific factors such as pH and water composition (Burns and Finch, 1999). Information about the solubility of different uranium compounds in different solvents is provided in Table 10.3.1.

Table 10.3.1. Solubility of selected uranium compounds in various solvents. Modified from Závodská et al. (2008).

Uranium compound	Solubility in water	Solubility in other solvents
Uranium (U)	Insoluble	in acids
Uranium dioxide (UO2)	Insoluble	in HNO3
Uranium trioxide (UO3)	Insoluble	in HNO3, HCl
Triuranium octaoxide (U3O8)	Insoluble	in HNO3, H2SO4
Uranium tetrafluoride (UF4)	Slightly soluble	in concentrated acids and alkalis
Uranium hexafluoride (UF6)	Decomposes	in CCl4 and chloroform
Uranium tetrachloride (UCl4)	Soluble	in ethanol
Uranyl fluoride (UO2F2)	Soluble	in ethanol
Uranyl acetate dehydrate	7.7g/100 cm^3 at 15°C	in ethanol
Uranyl nitrate hexahydrate soluble in ethanol	Miscible in water at 15°C	in ethanol
Ammonium diuranate	Insoluble	in acids
Uranium peroxide	Decomposes	no data available

In soils, sediments and tailings (where a portion of uranium is retained in tailings), uranium may occur in a dissolved, exchangeable, carbonate, oxide, organic or crystalline form. Partitioning is influenced by soil / sediment pH, Eh, oxygen content, the soil / water partition coefficient Kd, redox state, organic content, temperature, etc. (Zhang and Brady, 2002). For example, UO_2 displays decreased solubility and movement in soil under anaerobic conditions and increased solubility and movement in aerobic soils (Hinck et al., 2010).

Adsorption of uranium by soils and single-mineral phases is generally low at pH <3, increases rapidly with increasing pH in the pH interval from 3 to 5, reaches a maximum in adsorption in the pH range from 5 to 8, then decreases with increasing pH at pH >8 (U.S. EPA, 2008). This trend is related to the pH-dependent surface charge properties of the soil minerals and the complex aqueous behaviour of dissolved uranium (uranium (VI)). At neutral or above neutral (alkaline) pH conditions, dissolved uranium forms strong molecular complexes with dissolved carbonate. Differences in partial pressure of CO_2 have a major effect on uranium adsorption onto minerals at neutral pH conditions. In one study, the percentage of uranium (U (VI)) adsorbed on ferrihydrite (iron oxide mineral) was found to decrease from approximately 97% to 38% when CO_2 increased from ambient levels (0.03%) to elevated (1%) partial pressures (U.S. EPA, 2008). Based on this, the adsorption of uranium decreases rapidly at pH >8 for waters in contact with CO_2 or carbonate minerals. This means that in such situations, uranium becomes very mobile and subject to transport in soil and water away from waste sites. Additionally, soils containing larger percentages of iron oxide minerals and mineral coatings, organic material and / or clay minerals will exhibit higher sorption characteristics than soils dominated by quartz and feldspar minerals.

Radium is an alkaline earth element and is found naturally only in the +2 oxidation state. Radium-226 is a radioactive element formed from the decay of uranium-238 and thorium-230. Radium-228, radium-226 and radium-224 are chemically near-similar to calcium and barium and to some extent strontium.

In surface water, radium can be found dissolved in a pH range of 3-10. However, in the presence of sulphate-bearing waters, precipitation and dissolution of calcium, strontium and barium sulphates may control the concentration of dissolved radium.

Radium is known to be most strongly absorbed by ion exchange on clay minerals, organic materials and mineral oxides, especially in near neutral and alkaline pH conditions (U.S. EPA, 2004).

Thorium is highly abundant in the earth crust, in about three times the concentrations of uranium. Windblown terrestrial dust containing thorium, uranium and thorium deposits and volcanic eruptions are examples of natural sources, while mining, milling, tin processing, phosphate rock processing, phosphate fertilizer production, coal fire utilities and industrial boilers are man-made sources of thorium in the environment (Bhatti et all., 2012).

The soil / plant transfer ratio for thorium is less than 0.01, indicating that it does not bio-concentrate in plants from soil (Garten, 1978). In contrast, the bio-concentration of thorium can be significant in lower trophic level aquatic communities (NHB), but thorium is not biomagnified as the trophic level increases (Poston, 1982).

Radon (Ra-222) *and thoron* (Rn-220) are radionuclides in gas form originating from the decay of radium-226 and thorium-232. Radon and thoron are seven to eight times heavier than air (Ha et al., 2012).

Thoron has a short half-life of 55 seconds, whereas the half-life of radon is 3.8 days. It means that their radioactivity dissipates in a matter of few days if no radium-226 and thorium-232 are present. Radon is continually being formed in soil and released to air as a result of the long half-lives of uranium- 238 and radium-226 and their abundance in the Earth's crust.

Radon decays via alpha emission into short half-life radon daughters. The radon daughters are chemically reactive and attach almost immediately to aerosol particles in the atmosphere.

The radon concentration in the soil is a function of: a) the radium concentration, b) the soil moisture content, c) the soil particle size and d) the rate of exchange of soil-entrapped air pockets with the atmosphere (Papp et al., 2009). The release rate from a material depends also on its moisture content. If the moisture content is very low, the radon release is decreased by the effect of re-adsorption of radon atoms on surfaces in the pores. If the moisture content increases slightly, the radon release increases up to certain moisture content, above which the release of radon decreases again owing to a decreasing diffusion rate in water-filled pores. High porosity increases the diffusion rate. The diffusion rate and thereby the release rate of radon from the soil are influenced also by meteorological factors such as rainfall, snowfall, freezing and variations in atmospheric pressure.

Groundwater in contact with sediment and rock containing radium will be a source of radon. In groundwater, radon transportation is determined primarily by diffusion patterns and the direction of the water's mechanical flow. The solubility of radon in water is relatively low and with its short radioactive half-life, much of it will decay before being released from the groundwater.

10.4 Assessment of the radiation impact on non-human biota (NHB)

Past and current research studies are focused mostly on human biological effects from radiation exposure from the nuclear industry rather than from naturally occurring radionuclides and NHB radiation effects (Hink et al., 2010).

Ionizing radiation could result in mortality as well as reproduction, morbidity and mutation effects in NHB species where the screening value is exceeded (Table 10.4.1 – the data presented in this table are based on studies on man-made radionuclides). Studies of mammals, including reindeer in the Novaya Zemlya archipelago during nuclear tests, estimated that a dose of 8.7 Sv produced 50% mortality in young animals (Klevezal and Sokolov, 1999). Lethal dose (LD_{50}, 50%) values between 1.2 and 3.9 Sv have been shown to lead to death of mammals of the bone marrow syndrome (Kruglikov et al., 1992; UNSCEAR, 1996). Experimental data from dogs exposed to X-irradiation (1-3 Sv) demonstrated a life span shortening (9.5% and 20.7%) (Andersen and Rosenblatt, 1969).

Studies conducted on animals have shown that inhalation of insoluble uranium compounds can result in lung damage. In male rats and mice, exposure to uranium has been shown to decrease fertility, and uranium compounds on the skin cause skin irritation and mild skin damage in animals (ATSDR, 2013).

Neither the National Toxicology Program (NTP), the International Agency for Research on Cancer (IARC) nor the U.S. Environmental Protection Agency (EPA) have classified natural uranium with respect to carcinogenicity (ATSDR, 2013).

Compensatory processes supporting species survival in places with enhanced levels of radiation backgrounds have been reported by Geras'kin and collaborators (2007). The authors found stimulation of growth, photosynthesis and low molecular weight antioxidants synthesis in plants. These effects may be caused by an underlying mechanism with radio-adaptive response relating to DNA repair and cell cycle regulation.

Internationally, the ICRP, IAEA and UNSCEAR are addressing environmental protection as an element of their revision of Recommendations. The former position of the ICRP as paraphrased in the principle 'by protecting man from the effects of ionizing radiation, the environment is automatically protected' (ICRP, 1977; 1991) may be untenable. Within the last few years, ICRP has begun to formulate its thoughts concerning protection of the environment (ICRP, 2003), and an agreed set of numerical values and units, a set of reference dose models, reference dose-per-unit-intake data and reference fauna and flora (RAPs) have been proposed by the Commission (ICRP, 2005, 2007, 2008, 2014). ICRP (2008) have established Derived Consideration Reference Levels (DCRLs) for each reference animal and plant (RAP). The DCRL have been defined by ICRP as 'bands of dose rates to assist, inform and guide efforts on environmental protection' and the band / shaded area is to be used as a 'point of reference'. The DCRL are dose rates that could be used in management actions or in the decision-making process but are not intended to be regarded as dose limits.

Table 10.4.1. Derived Consideration Reference Levels (DCRLs) for Reference Animals and Plants (RAP). The band/shaded areas are referred to as 'points of reference'. Source: ICRP (2008).

Dose rate (mSv/day)	Reference Deer	Reference Duck	Reference Trout	Reference Flatfish	Reference Crab	Reference Wild grass	Reference Seaweed
> 1000	Mortality from bone marrow syndrome (1-8 Sv $LD_{50/30}$)	Mortality in adults and eggs (9 Sv LD $_{50/60}$ and 9-13 Sv LD_{50}).	Mortality in embryos (0.3 to 19 Sv LD_{50}).	Mortality for hatchlings (1.5 Sv LD_{50}); adults (10-22 $LD_{50/50}$).	Mortality in young (7 Sv/d for 50 days kills 95%).	Mortality (16-22 SvLD_{50}).	Deleterious effects expected at very high dose rates.
100-1000	Reduction in lifespan due to various causes.	Potential lethal effects on hatchlings.	Potential increased morbidity.	Some mortality expected in larvae and hatchlings.	Possible effects on growth rates.	Reduced reproductive capacity.	No information.
10-100	Increased morbidity. Possible reduced lifespan. Reduced reproductive success.	Increased morbidity.	Reduced reproductive success. Reduction in resistance to infections.	Reduced reproductive success.	No information.	Reduced reproductive capacity.	No information.
1-10	Potential for reduced reproductive success due to sterility of some adult males.	Potential for reduced reproductive success.	Possible reproductive success due to deformities.	Possible reproductive success due reduced fertility in males.	No information.	No information.	No information.

0.1-1	Very low probability of effects.	No information.	No information.	No information.	No information.	No information.	No information.
0.01-0.1	No observed effects.	No information.	No information.	No information.	No information.	No information.	No information.
< 0.01	Natural background.	Natural background.	Natural background.	Natural background.	Natural background.	Natural background.	Natural background.

Some countries already have requirements for assessing the impacts of ionizing radiation on NHB. For example, in England and Wales, the requirement to assess impacts affecting Natura 2000 sites has been interpreted to include ionizing radiation (http://ec.europa.eu/environment/nature/natura2000/index_en.htm). In the USA, biota protection guidelines and dose rates are contained in US DOE Orders 5400.5 and 450.1 (http://www.directives.doe.gov).

A number of models (e.g. RESRAD-BIOTA, ERICA, DosDiMEco) have been developed and are still under developed for dose and risk assessment of NHB resulting from exposure to ionizing radiation. Environmental assessment models can be used for evaluating the radiological impact of actual and potential releases of radionuclides to the environment. Those tools are used, for example, in the control of discharges to the environment and in planning measures to be taken in the event of accidental releases, etc. It is important to check, to the extent possible, the reliability of the predictions of such models, preferably through comparison with measured values in the environment or comparison with the predictions of other models.

Assessment of radiation exposure to NHB is performed by adopting reference exposure and dose models. The RAPs selected by ICRP are: earthworm/soil invertebrates, wild grass/grasses, herbs and crops, duck/bird, trout/pelagic fish, rat/burrowing mammal, pine tree/ tree, frog/amphibian, flatfish/benthic fish, bee/above-ground invertebrate, deer/herbivorous mammal, brown seaweed/macroalgae and crab/crustacean.

The ERICA (Environmental Risks from Ionizing Contaminants) Integrated Approach provides guidance on the assessment of impacts of ionizing radiation on the NHB, allowing the calculation of dose rates to and whole body activity concentrations in biota for terrestrial, marine and freshwater environments (Brown et al., 2008, UNSCEAR, 2013). The assessment used in the ERICA tool deals with the quantification of radiation risk to reference organisms in the environment through the application of transfer and dosimetric models and, for screening purposes, the comparison of predicted exposure dose rates with appropriately derived benchmarks. The assessment process in the tool includes three separate tiers. Tier 1 is highly conservative and minimum data are required for input. Tier 2 assessment is a site-specific less conservative tier and a variety of parameters are required. Tier 3 is probabilistic risk assessment and not a screening tier. The ERICA tool uses a screening dose rate of 10 µGy/h as the criterion that NHB risks are negligible. The ERICA 10µGy/h value is NOT a limit but a screening value, above 10µGy/h further investigations are recommended. The tool provides a database of default radionuclides, reference organisms, concentration ratios (CR), radiation weighting factors and a database of dose conversions coefficients (DCCs) to enable dose rate calculations from the input data.

The ERICA tool Integrated Approach:

- Does not consider the pathways for intake of radionuclides for each reference organism.
- Does not require sampling of local species and analyzing them for radionuclides.
- Does not consider NHB site-specific species present and subsequent application of specific parameters (intake pathways and radiation sensitivities) to each of the NHB site-specific species.
- Uses conservative factors such as transfer of radionuclides from the environment to the reference organism, radiological effects on the organism, etc.
- Uses kinetic models to calculate 'dynamic' concentrations in biota based on measured concentrations in media (i.e. air, soil, freshwater, seawater, sediment).
- Conducts an equilibrium assessment using concentration ratios (CR): activity concentration in biota whole-body (Bq/kg fresh weight)/activity concentration in media (soil, air and water) (Bq/kg dry weight (soil), Bq/m^3 (air), Bq/l (water)), where appropriate.

NHB radiation exposure depends on various factors such as contamination levels in the environment, the geometrical relationship between the radiation source and the organism, organism size, shielding properties of the medium, the time spent in the contaminated radioactive environment and the physical properties of the radionuclides present. ERICA uses a number of extreme simplifications (EMRAS, 2010). One simplification is the reduction of an organism to simple shapes such as ellipsoids and cylinders. Another simplification is the fact that radionuclide kinetics in the organism and organ distribution are not taken into account. The endpoint considered is the average absorbed dose rate for the whole body per unit of activity concentration in the organism and the surrounding media. The estimation of absorbed dose rates for non-human biota is in all existing models, defined as the amount of energy absorbed per unit mass of tissue of an organ or organism in Gray (Gy=J kg^{-1}).

More details regarding the different models can be found at EMRAS: http://www-ns.iaea.org/projects/emras/emras2/.

ERICA and associated documentation are freely available at: http://www.ceh.ac.uk/PROTECT/ERICAdeliverables.html..

10.5 References

Agency for Toxic Substances and Disease Registry (ATSDR), 2013. Toxicological Profile for Uranium. Atlanta, GA: U.S. Department of Health and Human Services, Public Health Service.

Andersen, A.C. and Rosenblatt, L.S. 1969. Effect of whole-body X-irradiationon the median life-span of female dogs (Beagle) - Rad. Res (in press).

Arctic Monitoring and Assessment Programme (AMAP), 1998. Arctic Pollution Issues, (AMAP, Oslo).

Beresford, N.A., Mayes, R.W., Barnett, C.L., Lamb, C.S., 2002. Radioprotection – Colloques, 37, 373.

Beresford, N.A., Wright, S.M., Barnett, C.L., Golikov, V., Shutov, V., Kravtsova, O., 2005. Approaches to estimating the transfer of radionuclides to Arctic biota. Radioprotection 40: S285-S290.

Berlin, M., Rudell, B., 1986. Uranium. In: Handbook on the toxicology of metals. 2nd edition. L. Friberg, G.F. Nordberg and V.B. Vouk (ed.). Elsevier Science Publishers, Amsterdam. pp. 623-637.

Bhatti, A.I., Hayat, M.A., Iqbal, M., 2012. Assessment of Thorium in the Environment (A Review), J. Chem. Soc. Pak. 34: No. 4

Bigu J. 1985. Radon daughter and thoron daughter deposition velocity and unattached fraction under laboratory-controlled conditions and in underground uranium mines. J. Aerosol. Sci. 16: 157-165.

Brown, J.E., Alfonso, B., Avila R., Beresford, N.A., Copplestone, D., Prohl., G., Ulanovsky, A. 2008. The ERICA Tool. Journal of Environmental Radioactivity 99 (2008) 1371e1383.

Burns, P., and Finch, R. 1999. Uranium, Mineralogy, Geochemistry and the Environment, Reviews in Mineralogy. Mineralogical Society of America, 38: 1-679.

Butler, A.P., Burne, S., Wheater, H.S., 1996, Observations of 'freezing-induced redistribution' in soil lysimeters. Hydrol. Process. 10: 471-474

Cothern, C.R., Lappenbusch, W.L., 1983. Occurrence of uranium in drinking water in the US. Health Phys. 45: 89-99.

CSA N288.4-10 (R2015) - Environmental monitoring programs at Class I nuclear facilities and uranium mines and mills.

EMRAS Biota Working Group, 2010. Modeling radiation exposure and radionuclide transfer for non-human species. International Atomic Energy Agency, Vienna.

Garten, C.T. Jr., 1978. A review of parameter values used to assess the transport of plutonium, uranium and thorium in terrestrial food chains. Environ. Res. 17: 437-452.

Geras'kin, S.A., Fesenko, S.V., Alexakhin, R.M. 2007. Effects of non-human species irradiation after the Chernobyl NPP accident. Environment International 34 (2008) 880 – 897.

Ha, N.T.T., Dung, B.D., Long, N.Q., Mai, T.T., Dao, H.T.A., 2012. Set up procedure determine thoron concentration in the air by lr-115 type ii. Vietnam Atomic Energy Institute: 116.

HansenV, 2011, PhD thesis, Chemical speciation and behaviour of radionuclides into the environment, DTU.

Hinck, J.E., Linder, G., Finger, S., Little, E., Tillitt, D., Kuhne, W., 2010, Biological pathways of exposure and ecotoxicity values for uranium and associated radionuclides. Hydrological, geological, and biological sites characterization of breccia pipe uranium deposits in Northern Arizona. United States Geological Survey, Scientific Investigations Report, 5025, 283-353.

ICRP, 1977. Recommendations of the International Commission on Radiological Protection. Publication 26. Pergamon Press, Oxford.

ICRP, 1991. Recommendations of the International Commission on Radiological Protection. Publication 60. Annals of the ICRP 21. Pergamon Press, Oxford.

ICRP, 2003. A framework for assessing the impact of ionizing radiation on non- human species. ICRP Publication 91.Ann. ICRP 33 (3).

ICRP, 2005. The Concept and use for Reference Animals and Plants for the purposes of Environmental Protection. Draft for discussion. Annals of the ICRP. Available at: www.icrp.org/

ICRP, 2007. Recommendations of the International Commission on Radiological Protection, Annals of the ICRP 37, 2-3. Pergamon Press, Oxford.

ICRP, 2008. Environmental Protection - the Concept and Use of Reference Animals and Plants. ICRP Publication 108, Ann. ICRP 38, 4-6.

ICRP, 2014. Protection of the Environment under Different Exposure Situations, Publication 124. Ann. ICRP 43(1).

Klevezal G.A., Sokolov A.A., 1999. Retrospective estimation of the state of reindeer population (Rangifer tarandus) from Novaya Zemlya during nuclear testing. Russian J. Zoology 3 (1): 224-233. [Zool. Zhurn. 78 (1): 102-110].

Kruglikov, B.P., A.V. Vasilyev and A.S. Shevchenko. Eficcts of ionizing radiations on agricultural animals. p. 174-195 in: Agricultural Radioccology (R.M. Alexakhin and N.A. Korneyev, eds.). Ecologia Publishers. Moscow, 1992.

Lide, D.R. (Ed.), 1992-93. Handbook of chemistry and physics. CRC Press, Boca Raton, FL.

Mudd, GM, 2004, A Compendium of Radon Data For the Rehabilitation of Australian Uranium Projects. Proc. 11TH International Conference on Tailings & Mine Waste ‘04, Taylor & Francis Group, ISBN 04 1535 939 2, pp 247-260.

Pentreath, R.J., 1998. Radiological protection Criteria for the natural environment. Radiat. Prot. Dosim. 75: 175-179.

Poston, T. M. 1982. Observations on the bioaccumulation potential of thorium and uranium in rainbow trout (*Salmo gairdneri*). Bull. Environ. Contam. Toxicol. 28: 682-690.

Sheppard, M.I., Ewing, L.L., Hawkins, J.L., 1994. Soil degassing of carbon-14 dioxide: Rates and factors. J. Environ. Qual. 23: 461-468.

UNSCEAR, 1996. Sources and effects of ionizing radiation. Scientific Annex: Effects of radiation on the environment. United Nations, New York.

UNSCEAR, 2008. Sources and effects of ionizing radiation. Volume II. Effects. Scientific Annexes C, D and E. U.N. sales publication E.11.IX.3. United Nations, New York.

UNSCEAR, 2013. Attachment F-1 Methodology for estimating doses to non-human biota. Annex A, Levels and effects of radiation exposure due to the nuclear accident after the 2011 great east-Japan earthquake and tsunami, Appendix F (Assessment of doses and effects for non-human biota). United Nations, New York.

U.S. EPA, 2004. U.S. Environmental Protection Agency. Understanding Variation in Partition Coefficient, Kd, Values, Vol 3: Review of Geochemistry and Available K_d Values for Americium, Arsenic, Curium, Iodine, Neptunium, Radium, and Technitium. EPA 402-R-04-002c. Washington, DC: U.S. EPA, July, 2004.

U.S. EPA, 2008. U.S. Environmental Protection Agency. Technologically Enhanced Naturally Occurring Radioactive Materials from Uranium Mining Volume 1: Mining and Reclamation Background (PDF). Chapter 3: Volume and Characteristics of Uranium Mine Wastes. EPA 402-R-08-005. Washington, DC: U.S. EPA, April 2008.

Zhang, P.C. and Brady, P.V. 2002. Geochemistry of soil radionuclides: Madison, Wis., Soil Science Society of America 252p.

Závodská, L., Kosorinova, E., Scerbakova, L., Lesny, J., 2008. Environmental chemistry of uranium. HV ISSN, 1418-7108.

Appendix A

Past and current environmental practices of uranium facilities

Some examples of environmental and health practices employed at uranium mines operating in the Arctic and elsewhere in the world are discussed. Please note that the below examples do not cover all worldwide uranium mines sites under operation, construction, exploration, decommissioning, long-term care and monitoring.

1. Canada

In response to a demand for military purposes, the exploration for uranium in Canada began in 1942. By 1959, a total of 23 uranium mines with 19 treatment plants were in operation. Elliot Lake in Ontario was the main production centre, but northern Saskatchewan also had plants. This first phase of Canadian uranium production peaked in 1959 when more than 12,000 tonnes of uranium were produced.

During the 1970s, the uranium exploration was focused on northern Saskatchewan's Athabasca Basin. The Rabbit Lake, Cluff Lake and Key Lake mines started up from 1975 to 1983. After this, the exploration moved even further north, resulting in the discoveries of Midwest, McClean Lake and Cigar Lake, and in 1988 the Cameco Corporation discovered the big McArthur River deposit.

In the early 1990s, the Saskatchewan government considered phasing out uranium mining, but this position was abandoned after a joint federal-Saskatchewan study found that the benefits of mining outweighed the adverse impacts and that the negative effects of any impacts could be minimized.

Today, the Canadian government actively supports uranium mining. In Canada, mining is usually governed by provincial regulations. However, uranium production is under federal jurisdiction. The Canadian Nuclear Safety Commission, an independent regulator, regulates uranium mines and mills and all subsequent stages of the nuclear fuel cycle, such as refining, conversion and fuel fabrication, to protect health, safety, security and the environment. An overview over the Canadian regulatory framework relative to uranium production for the nuclear fuel cycle is given in Chapter 3.

Most of Canada's reserves are located in the Athabasca Basin of northern Saskatchewan, which hosts the world's largest high-grade deposits (Fig. 1.1). For example, at the McArthur River mine, the deposits average 18 per cent uranium content, making it the highest grade uranium mine in the world. The deposits mined in Canada have grades that are 10 to 100 times greater than the average grade of deposits mined elsewhere in the world. Canada's uranium resources are the fourth largest in the world, after those of Australia, Kazakhstan and Russia (http://www.nrcan.gc.ca/energy/uranium-nuclear/7695).

The key producers are Cameco Corporation and AREVA Resources Canada Inc., which are among the world's leading uranium suppliers.

In Canada, clean waste rock is used for construction activities such as aggregate in concrete and the construction of roads. The clean rock that is left once the mining project has ended is usually left in piles on the surface, contoured to blend in with the natural environment and re-vegetated. Mineralized waste rock can contain significant concentrations of pollutants and can potentially generate acid or release contaminants at rates that could impact the local environment. During operations, mineralized waste rock is typically deposited on impermeable pads. Seepage and runoff from the mineralized waste rock piles are collected and treated to remove contaminants before they are released to the environment. Long-term management of mineralized waste rock includes depositing the rock in mined-out open pits, topping them with clean waste rock and covering surface piles to minimize the infiltration of water and erosion.

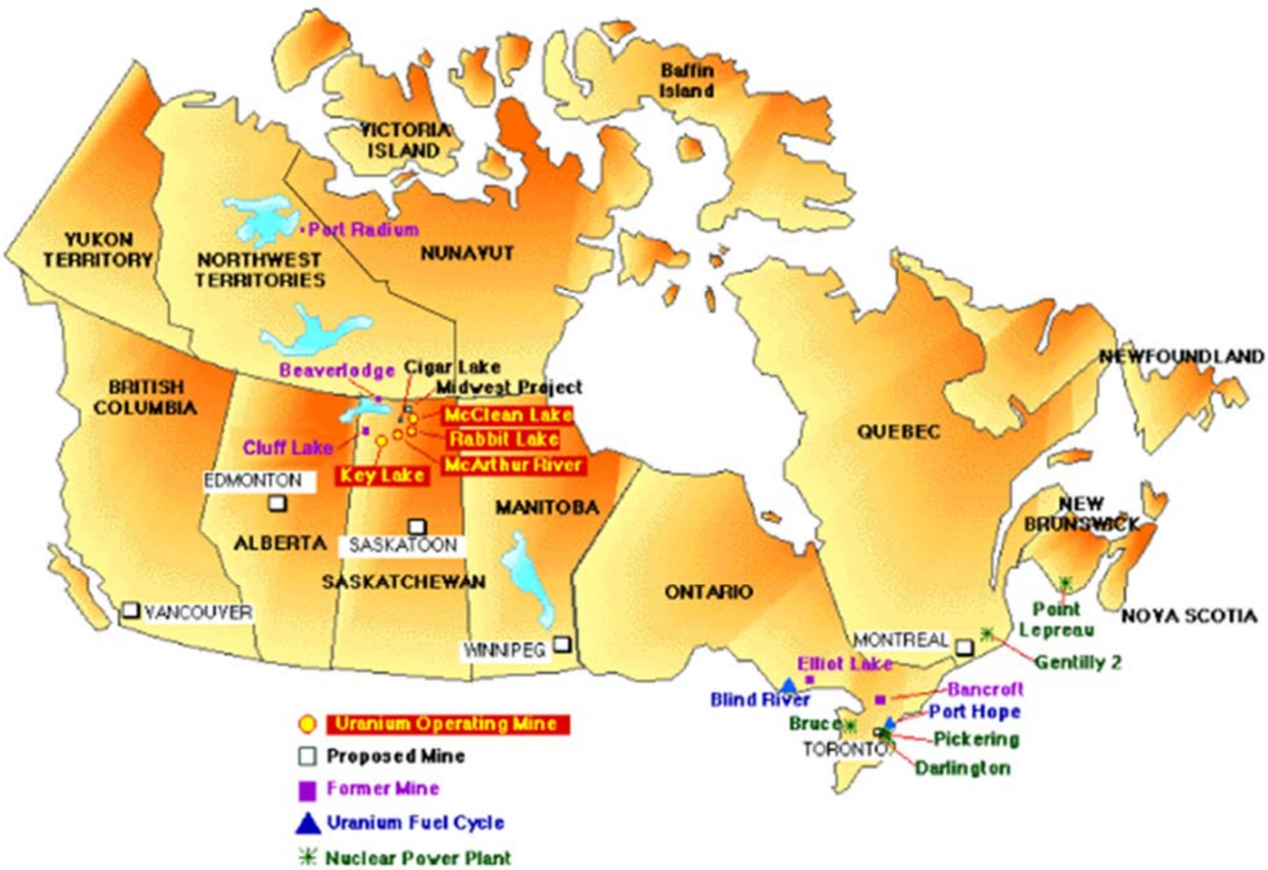


Figure 1.1. Uranium in Canada 2014. Source: http://www.world-nuclear.org/info/Country-Profiles/Countries-A-F/Canada--Uranium/.

Mine water management has been and remains a key issue for the operator and regulators of the Key Lake mine site:
(http://nuclearsafety.gc.ca/eng/uranium/mines-and-mills/nuclear-facilities/key-lake/index.cfm). The collection and treatment of all mine water are prioritized activities at the site. Extensive monitoring programmes to collect baseline environmental data are undertaken prior to the development of the mine. Environmental issues identified during the environmental assessment phase are used to objectively determine the operation's potential impact on the local environment. Also, it has been possible to successfully adjust water treatment programmes as concerns or mitigation strategies are identified. Environmental monitoring shows that the aquatic impacts do not extend beyond the limits of the facility and that they are within the levels predicted and authorized (CNSC, 2014).

Tailings management area (TMA) in Canada is an example of a new management approach. The main types of waste generated from mining and milling of uranium ore are tailings and waste rock. Tailings and waste rock must be managed over a long-term basis because they typically contain elevated levels of radioactive elements (thorium-230 and radium-226, sometimes uranium-238 and their associated decay products) and non-radioactive contaminants.

In Canada, tailings are contained in tailings management facilities (TMFs) such as engineered surface and near-surface waste management facilities located near the mines and mills. TMFs are designed to ensure that groundwater and surface water is diverted from the tailings in order to prevent any contamination. Furthermore, the tailings are isolated from the surrounding environment for a very long time. Tailings are usually deposited underwater to: (1) prevent oxidizing conditions, (2) shield against radiation emanating from the tailings and (3) stop dust from blowing off the surface of the tailings.

The tailings are deposited as slurry in TMFs. The solids tailings are allowed to settle in the TMF, while the liquids are later collected and processed through a water treatment plant to remove contaminants. The treated effluent must meet regulated quality requirements before it is allowed to be discharged into the environment.

In Canada, tailings are deposited in TMFs at Cameco Corporation's Key Lake and Rabbit Lake operations as well as at AREVA's McClean Lake operation (Fig. 1.2). There are also two inactive above-ground TMFs located at the Rabbit Lake and Key Lake operations. The tailings from the McArthur River and Cigar Lake Mines are stored at the Key Lake and McClean Lake TMFs. There are 20 TMFs located at closed or decommissioned uranium mines: 14 in Ontario, fourin Saskatchewan and two in the Northwest Territories.

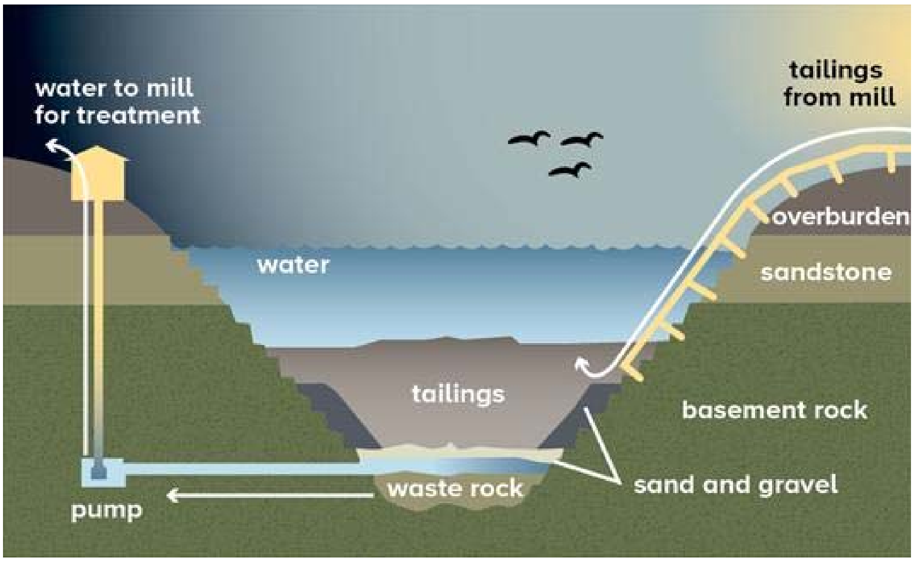


Figure 1.2. Canadian in-pit tailings management area. Source: http://nuclearsafety.gc.ca/eng/waste/uranium-mines-and-millswaste/index.cfm#Tailings.

From 1983 to 1995, tailings generated by the Key Lake mill were placed in an above-ground storage facility (approximately 45 hectares at the top). The tailings facility has a bentonite bottom seal and partial embankment seal, along with a sand drain and collection systems to return supernatant and drainage water to the mill. The tailings facility was designed with a 5.8 million m^3 volume capacity. In 1995, tailings deposition was changed from the above-ground storage facility to an in-pit facility in the Deilmann pit. This in-pit facility initially operated using subaerial tailings deposition and thus required an extensive dewatering system. A portion of the dewatering system was coupled with a bottom drain beneath the tailings to promote tailings consolidation. The conversion to subaqueous deposition started in 1998 and partial flooding of the Deilmann In-Pit Tailings Management Facility (DTMF) began in 1999. After complete flooding, water levels were controlled to levels about 10 m below their natural rebound level, in this way providing ongoing hydraulic containment for tailings leachate collection and for any leachate form of waste rock deposited near the pit.

For the Cluff Lake project, a nearby valley was chosen as treatment and disposal site, with the tailings retained in a dam built with an impermeable cut-off wall and a sophisticated groundwater monitoring network. The strategy was approved by the regulatory agencies following environmental assessment and public consultation. As additional deposits were exploited, the TMA was expanded to increase the tailings capacity and the TMA area was separated into a solid and a liquid area for better management of the waste products. A comparison of recent water quality with pre-operational data indicates increased concentrations of major ions in the water of Snake Lake as was predicted in the environmental assessment. Measurable impacts were observed on water and sediment quality and aquatic ecology (changes in zooplankton, benthic macroinvertebrates and fish communities). However, the potential adverse effects are not considered significant because they are moderate in magnitude, restricted to local populations in the lake and reversible, with substantial recovery expected in the first 50 to 100 years. The facility has been decommissioned and is now in the post-decommissioning monitoring phase
https://www.ceaa-acee.gc.ca/41B79974-docs/report_e.pdf,
http://www.nuclearsafety.gc.ca/eng/the-commission/pdf/2009-06-10-Decision-AREVA-e-Edocs3405423.pdf and http://kiggavik.ca/wp-content/uploads/2013/04/Cluff-Lake-Detailed-Decommissioning-Plan-V2-Feb2009.pdf.

McClean Lake tailings management facility (TMF) in Canada is an example of leading practice in tailings management because:

- A detailed assessment of tailings management options was developed well before milling began and included laboratory research and development carried out by the proponent, an intensive public EIA process and a thorough regulatory review at each licensing step, all of which fed into the final design characteristics.
- The tailings treatment was designed so that the geochemistry of the tailings in the disposal facility provides long-term control over the release of constituents of concerns.
- Hydrodynamic containment is provided during the operating period.
- A hydraulic conductivity contrast is established between the tailings and the surrounding host rock so that the groundwater will preferentially flow around the tailings in the long term.

Key features of the TMF at McClean Lake
(http://nuclearsafety.gc.ca/eng/uranium/mines-and-mills/nuclear-facilities/mcclean-lake/index.cfm) are designed to:

- Isolate the tailings from the surrounding environment for a very long time.

- Ensure hydraulic containment of tailings pore water during the operating period (≈40 years). A ring of dewatering wells has been installed around the edge of the deposition pit.
- Monitor groundwater levels using external observation wells installed within the mine ring area. In addition, internal monitoring wells are installed between the dewatering well ring and the pit.
- Collect tailings pore water while containing tailings solids above the filter using base drain and graded filter packages constructed of sand and crushed rock at the base of the TMF, thereby enhancing tailings consolidation by promoting dissipation of excess pore water pressure within the tailings mass.
- Use a reclaim water barge to precisely control the pond waste.
- Treat the tailings.

McClean Lake mine rock segregation in Canada is a good example of how a leading practice and management waste rock plan is developed and implemented. Clean and problematic waste rock has been effectively segregated during mining. Clean waste rock is managed in surface stockpiles or used for construction purposes. Problematic waste rock is managed by placing it into a mined-out open pit which is subsequently flooded.

Information related to the performance of uranium fuel cycle and processing facilities in Canada:
http://nuclearsafety.gc.ca/eng/resources/publications/reports/report-on-uranium-fuel-cycle-and-processing-facilities.cfm.

2. Russia

Production of uranium in the Soviet Union started in 1944 as part of the nuclear weapons programme. The first uranium mining and processing centre was the No 6 Mining and Chemical Combine. The facility was built in Tajikistan's Fergana valley by the company Vostokredmet. In the late 1940's, the focus shifted to already explored deposits in Eastern Europe, and the Soviet Union signed international agreements with Bulgaria, Czechoslovakia, Hungary, Poland, Romania and East Germany (Wismut Company). In the 1970s and 1980s, most of the Soviet uranium production was located in Kazakhstan, Kyrgyzstan, Tajikistan, Uzbekistan and Ukraine. The production peaked with 16,000-16,500 tonnes in 1985-1986 (Khlopkov and Chekina, 2014). In the mid-1980s, The Soviet Union had the world's largest uranium industry, which was concentrated in Kazakhstan, Russia, Ukraine and Uzbekistan.

The country's three uranium mining companies nowadays are Priargunsky mining and Chemical Company (PPGKhO), Dalur and Khiagda (Fig. 2.1). At present, ARMZ holding (subsidiary of the RosaTom state nuclear energy corporation) manages all uranium mining enterprises in Russia. It controls a stake of 89.5% of PPGKhO, 98.89% of Dalur and 100% of Khiagda, while simultaneously controlling more than 20% of the uranium reserves in Kazakhstan through joint ventures (Zarechnoye JV, Akbastau JV and Karatau JV). ARMZ Uranium Holding is also widely involved in uranium projects abroad. Thus, the company has initiated joint uranium exploration and mining projects in Kazakhstan, Mongolia, Namibia, Canada, Armenia and Ukraine. The near-term plans of the holding include organization of natural uranium production at its four new enterprises: Elkon Mining and Metallurgical Complex and Lunnoye in Yakutia; Gornoye Uranium Mining Company and Olovskoye Mining and Chemical Company in Transbaikalia. The Khiagda (Buryatia) and Dalur (Kurgan Region) mining enterprises produce uranium using in-situ leaching technology.

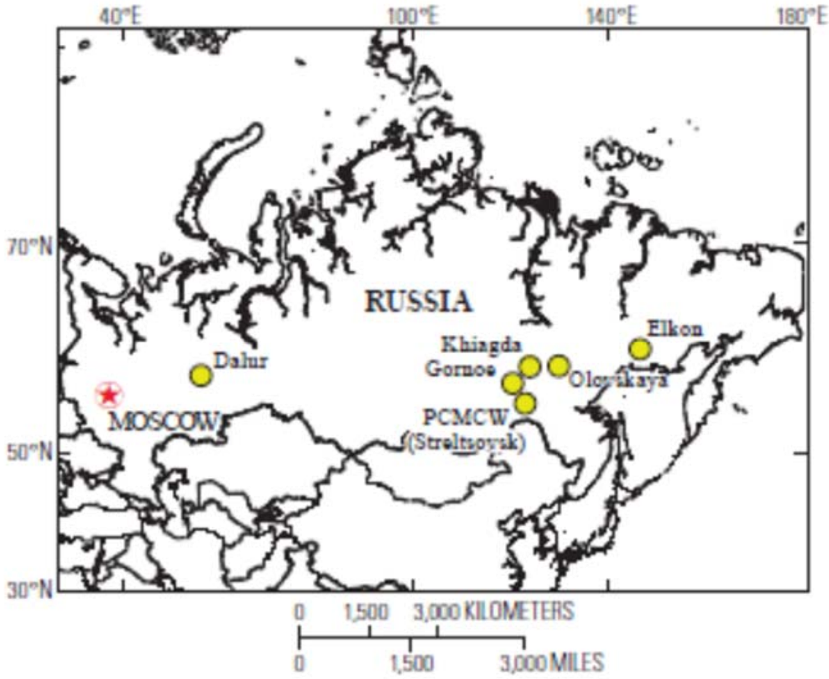


Figure 2.1. Location of uranium mines in Russia. Source: OECD/NEA-IAEA (2010).

Set up in 1968, Priargunsky Industrial Mining and Chemical Union (JSC PIMCU known also as PPGKhO / PPGHO) is currently the largest uranium mining company in Russia (http://www.priargunsky.armz.ru/eng/). Priargunsky operates in the Chita region in South-East Siberia, 18 km east of the town of Krasnokamensk, near the Chinese and Mongolian borders.

Priargunsky is the world's oldest operational uranium mining facility. For over 40 years, JSC PIMCU has been the principal natural uranium mining enterprise producing up to 90% of Russia's domestic natural uranium. Nowadays, JSC PIMCU performs underground mining of uranium at four mines: Mine No. 1, Mine No. 2, the Glubokiy Mine and Mine 6R. The end product is triuranium octoxide – U_3O_8. In addition to underground mining, the JSC PIMCU is involved in milling of uranium ores, lignite mining, sulphuric acid production for the reprocessing manufacture, electric power production and warm power supply of industry and municipal formations. The company's economic and financial indicators began to decline because of reduced ore grade in the remaining deposits and high production costs. The decision not to close the mine is mainly because of social and national energy security as it provides jobs to 10,000 people in the town of Krasnokamensk.

Comprehensive environmental (radio-ecological) and health assessments were carried out in the area of the Priargunskiy production mining and chemical association including also Krasnokamensk village (Filipchenko, 1994; Ehdwall et al., 1995; Ujba, 2007; Konstantin and Gongalsky, 2003; Shandala et al., 2011). Gamma dose rate surveys and sampling of air, soil, biota and water and the contents of natural radionuclides such as U-238, Th-232, Ra-226, Po-210 and Pb-210 were determined. Radon and thoron decay products were determined in indoor and outdoor air in addition to non-radioactive contaminants such as arsenic and heavy metals. Finally, medical and dose information has been collected and used in order to evaluate the health conditions of miners.

3. Finland

Historically, uranium mining and milling were conducted in Finland for a short period of time, from the mid-1950s to 1961. In 2007, Talvivaara Mining Company Plc. was permitted to exploit a black shale hosted Ni-Zn-Cu-Co sulphide deposit, which is the largest sulphidic nickel ore deposit in Europe. The open cut mine is located in Sotkamo in Eastern Finland (Fig. 3.1). The ore is very low grade, containing leachable nickel, zinc, copper, cobalt, manganese and uranium. Mining operations at the site started in spring 2008 and besides nickel, also zinc was produced by using bio-heap-leaching technology. Bioleaching is a process, whereby metals are leached from ore as a result of bacterial action.

In 2012, Talvivaara Mining Company Plc. was granted license to extract uranium as a by-product from its current operations (http://www.talvivaara.com/mediaen/Talvivaara_announcements/stock_exchange_releases/stock_exchange_release/t=talvivaara-uranium-permitting/id=27504542). Several Finnish and international authorities and organizations such as Ministry of Employment and the Economy- ELY-Centres for Economic Development, Finnish Safety and Chemicals Agency (Tukes), Regional State Administrative Agencies were involved in granting the uranium recovery permit to Talvivaara. According to Tukes, 'the safe recovery of uranium should increase the safety of operations, since it would result in less uranium in the mine's waste and products'.

Figure 3.1. Location of Talavivaara uranium mine in Finland, http://www.talvivaara.com/home.

In early November 2012, water containing uranium and other chemical reagents used in the milling processes was found leaking from a gypsum waste water pond at the Talvivaara mining site to the surrounding rivers and lakes and mining activities were consequently ceased. Reported uranium concentrations in the water leaking from the wastewater pond into the Talvivaara mining site were 100 to 200 Bq/L, which is equivalent to about 4000-7000 micrograms of uranium per litre of water. The typical concentration of uranium in Finnish groundwater and surface water is under 1 Bq/l (http://www.stuk.fi/stuk/tiedotteet/2012/en_GB/news_796/).

The Finish Radiation and Nuclear Safety Authority (STUK) monitors environmental radioactivity (e.g. water and bottom sediment samples) at both the Talvivaara mining site and in its surroundings. Past and recent environmental data are available at the STUK website: http://www.stuk.fi/sateily-ymparistossa/uraani/talvivaaran-kaivos/en_GB/talvivaaran-kaivosalueen-vesistojen-uraani/). Recent results on external radiation around Finland (Fig. 3.2) can be found here:
http://www.stuk.fi/sateily-ymparistossa/sateilytilanne/en_GB/sateilytilanne/.

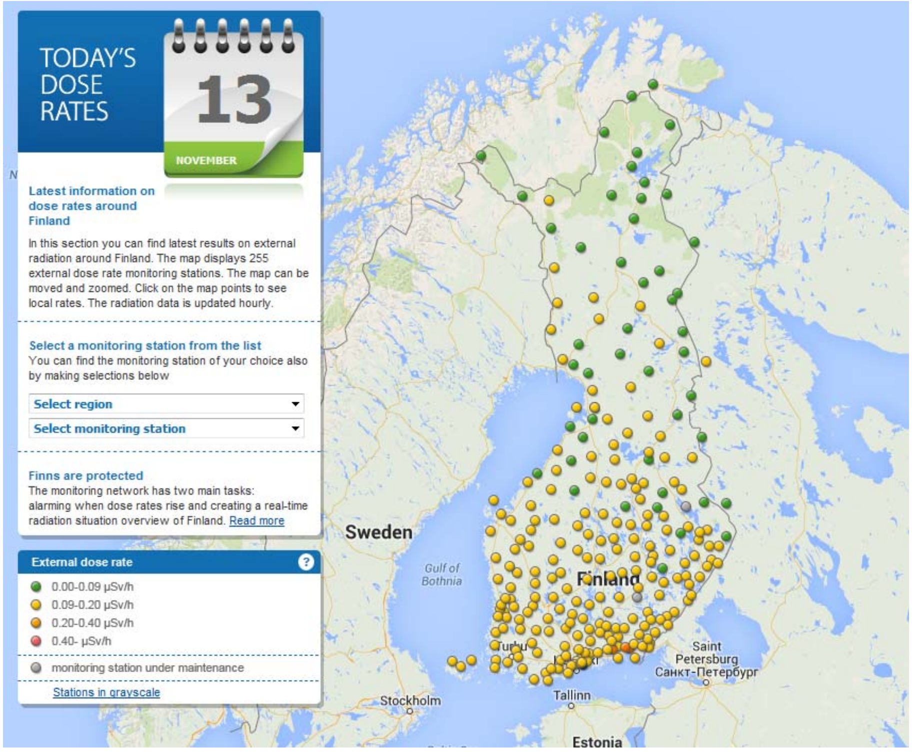


Figure 3.2. External radiation (dose rates) in Finland (13 November 2014), http://www.stuk.fi/sateily-ymparistossa/sateilytilanne/en_GB/sateilytilanne/.

4. Sweden

The Ranstad Västergötland alum shale (coal- and oil-bearing black shale) deposit, the only uranium mine (open pit) in Sweden, was in operation from 1959 to 1969 with a total production of 215 tonnes of uranium oxide. The high operating costs of the pilot plant due to the low concentration of uranium in the shale and the then availability of comparatively cheap uranium on the world market led to closure of the mine. The responsibility for restoring the tailings deposits and mining pits rested on the Swedish government. A remediation plan was established in the early 1990s. The County Administration of Skaraborg (later Västra Götaland) drew up plans for the restoration and the final document 'Reclamation Plan for the Ranstad Mine Area' ('Efterbehandlingsplan för gruvområdet i Ranstad'). Studsvik AB (formerly called AB Atomenergi) was engaged to carry out the plans and the work took place from 1990 to 1993. The open pit was flooded by natural infiltration and has now become a groundwater-fed lake. The surface runoff goes untreated via Pösan to Lake Hornborga. Tailings from the yellowcake production were covered during the rehabilitation work by a 1.8 m. thick layer of bentonite, limestone and gravel. A system of dikes was constructed to collect any water seeping out from the tailings. This water was then collected in dams and treated before its release into the recipient, Marbäcken.

Most of the facilities at Ranstad are no longer in use and some clean-up activities have already taken place. One of the facilities continues to be used actively by Ranstad Mineral AB (RMA) for the recovery of uranium from waste generated by nuclear fuel manufacturers. The recovery includes the handling of enriched uranium and is classified as a nuclear facility. Some of the older facilities are used for temporary storage of untreated and processed waste.

A report on the costs of decommissioning certain buildings and facilities at Ranstad was prepared in June 2008 by Swedish Nuclear Fuel and Waste Management Company International Consultants AB (SKB IC). The estimated total cost for decommissioning (e.g. preparation site characterization work, decontamination, equipment dismantling, support to actual decontamination and dismantling operations, conventional building demolition, waste disposal and final clearance) is estimated to 189.4 million Swedish kroner (http://www.stralsakerhetsmyndigheten.se/Global/Publikationer/Rapport/Avfall-transport-fysiskt-skydd/2009/SSM-Rapport-2009-31.pdf).

Sweden's geology provides excellent conditions for good uranium ores (Fig. 4.1). Thus, plans are on the way to resume uranium mining in Sweden. Several companies are exploring uranium or thorium deposits in Sweden, for instance Continental Precious Minerals Inc., Canada; Mawson Energi AB, Canada/Australia; AURA Energy, Australia; NorrskenEnergy Ltd.; joint venture by EVE, Energy Ventures Ltd, Australia, and International Gold Exploration AB, Sweden; Wiking Mineral AB, Sweden; Nordic Diamonds Ltd., Canada; MinMet, Ireland; BeowolfMining Plc., GB; Uranium Prospects Plc., GB; Mineralbolaget, Mirab, Sweden; Botnia Exploration AB, Sweden (thorium) (for more information on exploration, see http://www.bergsstaten.se/).

Aura Energy, an Australian based uranium company, has announced (http://www.auraenergy.com.au/home.html) that it has selected the Areva Mines as its preferred strategic partner for the Häggån uranium and polymetallic project located in Sweden's Alum Shale Province. The Häggån is estimated to be around 800 million pounds U3O8 (307,718 tU with an average grade of 160 ppm U3O8), making the Swedish project the second largest undeveloped uranium resource in the world. Uranium occurs with molybdenum, vanadium, nickel and zinc in black shales. Aura has reported yields of up to 85% uranium as well as 58% nickel and 18% molybdenum from bacterial heap leaching.

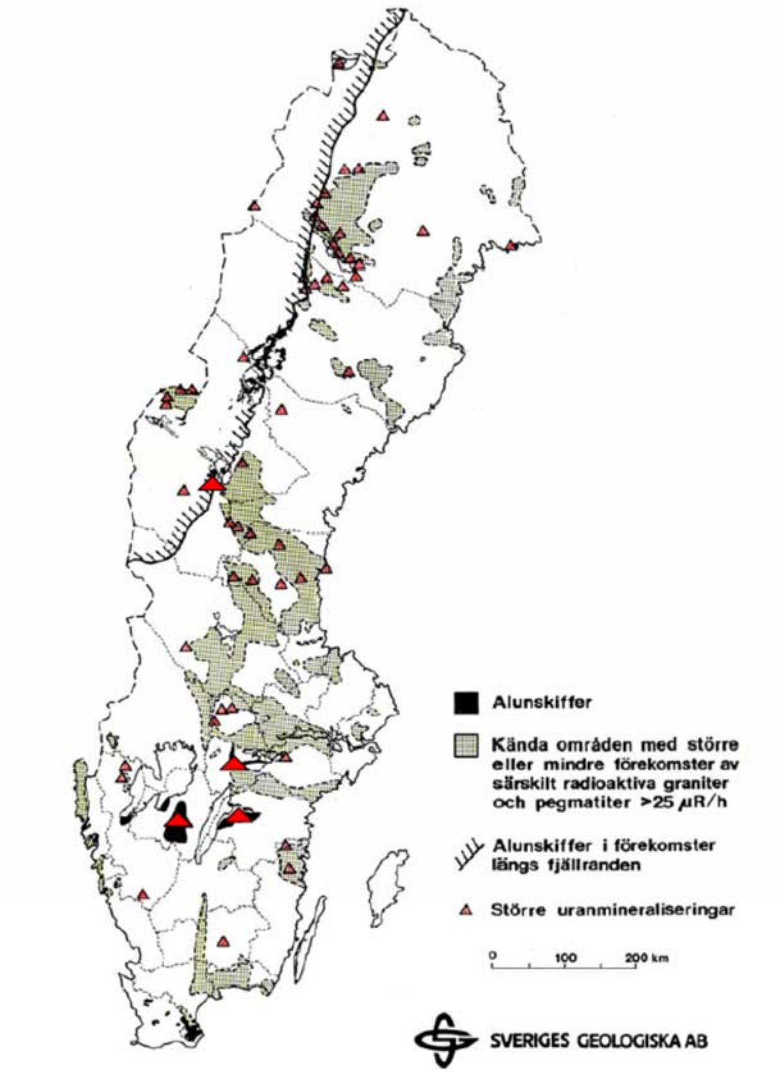


Figure 4.1. Swedish uranium deposits discovered during exploration 1954-1985. Source: Geologiska AB Sverige.

5.The U.S.

Uranium mining in the United States began in the 1940s primarily to produce uranium for weapons and later for nuclear fuel, both for domestic and international consumption. Then, uranium was produced as a byproduct of radium and vanadium and uranium was mined and handled much like any other mineral.

With 100 operating nuclear power plants and five under construction (http://www.iaea.org/PRIS/CountryStatistics/CountryDetails.aspx?current=US), the demand for enriched uranium in the U.S. is high. Even so, uranium mining in the U.S. today is undertaken by only a few companies on a relatively small scale.

In 2013, uranium mines in the U.S. produced 4.7 million pounds U_3O_8, which is 6% more than in 2012 and the largest amount since 1997 (U.S. EIA, 2013). The produced yellowcake came from underground mines and seven in-situ-leach (ISL) mines (Fig. 5.1). Overall, 10 mines operated during part or all of 2013. In addition to domestic production, the U.S. annually imports around 25 million kilograms of uranium in various forms from, among others, Kazakhstan, Australia, Canada, Russia, China and South Africa.

Currently, the operating uranium recovery facilities (Wyoming, New Mexico and Nebraska) are regulated by the U.S. Nuclear Regulatory Commission (NRC). NRC does not directly regulate the operating uranium recovery facilities in Texas, Colorado and Utah, which have entered into strict agreements with the NRC to exercise regulatory authority over this type of material (http://www.nrc.gov/info-finder/materials/uranium/index.html#licensed-facilities) (see Chapter 3).

The predominant uranium mining method employed in the U.S. today is in-situ leaching (ISL). ISL sites pose less environmental and health risk than sites mined using conventional mining methods. Among the advantages of ISL are: 1) minimal surface disturbance, 2) no ore surface exposure, 3) no waste rock dumps, 4) greatly reduced radiation exposure to workers and the community, 5) liquid waste, which may be disposed of in a deep disposal well or through an evaporation system and 6) release for unrestricted use when clean-up criteria are met at the end of the mine project.

Routine annual inspections by NRC at ISL site facilities in the western states reveal only few radiation safety violations, all of which have been relatively minor (www.nrc.org).

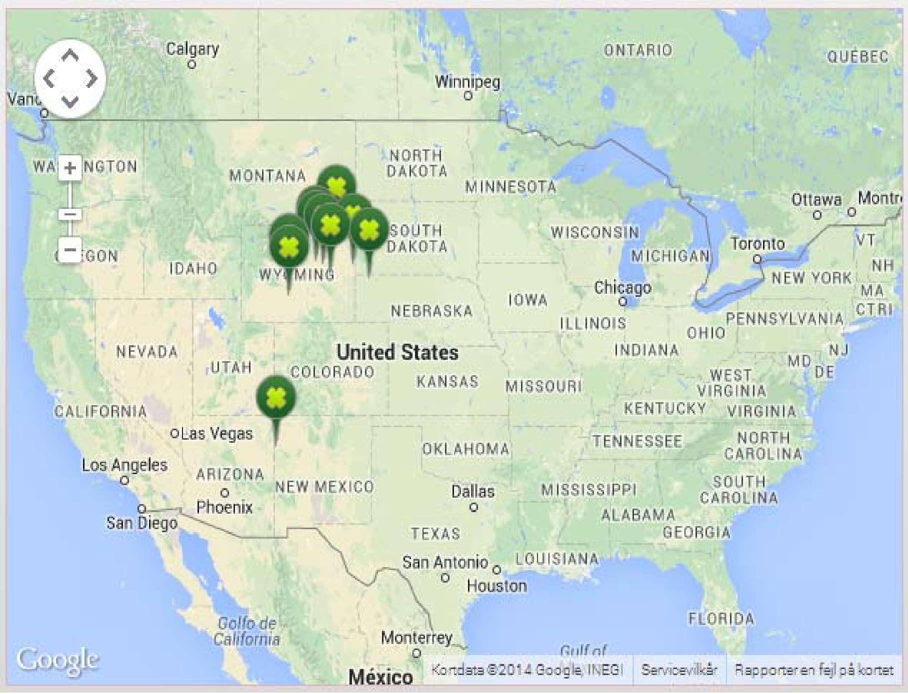


Figure 5.1. Operating uranium recovery facilities in the United States. Source: http://www.nrc.gov/info-finder/materials/uranium/index.html#licensed-facilities.

Past uranium mining practices in the U.S.

Case studies of Navajo Nation land (1944-1986)

The Navajo Nation extends into the states of Utah, Arizona and New Mexico, covering over 27.425 square miles (71,000 km^2). From 1944 to 1986, nearly four million tonnes of uranium ore were extracted from Navajo lands. When uranium mining started in Navajo Nation land, the labour was cheap, there were no taxes, no regulations on health, safety or the environment and few other jobs existed for the many Navajos recently home from service in World War II. The workers at the mine site were not aware of the radiation risks and the uranium was mined and handled much like all the other minerals. Pearl Nakai, daughter of a deceased miner, said at a hearing that 'No one ever told us about the dangers of uranium'.
(http://www.ratical.org/radiation/UraniumInNavLand.html).

One of the environmental pollution sources, which led also to health issues, was the waste rock casted aside near mine sites after the uranium had been extracted. One of the waste piles grew 21 m high (http://www.ratical.org/radiation/UraniumInNavLand.html). Hot, dry winds blew the dust from the tailings into local communities, filling the air and settling on the water supplies.

In February 1978, the Department of Energy released a Nuclear Waste Management Task Force report. According to this report, people living near the tailings had twice the risk of lung cancer of the general population. The Navajo Times carried reports of a Public Health Service study, asserting that one in six uranium miners had died of lung cancer. For some of the employees, the news came too late.

On July 16, 1979, more than 1,100 tonnes of uranium mining wastes (tailings) were released into the environment from a two-year old dam after a breach. With the tailings, radioactive water was also released through the dam before the crack was repaired. Some of the released tailings and contaminated water ended up in the Rio Puerco River, a major source of water in the area. The area is a high desert and the water from this river was used for irrigation. According to the Nuclear Regulatory Commission, the Rio Puerco River showed 7,000 times the allowable standard of radioactivity for drinking water below the broken dam shortly after the breach was repaired. By that time, the company (United Nuclear Corp.), which owns the dam, had cleaned up the site only partially. In 1983, a waste pile was detected leaking radioactive thorium into local groundwater.

Thirty years after mining started, an increasing number of deaths from lung cancer among the workers was reported. By that time, the underground mines were not ventilated. The first uranium miners were sent into shallow tunnels within minutes after blasting. They loaded the radioactive ore with their hands into wheelbarrows. Officials from the Public Health Service have estimated that these levels of exposure to radon gas were 100 and 1000 times the limit later considered safe. No one was monitoring the Navajo miners' health in the late 1940s.

By 1990, the death toll among former miners was reported to be 450 and the number was still rising. Relatives of the dead recalled how the miners had eaten their lunches in the mines, washing them down with radioactive water, never having been told that it was dangerous. Many of the men did not even speak English. The Navajo language contains no indigenous word for 'radioactivity'.

Even nowadays, a legacy of uranium contamination remains, including over 500 abandoned uranium mines as well as homes and drinking water sources with elevated levels of radiation (http://www.epa.gov/region09/superfund/navajo-nation/index.html). Radioactive and non-radioactive elements (selenium, arsenic, etc.) occur naturally at elevated levels in rock, soil, surface water and groundwater across the Navajo Nation.

In October 2007, the US.EPA, along with the Bureau of Indian Affairs (BIA), the Nuclear Regulatory Commission (NRC), the Department of Energy (DOE) and the Indian Health Service (IHS), developed a five-year plan to address uranium contamination in consultation with the Navajo Nation. The 'Five-

Year Plan' includes: a) assessment and clean-up of contaminated structures, b) assessment of contaminated water sources and provision of alternative water supplies, c) assessment of abandoned uranium mines, d) clean-up of the Northeast Church Rock mine site and additional high-priority abandoned mine sites, e) clean-up of the Tuba City Highway 160 site, f) clean-up of the Tuba City Dump, g) remediation of groundwater contamination at three former mill sites and h) case control studies of health risks faced by individuals residing near mill sites or abandoned mine sites (http://www.epa.gov/region09/superfund/navajo-nation/5-yr-plan-2014.html).

In January 2013, EPA, BIA, NRC, DoE, IHS and the Agency for Toxic Substances and Disease Registry, in consultation with the Navajo Nation, developed a second five-year plan (2014-2018) which includes: a) remediation of homes, b) increased water infrastructure in mining areas, c) focus on 43 priority mines located near homes, d) clean-up of the Northeast Church Rock mine, e) clean-up of the Tuba City Dump, f) treatment of groundwater at mill sites, g) health studies and h) expansion of interagency outreach. (http://www.epa.gov/region09/superfund/navajo-nation/5-yr-plan-2014.html).

6. Kazakhstan

Uranium exploration started in 1948 and, currently, Kazakhstan is the world's leading uranium producer http://www.world-nuclear.org/info/Country-Profiles/Countries-G-N/Kazakhstan/. Kazatomprom is the national atomic company, which was set up in 1997 and is owned by the government. It controls all uranium exploration and mining as well as other nuclear-related activities.

Uranium has been produced by in-situ-leaching since the early 1970s. Leaching solution is pumped down to the sandstone deposit where it dissolves the uranium in the sandstones. The leachate is then pumped up and the uranium is extracted from it. The method is cheap but uses much leaching agent, which is produced locally in conjunction with copper smelting and oil refining. In-situ-leaching has many environmental advantages, but it poses a risk for groundwater pollution.

7. Australia

Australia's known uranium resources are the world's largest (31% of the world's total resources). About 60 uranium deposits were identified from the 1950s to the late 1970s, but since then only two more deposits have been discovered.

Australia's past uranium mining practices

In 1944, systematic exploration for uranium began in Australia in response to a request from the British and U.S. governments. Four years later, a major deposit was discovered at Rum Jungle in the Northern Territory – the first of several uranium mines. The largest producers of uranium were Radium Hill, Rum Jungle and Mary Kathleen, now former mines.

The first Australian uranium mines (13 uranium mines, open pit and underground mines, high-grade ore) were located in South Alligator valley (1956-1964) in northern Australia (http://www.environment.gov.au/science/supervising-scientist/supervision/arr-mines/south-alligator-valley). The uranium produced here was for the British nuclear weapons programme. There were no health and environmental standards at that time and especially tailings management gave rise to environmental issues. The areas have recently (after 1988) been restored by the Commonwealth Government and included in the Kakadu National Park. Following the rehabilitation work, a long-term monitoring and care programme has been initiated to ensure that physical and radiological hazards reduction continues to be effective. Regular inspections for erosion and re-vegetation are supplemented with radiation surveys.

Rum Jungle in Northern Territory, Australia, one of the oldest and most famous uranium mines in the world, was the first large-scale uranium mine (consisting of three open pits) producing uranium for the American and British nuclear weapons programmes from 1950 to 1971. Minimal rehabilitation was carried out after closure and the area was abandoned. The geology was based on sulphide ores and the waste rock also contained significant amounts of sulphides. The site was ideal for the oxidation of the sulphides in the wet-dry tropical climate to produce acid mine drainage (AMD) releasing acid and metals into the East Finniss River. The toxic and polluting AMD was recognized very quickly in the mine's life but was ignored due to the military nature and political importance of the project. By the mid-1970s, the Rum Jungle site was well known as one of Australia's most polluted environments. In the 1980s, the Australian Government spent about $25 million in rehabilitating the site; however, the works have failed to be effective, even though the rehabilitation was supposed to be engineered to last for 100 years. Further rehabilitation work was performed in 1990-91. A new draft plan for a new rehabilitation strategy was submitted to the federal government in May 2013 and a project agreement was signed to progress further rehabilitation by mid-2016: http://www.world-nuclear.org/ and
http://www.nt.gov.au/d/rumjungle/index.cfm?header=Rum%20Jungle%20Home)

Nabarlek was a small high-grade uranium deposit (open pit) in the Alligator Rivers Region, it was in operation from 1979 until 1989 and was decommissioned in 1994/95
(http://www.environment.gov.au/science/supervising-scientist/supervision/arr-mines/narbalek). The ore body was mined out in one dry season in 1979, but the extraction of uranium from ore stockpiled finished in 1988. The mine site was rehabilitated. All tailings were disposed of in the mined pit. Part of the processing plant and some equipment that could not be decontaminated were buried in the mine pit. Waste rock completed the filling of the pit, and a layer of waste rock was applied over its surface as an erosion-resistant cover. Stockpiled topsoil completed the site landscaping earthworks. The whole area was then seeded with a mixture of grass and a wide range of native species in accordance with the authorized Decommissioning Plan. This work was completed at the end of 1995. After three years, vegetation was well established. Monitoring and research continue:
http://www.environment.gov.au/science/supervising-scientist/supervision/arr-mines/narbalek).

Radium Hill uranium mine, in operation from 1954 to 1961 in South Australia. A physical (heavy media) concentration process was conducted at Radium Hill and the concentrate was further chemically processed at Port Pirie. Tailings from the heavy media separation were stored on ground without any containment. Twenty years after mine closure, the area was covered by an inert media preventing wind erosion and dust spreading. The tailings from chemical processing were also covered 20 years after the uranium extraction of the Radium Hill ore concentrate ceased. The site is inspected regularly and repairs are made as required http://minerals.dmitre.sa.gov.au/mines__and__developing_projects/former_mines/radium_hill_mine.

Mary Kathleen was a uranium mine that operated in north-west Queensland between 1958 and 1982. Mary Kathleen was the first major rehabilitation project of a uranium mine in Australia. The rehabilitation plan developed by the mining company in 1976 included 64 hectares of waste dumps, 29 hectares of tailings dam and 60 hectares of evaporation ponds. The rehabilitation of the site was completed at the end of 1985 at a cost of A$ 19 million. This work won an award for environmental excellence from the Institution of Engineers Australia http://www.world-nuclear.org/info/Country-Profiles/Countries-A-F/Appendices/Australia-s-former-uranium-mines/.

Situated in South-East Australia, the **Honeymoon** is an ISL mine which operated from 2011 until November 2013 when it was closed and put on care and maintenance.

Australian uranium mines under operation

Regulations and environmental guidelines made under the Australian Radiation Protection and Nuclear Safety Act 1998 are available at: http://www.arpansa.gov.au/Regulation/guides.cfm. An overview of the Australian regulatory framework with references concerning uranium production for the nuclear fuel cycle is given in Chapter 3. The regulations in Western Australia are the newest regulations found as Western Australia only recently has allowed uranium mining. These regulations are described in so-called NORM (Naturally Occurring Radioactive Materials) documents. They describe in detail the regulations in Western Australia, how they should be implemented and how measurements and calculations should be performed. The Australian government requires applicants to address environmental and social concerns, alternative locations must be analyzed in mining proposals, as well as rehabilitation and long-term care and monitoring plans, externalities (and possible solutions), groundwater and infrastructure changes, gained or lost opportunities, socio-economic impacts and risks, as well as measures taken to reduce or eliminate the environmental and health risks associated with the proposed mining project.

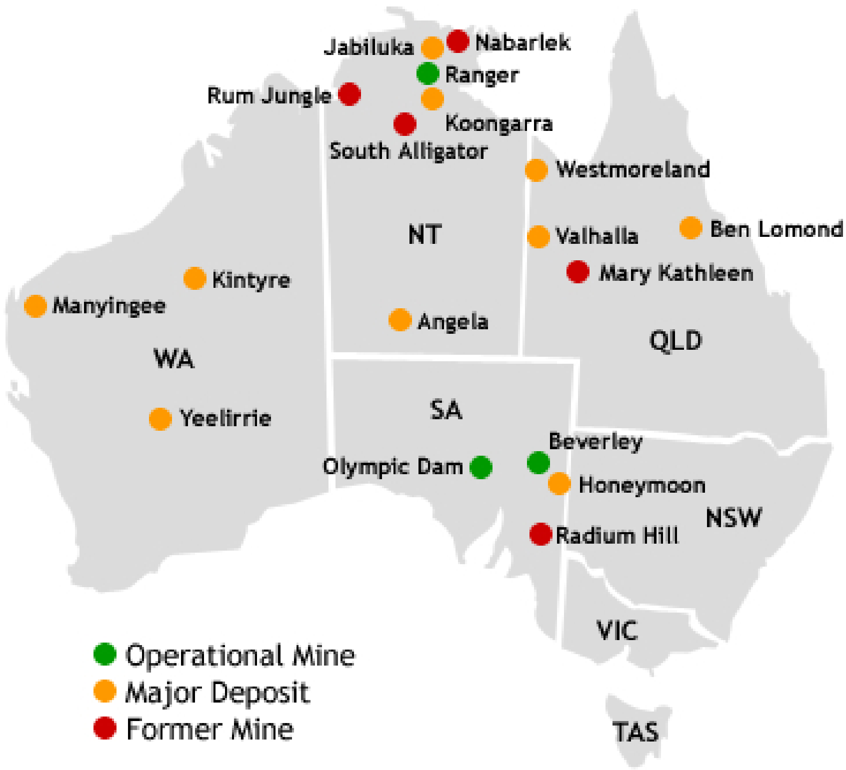
Three mines are currently operating in Australia: Ranger, Olympic Dam and Beverley (Fig. 7.2.1).

Ranger uranium mine

Located in the catchment area of the East Alligator River in Northern Australia, the Ranger uranium mine has been operated by the Energy Resources of Australia Ltd (ERA) since 1980 http://www.environment.gov.au/science/supervising-scientist/supervision/arr-mines/ranger.

Ranger is one of only three mines in the world that has produced in excess of 110,000 tonnes of uranium oxide (U_30_8) (http://www.energyres.com.au/).

Figure 7.2.1. Map of Australian uranium deposits and mines. Source: http://www.australianuranium.com.au/uranium-map.html.



Currently, ERA is undertaking a transition from open-cut mining (Pit 3 at Ranger) to underground exploration of the Ranger 3 Deeps mineral resource. In the meantime, progressive rehabilitation plans including Pit 1 and Pit 3, as well as tailings and brine management and the Jabiluka Interim Water Management Pond progressed significantly in 2013. Pit 3 is currently being backfilled with 30 million tonnes of waste material in preparation for the planned transfer of tailings from the Tailings Storage Facility and the storage of the brines from the Brine Concentrator. The backfilling project is ahead of schedule, with 22.8 million tonnes of waste material placed in Pit 3 on 31 December 2013 (http://www.environment.gov.au/system/files/resources/9c423c0e-0e70-453b-aac2-6c2019ff25f1/files/ir624.pdf).

Over 200 minor environmental incidents generated from Ranger activities since 1979 have been documented (https://en.wikipedia.org/wiki/Energy_Resources_of_Australia). In May 2005, the company was convicted for breaching environmental guidelines. Radioactively contaminated process water had contaminated the drinking water supply and some workers drank and washed in the contaminated water http://www.environment.gov.au/science/supervising-scientist/monitoring. The radiation exposure of workers was less than the regulatory limit, and no harmful long-term health effects are likely (Supervising Scientist2004).

On 7 December 2013 there was an incident at a mine site inside Kakadu National Park where about a million litres of slurry, comprising crushed ore and acid, were spilled, and the workers evacuated and production shut down. A leaching tank failure resulted in an uncontrolled release of mine slurry containing mineralized ore and acid within the processing area of the mine site (http://www.environment.gov.au/science/supervising-scientist/supervision/incidents).

The Supervisor Scientist Department (SSD) (an agency of the Government of Australia) undertook an investigation of the incident. The results showed that there was no offsite environmental impact resulting from the tank failure. SSD undertakes continuous monitoring of the waterways surrounding the mine lease and the results are made publically available via the webpage: http://www.environment.gov.au/science/supervising-scientist/monitoring.

Jabiluka deposit is located 22 kilometres north of Ranger (http://www.environment.gov.au/science/supervising-scientist/supervision/arr-mines/jabiluka). Jabiluka deposit is owned by ERA and is under long-term care and maintenance and is included in the rehabilitation programme, with the involvement of the Mirarr Traditional Owners. ERA together with Mirarr Traditional Owners safely dismantled the Interim Water Management Pond at Jabiluka during the 2013 dry season. Rehabilitation of the site is well advanced and re-vegetation was continued in 2014 and will probably be continued also in the future. Among other environmental projects currently undertaken by ERA are: maintenance of biodiversity, fire management, including control burning, terrestrial and aquatic weed control, feral animal control and rehabilitation of disturbed areas (including rock waste dumps, etc.). Issues studied include artificial wetland filters, soil formation from waste rock and hydrology.

With a large tailings dam on the site and a wet season from December to April (on average 1540 mm rain), considerable public concern about contamination of surface and ground water exists. A number of monitoring and research programmes to monitor and assess the impact of the Ranger mine on the surrounding environment are conducted by the Office of the Supervising Scientist (OSS) (http://www.environment.gov.au/science/supervising-scientist).

Olympic Dam

Mineral processing at Olympic Dam, a large copper and uranium mine, began in 1988. Even though the uranium ore grade is low (approximately 650ppm), Olympic Dam is known as the world's largest uranium deposit (http://www.bhpbilliton.com/home/investors/reports/Documents/bhpBillitonUraniumMacquarieEquitiesConferencePresentation.pdf and http://minerals.dmitre.sa.gov.au/mines__and__developing_projects/approved_mines/olympic_dam

The mine is located in an arid area, 560 km north of Adelaide in South Australia. The operations comprise a fully integrated underground mine and an above-ground metallurgical complex. A plan for a new open-pit mine operating simultaneously with the existing underground mine was included in the Environmental Impact Statement (EIS) prepared by BHP Billiton, the company that operates Olympic Dam.

During 1994, seepage of contaminated water from the tailings dams was discovered (http://www.world-nuclear.org/info/Country-Profiles/Countries-A-F/Appendices/Australia-s-Uranium-Mines/). This was of concern to the company, the regulators and the public because of the perceived threat to the quality of groundwater immediately below the tailings dams. Studies demonstrated that the pollutants in the seepage were quickly adsorbed on clays and limestone in the soil and rock under the tailings dams and, due to the low permeability and transmissivity of the rock, that there was no potential harm to the groundwater resource. The level of the groundwater under the tailings dams is monitored and modelled on a quarterly basis.

In February 2005, Olympic Dam was successful in obtaining ISO14001 certification for the site Environmental Management System. Environmental management activities account for approximately one third of expenditure from the overall environmental budget.

Beverley

Beverley is located on an arid plain, only a few hundred km from Olympic Dam and approximately 550 km north of Adelaide, South Australia (http://minerals.dmitre.sa.gov.au/mines__and__developing_projects/approved_mines/beverley). It is an in-situ leach mine that was opened in late 2000 following a lengthy period of development, study, consultation and review. Before mining commenced, the groundwater contained elevated levels of naturally occurring radionuclides such as uranium, radium and non-radioactive fluorides, exceeding drinking water regulatory limits, making it unsuitable for use as potable water and other domestic purposes (McKay and Mietzitis, 2001). All radiation doses associated with the mining activities have been well within the appropriate limits, with stable or decreasing doses since operations commenced (Kutty, 2010; Woods, 2011).

When the mining activity ends, the mining company is obliged, under the legislation, to decommission (dismantle and remove all unwanted infrastructure), rehabilitate and leave the site in a state compatible with the final land use approved by the regulatory body. As a regulatory requirement, the company will have to perform long-term care and environmental monitoring (water, soil and air) of radioactive and non-radioactive contaminants (http://www.epa.sa.gov.au/) before leaving the site. The cost of decommissioning and remediation is assessed annually (http://www.epa.sa.gov.au/).

8. Germany

After the end of World War II, the Soviet Union was in a hurry to produce a deterrent arsenal of nuclear weapons. The uranium for this purpose was to a large degree produced in East Germany (Fig. 8.1) in Saxony and Thuringia by the company SDAG Wismut (1946). Later (1954) it became a bi-national Soviet-German company – SDAG Wismut. It produced a total of 216,000 tonnes of uranium between 1946 and 1990 and made East Germany the fourth largest producer of uranium ore in the world at the time. Following the reunification of Germany (1990), the company was transferred into the Wismut GmbH Company, with the Federal Republic of Germany as sole shareholder. Mining operations were discontinued, and decommissioning of the former uranium mining and milling facilities, restoration and environmental clean-up are still ongoing.

After World War II, unemployment was high in Germany, and the Soviet Union ordered the employment centres across the country to supply them with workers. Thousands of people from all over Germany and refugees were drafted (forced) to work in the uranium mining centres. At the end of 1954, more than 120,000 people (including also women) worked for SDAG Wismut, most had never worked in the mining industry before and had no qualifications or radiation knowledge.

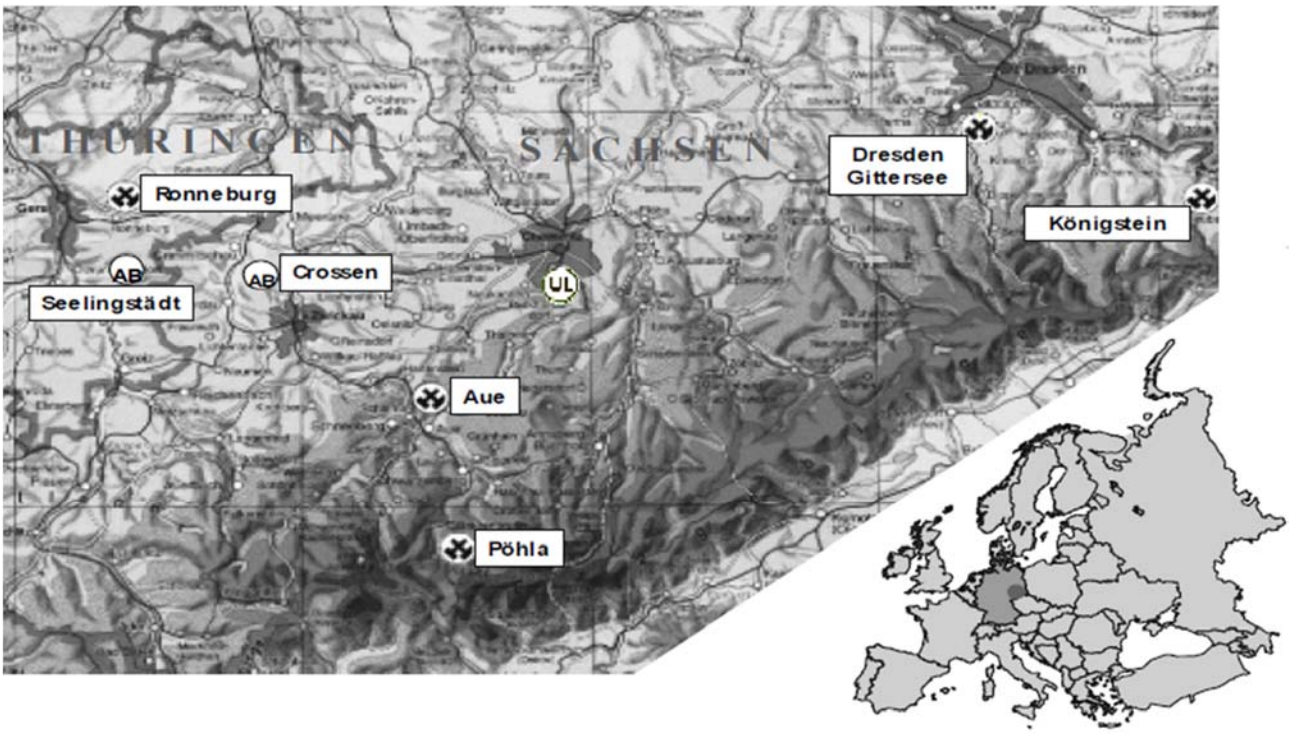


Figure 8.1. Location of the Wismut sites (from http://www.bmub.bund.de/fileadmin/bmu-import/files/pdfs/allgemein/application/pdf/jc_wismut_handout.pdf).

When the mine started its operation, there were neither environmental and health standards, a qualified work force nor mining equipment.

Following the reunification of Germany in 1990, uranium mining and milling was ceased (1990). There was widespread environmental devastation affecting public health and the environment. The mining legacy included 1,470 km of uranium facilities (Aue, Pöhle, Königstein, Ronneburg, Gittersee, Lichtenberg), two processing sites: Seelingstädt and Crossen, 311 million m³ of waste rock and 160 million m³ of radioactive sludges (tailings) located in densely populated areas.

Since 1991 more than 6.2 billion euro was paid by the German Federal Government for decommissioning and site rehabilitation.

Among the planned decommissioning and rehabilitation activities were:

- Disassembly and demolition of contaminated buildings and structures.
- Decontamination.
- Clean-up of areas.
- Release of lowly contaminated material for restricted reuse and safe disposal of higher contaminated material.
- Remediation of mine dumps and tailings ponds:
- Reshaping, slope stabilization, covering of waste rock dumps.
- Tailings dewatering, geotechnical stabilization, cover placement.
- Closure of mine openings, stabilization of underground galleries, controlled flooding. An example is Refilling open pit Lichtenberg with waste rock material and covering the pit (Fig. 8.2).
- Water treatment: contaminated mine water, seepage, pore and supernatant water from tailings management facilities treated in special plants employing active and passive water treatment procedures:

- http://www.bmwi.de/English/Redaktion/Pdf/20-years-wismut-gmbh
- http://ec.europa.eu/energy/sites/ener/files/documents/tech_report_wismut.pdf
- http://www.iaea.org/OurWork/ST/NE/NEFW/documents/RawMaterials/CD_TM_Swakopmund%20200710/17%20Paul.PDF
- http://www.wismut.de/en
- Environmental monitoring.

Figure 8.2. Backfilling the open pit Lichtenberg in 1992, 2015. Source: http://www.wismut.de/www/webroot/de/download.php?download=3509

In March 2014, the rehabilitation work was still ongoing and will be continued, http://www.wismut.de/en/. The Wismut area is densely populated and one of the aims of the remediation work is to bring the radiation dose to the population below 1mSV/y,
http://www.iaea.org/OurWork/ST/NE/NEFW/documents/RawMaterials/CD_TM_Swakopmund%20200710/17%20Paul.PDF.

9. France

Uranium mining in France started in 1948 and ended in 2001. France produced 76,000 tonnes uranium from 50 million tonnes ore and had to mine 200 million tonnes waste rock. All 210 uranium mines are closed (Fig. 9.1) and dismantled, and the sites have been remediated. Since 1990, remediation (decommissioning and rehabilitation of the sites) has been going on for most of AREVA's (formerly COGEMA) facilities under supervision of Regional Directorate for Industry, Research and Environment (DRIRE) and French Nuclear Safety Authority (ASN).

Remediation work was conducted on the structures left behind after the cease of mining operations: mines (open pits and underground mines), mills (e.g. decontamination and dismantling) and storage facilities of waste rock or tailings from the milling process (e.g. water treatment, covering tailings facilities, re-vegetation, etc.):

- http://www-ns.iaea.org/downloads/rw/projects/emras/emras-two/first-technical-meeting/fourth-working-group-meeting/working-group-presentations/workgroup2-presentations/presentation-4th-wg2-limousin-sites.pdf
- http://www.gepnucleaire.org/gep/sections/travauxgep/rapports/executive_summary/downloadFile/file/Executive_summary_Miseenligne_17.09.10.pdf

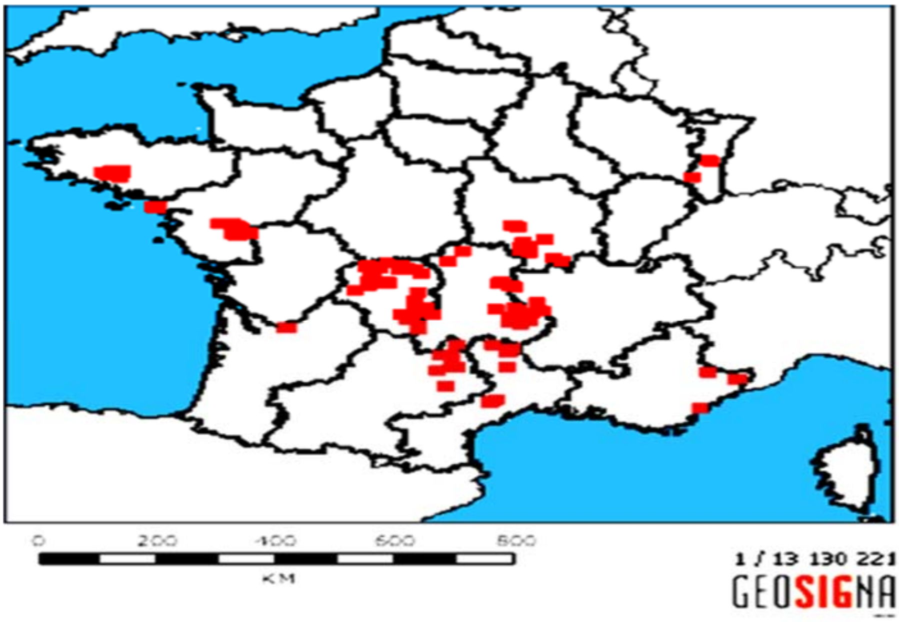


Figure 9.1. Former uranium mine sites in France. Source: Thierry Doursout.

The main objectives of remediation works conducted by AREVA were to obtain:

- Long-term stability of the remediated area in terms of safety and public health.
- Reduction, as far as reasonably possible, of the residual impacts.
- Prevention of risk resulting from intrusion.
- Reduction of total land consumption and the resulting need for institutional control.
- Promotion of possible industrial or leisure activities on the land and remaining buildings.
- Landscape integration, in co-operation with local intervening parties.

Since the remediation work ended, the final state of sites is controlled by means of geotechnical monitoring (to assure the stability of the waste piles (settlements, slope stability) and the integrity of the cover) and environmental monitoring, including also vegetation development. AREVA is now responsible for the long-term surveillance of most of the former French sites. Water treatment plants have been installed to treat water at some of the remediated facilities.

The long-term environmental monitoring programme includes:

- Gamma dose rate surveys.
- Water (parameters such as: pH, soluble and non-soluble uranium-238 and radium-226 are monitored before and during water treatment for the watercourses involved).
- Alpha radionuclides in sediments.
- Alpha radionuclides and radon concentrations in air.
- Uranium-238, radium-226 and lead-210 concentrations in vegetables (carrots, beets, leeks, apples, turnips, cabbages), milk, fish and animals (hens and rabbits).

The environmental monitoring programme was adapted from that used during the operational phase. After remediation of sites, the effective dose to the members of the public should not exceed 1mSv / y (1-5 mSv / year (maximum total exposure being 5 mSv / year). The radiological impact considered is the sum of the external exposure from radon and dust inhalation and U / Ra ingestion.

Monitoring results, highlighting some examples of the direct influence of the remediation work and calculations of public exposure, are given in Doursout (2005) and the GEP Report (2013). Other monitoring results from former French uranium mines can also be found here: http://www.pays-de-la-loire.developpement-durable.gouv.fr/gestion-des-steriles-miniers-des-a2268.html, the website of the Ministry of Ecology, Sustainable Development and Energy, France.

The measurements are complemented with regular control (long-term care and maintenance of closed sites may include rehabilitated tailings) to observe the gradual return to a natural and stable equilibrium.

10. Namibia

Namibia has two operating uranium mines (Rössing and Langer Heinrich) that account for 10% of the world's uranium production (https://infcis.iaea.org/UDEPO/About.cshtml). AREVA Resources Namibia's Trekkopje mine is currently under 'Care and Maintenance' (Uranium Institute Annual Review, 2013). Other projects are under development, see http://namibianuranium.org/developing-mines/, for instance the Husab, Norasa projects.

The Namibia government strongly supports uranium mining activities, which are regulated under the Constitution of Namibia, Atomic Energy and Radiation Protection Act in force as of January 2013, Radiation Protection and Waste Disposals Regulations 201, in force as of January 2013 (only Radiation Management Plan apply to uranium mining), Labour Act, Environmental Management Act 2007, Minerals Act 1992, National Regulations and Guidelines & Strategic Environmental Management Plan (SEMP), Radiation Management Plan (RMP) and Code of Practices (http://www.aebofnamibia.org/index.php?option=com_content&view=article&id=47&Itemid=53).

Key national bodies responsible for regulation of the uranium mining industry in Namibia are: the Ministry of Environment & Tourism (grants environmental clearance and regulates environmental impacts); the Ministry of Mines & Energy (issues exploration and Mining License and is also responsible for general mine safety), the Ministry of Agriculture, Water & Forestry (grants permits relating to quality of water), the Ministry of Labour & Social Welfare (administer provisions on labor issues) and the Ministry of Health and Social Services NRPA (issues permissions relating to activities associated with radiation exposure and is also responsible for occupational health issues).

Namibia is party to the Nuclear Non-Proliferation Treaty and has had a comprehensive safeguards agreement in force since 1998 and in 2012 the country ratified the Additional Protocol and the Pelindaba Agreement (http://namibianuranium.org/).

The WNA policy document 'Sustaining Global Best-Practices in Uranium Mining and Processing: Principles for Managing Radiation, Health and

Safety, Waste and the Environment' was adopted as an official guiding document in January 2008. This policy covers aspects of sustainable development, uranium stewardship and corporate social responsibility (CSR). Namibian authorities were assisted also by Finland's Radiation & Nuclear Safety Authority (STUK) to develop a nuclear fuel cycle policy to ensure safeguards and a non-proliferation regime.

The Atomic Energy Board of Namibia (AEBN) was established along with a National Radiation Protection Authority. In 2013, the Sustainable Development Advisory Council was established under the Environment Management Act 2007. The Namibian Environmental Restoration and Monitoring Unit (NERMU) was established to function as a key monitoring agent for the SEMP, to drive restoration research and implementation and to develop skills in critical environmental management-related fields. The Chamber of Mines' uranium committee, transformed in 2013 into the Namibian Uranium Association (NUA), was established to uphold mining practices in Namibia to the highest standards, to observe international conventions and to ensure positive development of Namibia's reputation as a mining nation. The Uranium Institute, established in 2009, was renamed to Namibian Uranium Institute's (NUI) after the Fukushima nuclear power plant accident. NUI aims to co-ordinate occupational health, radiological safety / security, environmental management issues and national training programmes.

Although the safety regulations have improved considerably in the Namibian uranium mining industry, current challenges for the Namibian government and the uranium industry are: fragmented system of regulation with too many Government entities with various and different regulatory functions makes enforcement / implementation challenging, staff levels not responsive to current scope of practices to be regulated, need to ensure regulators are familiar with mining and milling processes, regional economy, transport, ecological sensitivities, landscape integrity and mine closure and rehabilitation (Swiegers and Tibinyane, 2014).

The absence of a programme for implementation of environmental and health standards (''it is still up to the respective mining company to comply with international standards'', Kohrs, 2014),a challenge with training programmes for staff / regulators and, not least, the high unemployment rate in African countries are some of the factors that easily may lead to environmental contamination and health risks to not only the workers but also to the residents of the nearby towns (Kohrs, 2014).

Rössing uranium mine is a low grade Alaskite open-pit mine located close to the town of Arandis (established for the mine workers) and 65 km inland, north-east of Swakopmund in Namibia, Africa. The mine is operated in a unique environment, the Namib Desert, since 1976 by Rössing Uranium Ltd. Rio Tinto, a British-Australian multinational metal and Mining Corporation, owns 69% of the mine and other shareholders are the government of Namibia owning 3%, the government of Iran owning 15%, the Industrial Development Corporation (IDC) of South Africa owning 10% and local individual shareholders owning 3% (Rössing, 2009). Currently, Rössing is the fifth largest producer of uranium in the world and accounts for about 7% of the world's uranium oxide production (Kohrs, 2014).

At the time Rössing started, there were neither environmental concerns nor safety standards for the workers and members of the public. The company did not develop a radiation management plan, a radioactive waste management plan or conduct an environmental impact assessment before the mine commenced its activities, a fact confirmed by External Officer Mr. Alwyn Lubbe:

''At the time when the mine planning and construction started no formal legislation were in place for EIA studies. In fact, it was not even a well know concept. In the case of Rössing various studies and related actions were taken in terms of identified environmental issues taken up in an environmental management plan. For example, at the time of construction of the mine it was decided to install boreholes around the tailings dam to monitor water flow. Another action taken is that all quiver trees and other plants were rescued where the open pit was excavated. These plants were then relocated to the Botanical Gardens in Windhoek where they can still be seen today.''

The environmental, safety and health conditions changed and recently Rio Tinto has developed a strategic environmental management plan, a radiation management plan and mine closure plans. The mine was ISO 14001 certified in 2001.

The Environmental monitoring programme for the Rössing site comprises radionuclides analyses of water samples from monitoring boreholes, particulate matter (10 µm; PM10) monitoring at Arandis and on the southwestern mine boundary and monitoring of radon concentrations on and near the mine site (Rio Tinto, 2013). Few environmental results have been reported by Rio Tinto (2013).

11. Brazil

The Poços de Caldas (1982-1995) waste rock disposal in Brazil illustrates the impacts and long-term problems that arise when the disposal of waste rock is neither planned nor characterized and treated properly during the feasibility study and operations (Fernandes et al., 1998). Depositing the material at a convenient, nearby location without understanding its geochemical properties or long-term management challenges can lead to environmental issues. Drainage of sulphuric acid-rich water and release of contaminants of concern, such as iron, manganese, radium, lead-210, polonium-210 and uranium needing to be treated involve annual costs ranging from 1 to 1.2 million USD. This is not a unique example as impacts of the waste management options were not investigated for numerous mines in the early phase of uranium mining; as a result, legacy issues were created by not treating problematic waste rock accordingly.

12. Republic of Tajikistan

The Taboshar (1936-1965) legacy uranium facility in Tajikistan is an example of how lack of regulatory framework (Jakubick et al., 2008), planning and old mining practices have had significant adverse environmental impacts. The Taboshar site extends over 400 ha (Fig. 12.1).

The legacy wastes comprise a large open pit, two abandoned underground mine access points, two waste rock piles, the abandoned structure and bunkers of the low-grade ore processing facility, a pile of ground, low grade ore next to the processing plant that had been prepared for leaching and several tailings piles connected to the developmental stages of the hydrometallurgical process plant used to recover uranium.

Figure 12.1. The Taboshar abandoned uranium mine and mill site. Source: Peter Woods, Uranium best practice workshop, Copenhagen 2014.

These mining and processing facilities are perhaps the most significant legacy of these early operations in terms of health impacts on the local population. In addition to the health impacts caused by the contaminated site itself, additional impacts are likely due to the spread of contaminants via streams draining the mountainous site to agricultural plains where the water is used to irrigate crops (Jakubick et al., 2008). The health impacts of this site are chronic in nature due to the continuous spread of contaminants from the waste piles into the city, settlements and the valleys (Jakubick et al., 2008).

References

AEBN - Atomic Energy Board of Namibia, Annual Review, 2012/2013. http://www.aebofnamibia.org/index.php?option=com_content&view=article&id=71&Itemid=73

CNSC, 2014. Regulatory Oversight Report for Uranium Mines and Mills in Canada: 2014. Canadian Nuclear Safety Commission (CNSC) 2015 PWGSC catalogue number: CC171-23/2014E-PDF ISBN: 978-0-660-04013-4.

Doursout, T. 2005. An overview of uranium mining in France with focus on the Limousin region:
http://www-ns.iaea.org/downloads/rw/projects/emras/emras-two/first-technical-meeting/fourth-working-group-meeting/working-group-presentations/workgroup2-presentations/presentation-4th-wg2-limousin-sites.pdf

Ehdwall, H. et al., 1995. An assessment of the health and environmental situation in the mining community Krasnokamensk, East Siberia, Russian Federation. SSI-rapport 95-21/Stockholm 1995.

Fernandes, H.M., Franklin, M.R. & Veiga, L.H., 1998. Acid rock drainage and radiological environmental impacts. A study case of the Uranium mining and miling facilities at Poços de Caldas. Waste Manage. 18, 169-181. http://dx.doi.org/10.1016/S0956-053X(98)00019-1

Filipchenko, I.A. et al., 1994. Report on the results of radioecological work in the village Octyabrskij in accordance with geological order 324-42 for 1990-1993. Irkutsk 1994. (In Russian)

GEP Report, 2013. Mission complémentaire du groupe d'expertise pluraliste sur les sites miniers d'uranium: http://www.irsn.fr/FR/connaissances/Environnement/expertises-locales/sites-miniers-uranium/Documents/GEP_Rapport-Mission-Complementaire_2013.pdf

Jakubick A et al., 2008. ''Monitoring and Remediation of the legacy sites of uranium mining in Central Asia'', Uranium, Mining and Hydrology, Springer-Verlag, Berlin Heidelber.

Khlopkov, A., and Chekina V., 2014. Governing Uranium in Russia. DIIS Report 2014:19.

Kohrs, B., Kafuka, P., 2014. Study on low level radiation of Rio Tinto's Rössing Uranium mine workers. EJOLT & Earthlife Namibia Report.

Konstantin, B., Gongalsky, G., 2003. Impact of pollution caused by uranium production on soil macrofauna. Environ. Monit. Assess. 89: 197-219.

Kutty, S., Woods, P., Dayal, E., Jagger, A., 2010. Keeping radiation management at Beverley Uranium Mine at best practice; plans, responses and outcomes [online], 35th Australasian Radiation Protection Society Conference, Adelaide, 18-20 October 2010.

McKay, S.D., Miezitis, Y., 2001. Australia's Uranium Resources, Geology and Development of Deposits, Geoscience Australia, Canberra.

OECD/NEA-IAEA, 2010. Organization for Economic Co-operation and Development Nuclear Energy Agency and International Atomic Energy Agency, 2010, Uranium 2009 – Resources, production and demand. Organization for Economic Co-operation and Development Publishing, 456 p.

Rio Tinto, 2013. Rossing Uranium Limited 2013 Report to Stakeholders.

Shandala, K.N., Kiselev, S.M., Alekseev, M.V. Titov, A.V., Metlyaev, E.G., 2011. WM2011 Conference, February 27-March 3, 2011, Phoenix, AZ.

Swiegers, W., Tibinyane, A., 2014. The Namibian uranium mining model. International Symposium on Uranium Raw Material for the Nuclear Fuel Cycle: Exploration, Mining, Production, Supply and Demand, Economics and Environmental Issues (URAM-2014), 23-27 June 2014.

Ujba, V.V., Kiselev, M.F., Romanov, V.V., Shandala, N.K., Khohlova, E.A., 2007. Life on the fault: investigation results. Environmental safety, No 2: 68-71.

US Energy Information Administration (EIA), Domestic Uranium Production Report, 2013. U.S. Uranium Mine Production and Number of Mines and Sources, www.eia.gov/uranium/production/annual/pdf/dupr.pdf

Woods, P., 2011. MAusIMM(CP), Environment, Safety and Health Manager, Heathgate Resources Pty Ltd, Sustainability aspects of the Beverley Uranium Mines.

Woods, P., Uranium best practice workshop, Copenhagen 2014.

Appendix B.

IAEA Safety standards

Table 3.1. IAEA publications related to uranium mining and milling.

IAEA safety standards – Uranium Mining and Milling	
Safety Fundamentals	Fundamental Safety Principles, Series No. SF-1, published Tuesday, November 07, 2006
General Safety Requirements	Preparedness and Response for a Nuclear or Radiological Emergency, Safety Requirements, Series No. GS-R-2, published Wednesday, November 06, 2002
	The Management System for Facilities and Activities, Safety Requirements, Series No. GS-R-3, published Friday, July 21, 2006
	Governmental, Legal and Regulatory Framework for Safety, General Safety Requirements Part 1, Series No. GSR Part 1, published Monday, October 04, 2010
	Radiation Protection and Safety of Radiation Sources: International, Basic Safety Standards, Series No. GSR Part 3, published Saturday, July 19, 2014
	Safety Assessment for Facilities and Activities, General Safety Requirements Part 4, Series No. GSR Part 4, published Tuesday, May 19, 2009
	Predisposal Management of Radioactive Waste, General Safety Requirements Part 5, Series No. GSR Part 5, published Tuesday, May 19, 2009
	Decommissioning of Facilities, General Safety Requirements Part 6, Series No. GSR Part 6, published Tuesday, July 08, 2014
	Remediation of Areas Contaminated by Past Activities and Accidents, Safety Requirements, No. WS-R-3, published 2003
General Safety Guides	Arrangements for Preparedness for a Nuclear or Radiological Emergency, Safety Guide, Series No. GS-G-2.1, published Wednesday, May 23, 2007
	Application of the Management System for Facilities and Activities, Safety Guide, Series No. GS-G-3.1, published Friday, July 28, 2006
	The Management System for Technical Services in Radiation Safety, Safety Guide, Series No. GS-G-3.2, published Wednesday, July 02, 2008
	The Management System for the Processing, Handling and Storage of Radioactive Waste, Safety Guide, Series No. GS-G-3.3, published Wednesday, July 02, 2008
	Classification of Radioactive Waste, General Safety Guide, Series No. GSG-1, published Monday, December 28, 2009
	Criteria for Use in Preparedness and Response for a Nuclear or Radiological Emergency, General Safety Guide, Series No. GSG-2, published Thursday, March 17, 2011
	The Safety Case and Safety Assessment for the Predisposal Management of Radioactive Waste, Series No. GSG-3, published Thursday, April 18, 2013
	Use of External Experts by the Regulatory Body, Series No. GSG-4, published Thursday, February 21, 2013
	Occupational Radiation Protection, Safety Guide, Series No. RS-G-1.1, published Wednesday, October 13, 1999
	Assessment of Occupational Exposure Due to Intakes of Radionuclides, Safety Guide, Series No. RS-G-1.2, published Tuesday, November 02, 1999
	Assessment of Occupational Exposure Due to External Sources of Radiation, Safety Guide, Series No. RS-G-1.3, published Tuesday, September 28, 1999
	Building Competence in Radiation Protection and the Safe Use of Radiation Sources, Safety Guide -Series No. RS-G-1.4, published Tuesday, May 08, 2001
	Application of the Concepts of Exclusion, Exemption and Clearance, Safety Guide, Series No. RS-G-1.7 published 2004
	Environmental and Source Monitoring for Purposes of Radiation Protection, Safety Guide, Series No. RS-G-1.8, published Monday, August 22, 2005
	Categorization of Radioactive Sources, Safety Guide, Series No. RS-G-1.9, published Monday, August 15, 2005
	Regulatory Control of Radioactive Discharges to the Environment, Safety Guide, Series No. WS-G-2.3, published Friday, September 15, 2000
	Predisposal Management of Low and Intermediate Level Radioactive Waste, Safety Guide, Series No. WS-G-2.5, published Wednesday, April 30, 2003
	Predisposal Management of High Level Radioactive Waste, Safety Guide Series No. WS-G-2.6, published Wednesday, April 30, 2003
	Remediation Process for Areas Affected by Past Activities and Accidents, Safety Guide Series No. WS-G-3.1, published Thursday, March 01, 2007
	Release of Sites from Regulatory Control on Termination of Practices, Safety Guide Series No. WS-G-5.1, published Wednesday, November 08, 2006
	Safety Assessment for the Decommissioning of Facilities Using Radioactive Material, Safety Guide Series No. WS-G-5.2, published Tuesday, February 24, 2009
	Storage of Radioactive Waste, Safety Guide Series No. WS-G-6.1, published Tuesday, November 28, 2006
Specific Requirements	Decommissioning of Facilities, General Safety Requirements Part 6, Series No. GSR Part 6, published Tuesday, July 08, 2014
	Disposal of Radioactive Waste, Specific Safety Requirements, No. SSR-5, published 2011
	Regulations for the Safe Transport of Radioactive Material, Specific Safety Requirements, No. SSR-6, published 2012
Specific Safety Guides	Occupational Radiation Protection in the Mining and Processing of Raw Materials Safety Guide, Series No. RS-G-1.6, published Thursday, May 13, 2004
	Management of Radioactive Waste from the Mining and Milling of Ores Safety Guide, Series No. WS-G-1.2, published Thursday, October 10, 2002
http://www-ns.iaea.org/standards/documents/default.asp?s=11&l=90&sub=50	

Table 3.2. IAEA safety standards applicable to all facilities and activities.

Safety Standards applicable to all facilities and activities	
Safety Fundamentals	Fundamental Safety Principles, Series No. SF-1, published Tuesday, November 07, 2006
General Safety Requirements	Preparedness and Response for a Nuclear or Radiological Emergency Safety Requirements, Series No. GS-R-2, published Wednesday, November 06, 2002
	The Management System for Facilities and Activities Safety Requirements Series No. GS-R-3, published Friday, July 21, 2006.
	Governmental, Legal and Regulatory Framework for Safety General Safety Requirements Part 1 Series No. GSR Part 1, published Monday, October 04, 2010
	Radiation Protection and Safety of Radiation Sources: International Basic Safety Standards Series No. GSR Part 3, published Saturday, July 19, 2014
	Safety Assessment for Facilities and Activities General Safety Requirements Part 4, Series No. GSR Part 4, published Tuesday, May 19, 2009
	Predisposal Management of Radioactive Waste General Safety Requirements Part 5, Series No. GSR Part 5, published Tuesday, May 19, 2009
	Decommissioning of Facilities General Safety Requirements Part 6 Series No. GSR Part 6, published Tuesday, July 08, 2014.
General Safety Guides	Arrangements for Preparedness for a Nuclear or Radiological Emergency Safety Guide Series No. GS-G-2.1, published Wednesday, May 23, 2007
	Application of the Management System for Facilities and Activities Safety Guide Series No. GS-G-3.1, published Friday, July 28, 2006
	The Management System for Technical Services in Radiation Safety Guide Series No. GS-G-3.2, published Wednesday, July 02, 2008
	The Management System for the Processing, Handling and Storage of Radioactive Waste Safety Guide Series No. GS-G-3.3, published Wednesday, July 02, 2008
	Classification of Radioactive Waste General Safety Guide, Series No. GSG-1, published Monday, December 28, 2009
	Criteria for Use in Preparedness and Response for a Nuclear or Radiological Emergency General Safety Guide, Series No. GSG-2, published Thursday, March 17, 2011
	The Safety Case and Safety Assessment for the Predisposal Management of Radioactive Waste Series No. GSG-3, published Thursday, April 18, 2013
	Use of External Experts by the Regulatory Body Series No. GSG-4, published Thursday, February 21, 2013
	Justification of Practices, Including Non-medical Human Imaging Series No. GSG-5, published Friday, October 17, 2014
	Occupational Radiation Protection Safety Guide Series No. RS-G-1.1, published Wednesday, October 13, 1999
	Assessment of Occupational Exposure Due to Intakes of Radionuclides Safety Guide Series No. RS-G-1.2, published Tuesday, November 02, 1999
	Assessment of Occupational Exposure Due to External Sources of Radiation Safety Guide Series No. RS-G-1.3, published Tuesday, September 28, 1999
	Building Competence in Radiation Protection and the Safe Use of Radiation Sources Safety Guide - Series No. RS-G-1.4, published Tuesday, May 08, 2001
	Environmental and Source Monitoring for Purposes of Radiation Protection Safety Guide Series No. RS-G-1.8, published Monday, August 22, 2005
	Categorization of Radioactive Sources Safety Guide Series No. RS-G-1.9, published Monday, August 15, 2005
	Regulatory Control of Radioactive Discharges to the Environment Safety Guide Series No. WS-G-2.3, published Friday, September 15, 2000
	Predisposal Management of Low and Intermediate Level Radioactive Waste Safety Guide Series No. WS-G-2.5, published Wednesday, April 30, 2003
	Predisposal Management of High Level Radioactive Waste Safety Guide Series No. WS-G-2.6, published Wednesday, April 30, 2003
	Remediation Process for Areas Affected by Past Activities and Accidents Safety Guide Series No. WS-G-3.1, published Thursday, March 01, 2007
	Release of Sites from Regulatory Control on Termination of Practices Safety Guide Series No. WS-G-5.1, published Wednesday, November 08, 2006
	Safety Assessment for the Decommissioning of Facilities Using Radioactive Material Safety Guide Series No. WS-G-5.2, published Tuesday, February 24, 2009
	Storage of Radioactive Waste Safety Guide Series No. WS-G-6.1, published Tuesday, November 28, 2006
http://www-ns.iaea.org/standards/documents/general.asp	

Table 3.3. IAEA publications on exposure to radiation from natural sources.

Exposure to Radiation from Natural Sources	
Safety Standards series	Radiation Protection and Safety of Radiation Sources: International Basic Safety Standards - INTERIM EDITION - GSR Part 3
	Application of the Concepts of Exclusion, Exemption and Clearance Safety Guide, Safety Standards Series No. RS-G-1.7, 2004
	Occupational Radiation Protection in the Mining and Processing of Raw Materials Safety Guide, Safety Standards Series No. RS-G-1.6, 2004
	Management of Radioactive Waste from the Mining and Milling of Ores Safety Guide, Safety Standards Series No. WS-G-1.2, 2002
	Occupational Radiation Protection Safety Guide, Safety Standards Series number RS-G-1.1, 1999
Safety Reports series	Radiation Protection and NORM Residue Management in the Production of Rare Earths from Thorium containing Minerals, Safety Report Series No. 68, 2011
	Assessing the Need for Radiation Protection Measures in Work Involving Minerals and Raw Materials, Safety Reports Series No. 49, 2006
	Monitoring and Surveillance of Residues from the Mining and Milling of Uranium and Thorium, Safety Reports Series No. 27, 2002
Technical Reports series	Measurement and Calculation of Radon Releases from NORM Residues, Technical Report Series No. 474, 2013
	Extent of Environmental Contamination by Naturally Occurring Radioactive Material (NORM) and Technological Options for Mitigation, Technical Reports Series No. 419, 2003
	Current Practices for the Management and Confinement of Uranium Mill Tailings, Technical Reports Series No. 335, 1992
	Measurement and Calculation of Radon Releases from Uranium Mill Tailings, Technical Reports Series No. 333, 1992
	The Environmental Behaviour of Radium Vol. 1, Technical Reports Series No. 310, 1990
	The Environmental Behaviour of Radium Vol. 2, Technical Reports Series No. 310, 1990
TECDOC series	Regulatory Control for the Safe Transport of Naturally Occurring Radioactive Material (NORM), IAEA-TECDOC 1728, 2014
	Management of NORM Residues, IAEA-TECDOC 1712, 2013
	Regulatory and Management Approaches for the Control of Environmental Residues Containing Naturally Occurring Radioactive Material (NORM) – Proceedings of a Technical Meeting held in Vienna, 6-10 December 2004, IAEA-TECDOC-1484, 2006
	Naturally occurring radioactive materials (NORM IV): Proceedings of an international conference held in Szczyrk, Poland, 17-21 May 2004, IAEA-TECDOC-1472, 2005
	Technologies for the Treatment of Effluents from Uranium Mines, Mills and Tailings, IAEA TECDOC Series No. 1296, 2002
	Impact of New Environmental and Safety Regulations on Uranium Exploration, Mining, Milling and Management of its Waste, IAEA TECDOC Series No. 1244, 2001
	Guidebook on Good Practice in the Management of Uranium Mining and Mill Operations and the Preparation for their Closure, IAEA TECDOC Series No. 1059, 1998
	Planning for Environmental Restoration of Uranium Mining and Milling Sites in Central and Eastern Europe, IAEA TECDOC Series No. 982, 1998
	Environmental Impact Assessment for Uranium Mine, Mill and In Situ Leach Projects, IAEA TECDOC Series No. 979, 1997
	Planning and Management of Uranium Mine and Mill Closures, IAEA TECDOC Series No. 824, 1995
http://www-ns.iaea.org/publications/norm-publications.asp	

Other relevant IAEA publications regarding uranium production for the nuclear fuel cycle include but are not limited to:

- Best Practice in Environmental Management of Uranium Mining, IAEA Nuclear Energy Series No. NF-T-1.2, Published 2010
- Establishment of Uranium Mining and Processing Operations in the Context of Sustainable Development, IAEA Nuclear Energy Series NF-T-1.1, Published 2009
- Generic models for use in assessing the impact of discharges of radioactive substances to the environment, Safety Reports Series No. 19, Published 2001
- Monitoring and surveillance of residues from the mining and milling of uranium and thorium, Safety Reports Series No. 27, Published 2002
- Assessing the Need for Radiation Protection Measures in Work Involving Minerals and Raw Materials, Safety Reports Series No. 49, Published 2006
- Programmes and systems for source and environmental radiation monitoring, Safety Reports Series No. 64, Published 2010
- Monitoring for Compliance with Exemption and Clearance Levels, Safety Reports Series No. 67, Published 2012
- Monitoring for Compliance with Remediation Criteria for Sites, Safety Reports Series No. 72, Published 2012
- Code of Conduct on the Safety and Security of Radioactive Sources (2003)
- The long term stabilization of uranium mill tailings, IAEA - TECDOC-1403 – 2004.

Appendix C

ICRP publications for radiological protection

ICRP, 2014. Protection of the Environment under Different Exposure Situations. ICRP Publication 124. Ann. ICRP 43(1)

ICRP, 2009. Environmental Protection: Transfer Parameters for Reference Animals and Plants. ICRP Publication 114, Ann. ICRP 39(6)

ICRP, 2008. Environmental Protection - the Concept and Use of Reference Animals and Plants. ICRP Publication 108. Ann. ICRP 38 (4-6)

ICRP, 1979. Radionuclide Release into the Environment - Assessment of Doses to Man. ICRP Publication 29. Ann. ICRP 2 (2)

ICRP, 2013. Radiological protection in geological disposal of long-lived solid radioactive waste. ICRP Publication 122. Ann. ICRP 42(3)

ICRP, 2009. Application of the Commission's Recommendations to the Protection of People Living in Long-term Contaminated Areas After a Nuclear Accident or a Radiation Emergency. ICRP Publication 111. Ann. ICRP 39 (3)

ICRP, 2009. Application of the Commission's Recommendations for the Protection of People in Emergency Exposure Situations. ICRP Publication 109. Ann. ICRP 39 (1)

ICRP, 2007. The 2007 Recommendations of the International Commission on Radiological Protection. ICRP Publication 103. Ann. ICRP 37 (2-4)

ICRP, 1991. 1990 Recommendations of the International Commission on Radiological Protection. ICRP Publication 60. Ann. ICRP 21 (1-3)

ICRP, 1982. General Principles of Monitoring for Radiation Protection of Workers. ICRP Publication 35. Ann. ICRP 9 (4)

ICRP, 1982. Limits for Intakes of Radionuclides by Workers. ICRP Publication 30 (part 1 - 4 + supplements). Ann. ICRP 8 (4)

ICRP, 1981. Limits for Inhalation of Radon Daughters by Workers. ICRP Publication 32. Ann. ICRP 6 (1)

ICRP, 1985. Principles of Monitoring for the Radiation Protection of the Population. ICRP Publication 43. Ann. ICRP 15 (1)

ICRP, 2006. Assessing Dose of the Representative Person for the Purpose of the Radiation Protection of the Public. ICRP Publication 101a. Ann. ICRP 36 (3)

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

ICRP, 2010. Conversion Coefficients for Radiological Protection Quantities for External Radiation Exposures. ICRP Publication 116, Ann. ICRP 40(2-5)

Appendix D

Australian laws, regulations and guidelines governing uranium production for the nuclear fuel cycle

Commonwealth laws

- Australian Radiation Protection and Nuclear Safety Act (ARPANSA), Act No. 133 of 1998 as amended, Administered by: Health, http://www.comlaw.gov.au/Details/C2012C00294)
- Australian Radiation Protection and Nuclear Safety (Licence Charges) Act 1998, Act No. 134 of 1998, Administered by: Health, http://www.comlaw.gov.au/Series/C2004A00384
- Australian Radiation Protection and Nuclear Safety (Consequential Amendments) Act 1998, Act No. 135 of 1998 as amended, Administered by: Health, http://www.comlaw.gov.au/Details/C2004C01009
- Mining Act 1971, Administered by: Minister for Mineral Resources and Energy, http://www.legislation.sa.gov.au/LZ/C/A/MINING%20ACT%201971.aspx
- Environment Protection and Biodiversity Conservation Act 1999 (EPBC Act), Administered by: Environment, http://www.environment.gov.au/about-us/legislation
- Aboriginal and Torres Strait Islander Heritage Protection Act 1984, Administered by: Attorney-General's, Environment, http://www.environment.gov.au/about-us/legislation
- Customs Act 1901, Administered by: Immigration and Border Protection, Industry, http://www.comlaw.gov.au/Details/C2013C00064/Download.

Commonwealth regulations made under the ARPANSA Act

Australian Radiation Protection and Nuclear Safety Regulations 1999 as amended, SR 1999 No. 37, Administered by: Health, http://www.comlaw.gov.au/Details/F2014C00857.

Commonwealth guides made under the ARPANSA Act

- Frequency of calibration of radiation monitoring instruments
- Reporting an accident
- Reporting compliance
- What to expect during an ARPANSA inspection
- http://www.arpansa.gov.au/Regulation/guides.cfm#17
- Transport of radioactive material.

State laws, regulations and guidelines – South Australia laws

Department for Manufacturing, Innovation, Trade, Resources and Energy (DMITRE) is the agency responsible for facilitation and regulation of mining projects through the Mining Act 1971. DMITRE administers the assessment process for new proposals (http://www.minerals.dmitre.sa.gov.au/).

Environment Protection Authority (EPA) is responsible for administration of the Environment Protection Act and Radiation Protection Act. EPA's role in the assessment process is to ensure that new projects comply with EPA regulation and policy. The EPA Act regulates environmental aspects. The RPC Act is applied to manage environmental and occupational risks associated with radiation through conditions on the license that require compliance with the

‘National Code of Practice for Radiation Protection Radioactive Waste Management in Mining and Mineral Processing’, published by the Australian Radiation Protection and Nuclear Safety Agency (ARPANSA).

- Environmental Protection Act 1993, Administered by: Minister for Sustainability, Environment and Conservation, http://www.legislation.sa.gov.au/LZ/C/A/ENVIRONMENT%20PROTECTION%20ACT%201993.aspx
- Radiation Protection and Control Act 1982, Administered by: Minister for Sustainability, Environment and Conservation (health, radioactive waste management, closure -licence) http://www.legislation.sa.gov.au/lz/c/a/radiation%20protection%20and%20control%20act%201982.aspx
- Mining Act 1971, Administered by: Minister for Mineral Resources and Energy, http://www.legislation.sa.gov.au/LZ/C/A/MINING%20ACT%201971.aspx
- Natural Resources Management Act 2004, Administered by: Minister for Sustainability, Environment and Conservation, http://www.legislation.sa.gov.au/LZ/C/A/Natural%20Resources%20Management%20Act%202004.aspx
- Development Act 1993, Administered by: Minister for Planning and Minister for Urban Development, Planning and the City of Adelaide http://www.epa.sa.gov.au/environmental_info/legislation/related_legislation
- Customs Act 1901, Administered by: Immigration and Border Protection, Industry, http://www.comlaw.gov.au/Details/C2013C00064/Download.

Regulations

- Environment Protection and Biodiversity Conservation Regulations 2000, Statutory Rules No. 181, 2000 as amended, made under the Environment Protection and Biodiversity Conservation Act 1999, Administered by: Environment, http://www.comlaw.gov.au/Details/F2014C00950
- IAEA Regulations for the Safe Transport of Radioactive Material 2012, Specific safety Requirements No. SSR-6, (for all types of transport), www.iaea.org
- Regulations for the Safe Transport of Radioactive Material, 2009 Edition, Series No. TS-R-1, published Tuesday, May 05, 2009,
- http://www-ns.iaea.org/standards/documents/topics.asp?sub=250
- Code of Practice for the Safe Transport of Radioactive Material (2008) – ARPANSA, www.arpansa.gov.au
- South Australian Radiation Protection and Control (Transport of Radioactive Substances) Regulations 2003, under the Radiation Protection and Control Act 1982 http://www.epa.sa.gov.au/environmental_info/legislation/radiation_legislation
- South Australia’s role in uranium product shipment (NT and potentially WA and QLD).

Guidance

- Radiation Protection Guidelines on Mining in South Australia: Mineral exploration 2010, http://www.epa.sa.gov.au/environmental_info/radiation/mining_and_mineral_processing/guidelines_and_safety_guides

- MG2 Preparation of a Mining Lease Proposal or Mining Rehabilitation Program (MARP) in South Australia, January 2011, includes provisions under the amended Mining Act (http://www.pir.sa.gov.au/minerals/forms_and_guidelines/guidelines)
- MG5 Guidelines for miners: tailings and tailings storage facilities in South Australia, September 2009, http://www.epa.sa.gov.au/environmental_info/radiation/mining_and_mineral_processing/guidelines_and_safety_guides
- MG6 Guidelines for miners: preparation of a program for environment protection and rehabilitation (PEPR) for extractive mineral operations in South Australia, April 2012 (http://www.pir.sa.gov.au/minerals/forms_and_guidelines/guidelines
- MG8 Guidelines: program for environment protection and rehabilitation (PEPR) for low impact mineral exploration in South Australia, August 2013 (http://www.pir.sa.gov.au/minerals/forms_and_guidelines/guidelines)
- MG11 Guidelines: preparation of an environmental management plan for in situ recovery uranium mines, in prep (http://www.pir.sa.gov.au/minerals/forms_and_guidelines/guidelines)
- Code of Practice and Safety Guide for Radiation Protection and Radioactive Waste Management in Mining and Mineral Processing (2005) RPS9 ARPANSA http://www.arpansa.gov.au/Publications/codes/index.cfm
- Safety Guide for Monitoring, Assessing and Recording Occupational Radiation Doses in Mining and Mineral Processing (2011) RPS9.1 ARPANSA http://www.arpansa.gov.au/Publications/codes/index.cfm
- RPS 15 Safety Guide for Management of Naturally Occurring Radioactive Material (NORM) (2008) RPS 15 ARPANSA.

Other guidance

- IAEA WS-G-1.2 Management of Radioactive Waste from the Mining and Milling of Ores
- IAEA NF-T-1.1 Establishment of Uranium Mining and Processing Operations in the Context of Sustainable Development
- International Maritime Dangerous Goods (IMDG) Code (worldwide sea transport of radioactive materials), http://www.imo.org/blast/mainframe.asp?topic_id=158
- International Air Transport Association (IATA) - Dangerous Goods Regulations (DGR) (worldwide air transport of radioactive materials), http://www.iata.org/publications/dgr/Pages/index.aspx
- United Nations Economic Commission for Europe (UNECE) - European Agreement concerning the International Carriage of Dangerous Goods by Road (ADR), regional road transport of radioactive materials, http://www.unece.org/trans/danger/publi/adr/adr_e.html

Appendix E

Canadian laws, regulations and guidelines governing uranium production for the nuclear fuel cycle

CNSC Law

- Nuclear Safety and Control Act (NSCA) of May 31, 2000 (http://laws-lois.justice.gc.ca/eng/acts/N-28.3/).

CNSC – Regulations made under NSCA

- Uranium Mines and Mills Regulations (SOR/2000-206)
- General Nuclear Safety and Control Regulations (SOR/2000-202)
- Radiation Protection Regulations (SOR/2000-203)
- Section 3 of the Nuclear Substances and Radiation Devices Regulations (SOR/2000-207)
- General Nuclear Safety and Control Regulations (SOR/2000-202)
- Management of Uranium Mine Waste Rock and Mill Tailings, RD/GD-370, 2012 (includes legal requirements, but guidance (recommendations) is also included) http://nuclearsafety.gc.ca/eng/acts-and-regulations/acts/index.cfm#sec2
- P-290, Managing Radioactive Waste and P-223, Protection of the Environment
- S-296, Environmental Protection Policies, Programs and Procedures for Class I Nuclear Facilities and Uranium Mines and Mills
- G-296, Developing Environmental protection Policies, Programs and Procedures at Class I Nuclear Facilities and Uranium Mines and Mills
- G-129, Keeping Radiation Exposures and Doses 'As Low as Reasonably Achievable' (ALARA)
- Sections 15 to 23 of the Packaging and Transport of Nuclear Substances Regulations (SOR/2000-208).

CNSC – Guidance

- Guidelines for Handling Packages Containing Nuclear Substances INFO-0744 http://www.nuclearsafety.gc.ca/eng/.

Other federal legislation/regulations that mining license applicants must respect in Canada

- Canadian Environmental Protection Act, 1999, (CEPA 1999) Administered by: Environment Canada http://laws-lois.justice.gc.ca/eng/acts/C-15.31/index.html
- Canadian Environmental Assessment Act, (CEAA) 2012, Administered by: Canadian Environmental Assessment Agency http://laws-lois.justice.gc.ca/eng/acts/C-15.21/page-1.html
- Environmental Code of Practice for Metal Mines, 2009 Administrated by: Environment Canada, http://nuclearsafety.gc.ca/eng/acts-and-regulations/index.cfmhttp://nuclearsafety.gc.ca/eng/acts-and-regulations/index.cfm
- Metal Mining Effluent Regulations (SOR/2002-222), http://laws-lois.justice.gc.ca/eng/regulations/sor-2002-222/index.html
- Species at Risk Act (S.C. 2002, c. 29), Administered by: Environment Canada, http://laws-lois.justice.gc.ca/eng/acts/S-15.3/index.html
- Fisheries Act (FA) (R.S.C., 1985, c. F-14), Administered by: Fisheries and Oceans Canada http://laws-lois.justice.gc.ca/eng/acts/F-14/index.html

- Transportation of Dangerous Goods Act, 1992 (S.C. 1992, c. 34), Administered by: Transport Canada, http://laws-lois.justice.gc.ca/eng/acts/t-19.01/
- Navigation Protection Act (R.S.C., 1985, c. N-22), Administered by: Transport Canada, http://laws-lois.justice.gc.ca/eng/acts/N-22/page-1.html
- Canada Labour Code (R.S.C., 1985, c. L-2), Administered by: Human Resources and Skills Development Canada, http://laws-lois.justice.gc.ca/eng/acts/L-2/
- Land Claim Agreements, Administered by: Aboriginal Affairs and Northern Development Canada, https://www.aadnc-aandc.gc.ca/eng/1100100028568/1100100028572.

Canadian guidelines for uranium

- Occupational Health & Safety Radiation Protection Guidelines for Uranium Exploration: http://www.lrws.gov.sk.ca/radiation-protection-guidelines-uranium-exploration
- Guidance Document for the Sampling and Analysis of Metal Mining Effluents: http://publications.gc.ca/site/eng/236853/publication.html
- Guidelines for the Assessment of Alternatives for Mine Waste Disposal, Environment Canada (EC), http://ec.gc.ca/pollution/default.asp?lang=En&n=125349F7-1.

Local laws and regulations (equivalent to state)

- Provincial: Saskatchewan Provincial Regulations on U mines (Canada). Saskatchewan Province is the only place in Canada where uranium is recovered.
- The Environmental management and Protection Act, 2002, http://www.publications.gov.sk.ca/details.cfm?p=489
- The Environmental Assessment Act, 2010, http://www.publications.gov.sk.ca/details.cfm?p=488
- The Occupational Health and Safety Act, 1993, http://www.publications.gov.sk.ca/
- The Mineral Industry Environmental Protection Regulations, 1996, http://www.publications.gov.sk.ca/details.cfm?p=1060
- The Mines Regulations, 2003, http://www.publications.gov.sk.ca/details.cfm?p=678.

Appendix F

U.S. laws, regulations and guidelines governing uranium production for the nuclear fuel cycle

US NRC - Laws

- Atomic Energy Act of 1954
- National Environmental Policy Act of 1969
- Uranium Mill Tailings Radiation Control Act of 1978.

US OSMRE – Laws

- Surface Mining Control and Reclamation Act (SMCRA) of 1977.

US Environmental Protection Agency - Laws (http://www2.epa.gov/laws-regulations/laws-and-executive-orders)

- Resource Conservation and Recovery Act (RCRA) of 1976
- Clean Air Act (CAA) of 1970 / 1977
- Clean Water Act (CWA) of 1972
- Safe Drinking Water Act of 1974
- Pollution Prevention Act (PPA) of 1990.

US - Regulations - Code of Federal Regulations (CFR) (http://www.nrc.gov/materials/uranium-recovery/regs-guides-comm.html)

- 10 CFR Part 2 includes regulations for general rules of practice for licensing
- 10 CFR Part 20 includes standards for protection against radiation
- 10 CFR Part 40 includes regulations addressing licensing source and by-product material and Appendix A to 10 CFR Part 40
- 10 CFR Part 51 includes regulations addressing protection of the environment
- 10CFR Part 110 includes regulations addressing Import / Export
- 49 CFR Chapter 1, Subpart A 'Hazardous materials' includes regulations addressing transportation
- 40 CFR (Clean Air; Clean Water) Environmental Protection Agency (EPA) regulations
- Mining Regulations: Mine Safety and Health Administration; States.

Guidance for license applications (http://www.nrc.gov/materials/uranium-recovery/regs-guides-comm.html)

- Regulatory Guide 3.5: Standard Format and Content of License Applications for Uranium Mills
- NUREG-1748: Environmental Review Guidance for Licensing Actions Associated with NMSS Programs.

Guidance for operations (http://www.nrc.gov/materials/uranium-recovery/regs-guides-comm.html)

- Regulatory Guide 3.8: Preparation of Environmental Reports for Uranium Mills
- Regulatory Guide 3.11: Design, Construction, and Inspection of Embankment Retention Systems at Uranium Recovery Facilities
- Regulatory Guide 3.51: Calculation Models for Estimating Radiation Doses to Man from Airborne Radioactive Materials Resulting from Uranium Milling Operations
- Regulatory Guide 3.56: General Guidance for Designing, Testing, Operating, and Maintaining Emission Control Devices at Uranium Mills

- Regulatory Guide 3.59: Methods for Estimating Radioactive and Toxic Airborne Source Terms for Uranium Milling Operations
- Regulatory Guide 3.63: Onsite Meteorological Measurement Program for Uranium Recovery Facilities – Data Acquisition and Reporting
- Regulatory Guide 4.14: Radiological Effluent and Environmental Monitoring at Uranium Mills
- Regulatory Guide 8.11: Applications of Bioassay for Uranium
- Regulatory Guide 8.31: Information Relevant to Ensuring that Occupational Radiation Exposures at Uranium Recovery Facilities Will Be as Low as Is Reasonably Achievable.

Guidance for closure (http://www.nrc.gov/materials/uranium-recovery/regs-guides-comm.html)

- Regulatory Guide 3.64: Calculation of Radon Flux Attenuation by Earthen Uranium Mill Tailings Covers
- NUREG-1620: Standard Review Plan for the Review of a Reclamation Plan for Mill Tailings Sites under Title II of the Uranium Mill Tailings Radiation Control Act of 1978
- NUREG-1623: Design of Erosion Protection for Long-Term Stabilization.

Appendix G

Mine closure, post closure monitoring, maintenance and institutional control of mine sites in Canada, Australia and the U.S.

1. Case study: Canada

Cluff Lake is considered a model mining reclamation programme, which was planned from the very beginning of the project. The site is being environmentally monitored today to track the change in conditions over time.

- https://www.ceaa-acee.gc.ca/41B79974-docs/report_e.pdf
- http://www.nuclearsafety.gc.ca/eng/the-commission/pdf/2009-06-10-Decision-AREVA-e-Edocs3405423.pdf
- http://kiggavik.ca/wp-content/uploads/2013/04/Cluff-Lake-Detailed-Decommissioning-Plan-V2-Feb2009.pdf
- http://us.areva.com/EN/home-983/areva-resources-canand-activities.html.

In Canada, ongoing monitoring, care and maintenance following rehabilitation of the mine are required. The principal beneficiary of the mine, the proponent is held responsible either through continued management of the site while maintaining financial guarantees or through posting sufficient financial resources so that either the jurisdiction or a third party can continue the necessary work. Sufficient funding to address these long-term needs and emergency situations should be provided. Mine closure plans and financial security must be filed and approved prior to a permit being granted for a new mine operation.

Institutional custodianship policy is fundamental to the management of closed-out mine sites which may require some form of continuing supervision. This may range from passive controls, such as registered land use restrictions, to active controls, which may range from monitoring (depending on the site status), fencing hazards in perpetuity or water treatment for significant periods of time.

The institutional controls must be authorized by legislation; the actual work may be completed by a government department, an agency contracted by the government or some other body.

2. Case study: Australia

Ranger uranium mine in Northern Australia has begun the transition from open-cut mining to underground exploration. Rehabilitation plans developed by Energy Resources of Australia Ltd (ERA) progressed significantly in 2013, focusing on Pit 1 and Pit 3, as well as tailings and brine management and the Jabiluka Interim Water Management Pond
(http://www.energyres.com.au/):

- http://www.environment.gov.au/system/files/resources/9c423c0e-0e70-453b-aac2-6c2019ff25f1/files/ir624.pdf
- http://www.iaea.org/OurWork/ST/NE/NEFW/Technical-Areas/NFC/documents/uranium/tm-UMREG-2014/22_Tayler_UMREG-2014_Closure_planning_Ranger_U_mine.pdf

South Alligator Valley – **for instance the Sleisbeck mine site**:

- http://www.iaea.org/OurWork/ST/NE/NEFW/Technical-Areas/NFC/documents/uranium/tm-UMREG-2014/20_Waggitt_UMREG-2014_Sth_Alligator_Valley_5yr_report.pdf
- http://www.environment.gov.au/system/files/resources/d5f77054-2517-4b22-b25d-03e44144003a/files/ir561.pdf
- http://www.environment.gov.au/system/files/resources/1c1c2a3e-fc98-4b21-95a8-31272b2c2b2d/files/radioactivity-sav.pdf

After the mine is abandoned, rehabilitated sites should be inspected and monitored at intervals in such a way as is approved by the relevant regulators. This requirement must be incorporated into the development of the post closure monitoring programme and referenced in the mine closure plan as appropriate.

When submitting the mine closure plans, the following information with regard to monitoring and maintenance program is required:

- Use of recognized or acceptable monitoring methodologies and standards.
- Monitoring that takes into account the wider receiving environments, receptors and exposure pathways.
- Monitoring using appropriate quality control systems and procedures in sampling, analysis and reporting of results.
- Referencing trends against expected or predicted performance based on agreed closure criteria.
- Contingency strategies if monitoring data indicates that key environmental indicators move outside agreed closure criteria.
- Post-closure monitoring to continue until agreed completion criteria have been demonstrated to be met.

The monitoring and maintenance period will extend for many years after closure until it can be demonstrated that closure outcomes and completion criteria have been met. In the early stages of the project or where detailed information on closure performance is not available, a minimum monitoring period after closure should be provided for in the mine closure plans, usually in the order of 10 years.

3. Case study: the U.S.

Closure outcomes:

- Conventional mills and tailings
    - Unrestricted release for sites from which the tailings were moved to another disposal site (in the U.S. there are several uranium tailings sites).
    - U.S. Department of Energy (DOE) is long-term custodian of tailings under the Part 40 general license.
- ISL:
    - Unrestricted release.

Responsibilities:

The Environmental Protection Agency sets the standards.

The Nuclear Regulatory Commission (NRC) develops regulations and guidance and reviews and concurs in design and construction.

The Department of Energy (DOE) or the licensee designs and constructs to meet standards; DOE is long-term custodian.

The owner or operator must close the facility in a manner that:

- Minimizes the need for further maintenance.
- Controls, minimizes or eliminates post-closure escape of hazardous materials to ground or surface waters or to the atmosphere.
- Control of radioactive materials, non-radioactive contaminants and their listed constituents shall be designed to be effective for up to one thousand years, to the extent reasonably achievable, and, in any case, for at least 200 years.
- Land clean-up.
- Building clean-up.
- Groundwater clean-up and protection.
- Requirements for embankment and cover of tailings facility.

Long-term funding

A charge (e.g. US.$250,000) for long-term surveillance must be paid by each mill operator. Variance in funding requirements may be specified by the NRC.

The U.S. Uranium Mill Tailings Radiation Control Act stipulates that:

- The tailings waste must be transferred to DOE when DOE and NRC determine that remedial action is completed (http://www.nrc.gov/reading-rm/doc-collections/fact-sheets/mill-tailings.html).

Closure process – conventional mills and legacy sites

- Operator or DOE submits a final long-term surveillance plan (LTSP) for the site; NRC reviews and approves the plan.
- Long-term licenses.
- General license issued to DOE for multiple sites in the U.S.
- Effective when NRC accepts a site long-term surveillance plan (LTSP).
- Specifies general LTSP content.

Long-term surveillance plan should include:

- Description of the disposal site.
- Detailed description of final site conditions, including groundwater characterization.
- Description of the surveillance programme.
- Inspection and reporting frequency.
- Frequency and extent of any monitoring.
- Constituent limits for groundwater.
- Inspection personnel qualifications. Inspection procedures.
- Record keeping.
- Criteria for follow-up inspections.
- Criteria for instituting maintenance.

DOE long-term care and inspection:

- An inspection is conducted by the operator at least annually at each disposal site, reports to NRC are required.
- A site inspection team consists of at least two inspectors with appropriate technical experience.
- During an inspection, the site inspectors must:

- Observe the conditions of the site (e.g. erosion features such as gullies or rills, sediment accumulations, vandalism, animal intrusion and plant growth).
- Record observations.
- Take and record photographs, as necessary, to document conditions at the disposal site and to provide a continuous record for monitoring changing conditions over time.
- Collect monitoring data as required by the specific LTSP.

Examples of maintenance or repair:

- Planned maintenance: grass mowing, road maintenance, removal of weeds or debris, vegetation control or replacement of signs.
- Unscheduled maintenance: removal of deep-rooted or other unwanted vegetation on the disposal cell.
- Repair: damage to disposal cell, fence, gate or locks, surveillance features, wells or roads.

Examples of disposal site conditions that may require emergency measures:

- Surface rupture of the disposal cell through subsidence, cracking, sliding or slope instability.
- Deterioration of the erosion protection rock on the disposal cell or in the drainage ditches.
- Monitored or observed seepage.
- Development of gullies on or adjacent to disposal site property that could affect the integrity of the disposal cell.

References

http://environment.gov.sk.ca/legislation/

The reclaimed Industrial Sites Act. An act respecting the Monitoring and Maintenance of Industrial Sites after Reclamation:
http://www.publications.gov.sk.ca/details.cfm?p=23009

The Reclaimed Industrial Sites Regulations:
http://www.publications.gov.sk.ca/details.cfm?p=23130
http://www.dmp.wa.gov.au/19089.aspx

Appendix H

Important parameters of radioactive waste that may be considered when classifying tailings from uranium milling

Origin

Radiological properties:

- Half-lives of radionuclides
- Activity concentration of radionuclides
- Surface contamination
- Dose factors of relevant radionuclides
- Decay products

Physical properties:

- Physical state (solid, liquid or gaseous)
- Size and weight
- Compactibility
- Dispersibility
- Volatility
- Miscibility
- Free liquid content

Chemical properties:

- Chemical composition
- Solubility and chelating agents
- Potential chemical hazard
- Corrosion resistance / corrosiveness
- Organic content
- Combustibility and flammability
- Chemical reactivity and swelling potential
- Gas generation
- Sorption of radionuclides

Biological properties:

- Potential biological hazards
- Bio-accumulation

Other factors:

- Volume
- Amount arising per unit of time
- Physical distribution

Source: IAEA (2009) Safety Standards, General Safety Guide, No. GSG-1, Classification of Radioactive Waste

Appendix I

The advantages and disadvantages of the different uranium tailings containments and methods for stabilizing and isolating uranium mill tailings.

A comparison of the advantages and disadvantages of the different approaches to uranium mill tailings containment [compiled by S. Needham] modified from IAEA (2004).

Disposal option	Advantages	Disadvantages	Cold weather considerations
Above-ground	Can operate simultaneously with mining. May be cheap to establish if tailings are used in construction. Valley fill sites may have low construction costs. Whole tailings can be contained. Tailings pond can also function as an evaporative pan assisting in mine water management. Most widely used. Tailings easily accessed for reworking, if required.	Authorities may regard this type as only temporary storage & tailings may need to be relocated, for instance below ground level at end of mine life. May require construction of associated structures to minimize risk of environmental impact in the case of failure or to collect/treat seepage, etc. Seepage control essential. Expensive if built as water containment structure. Post close-out settlement may take a long time and lengthen the period before operator can be released of responsibility. Requires long-term maintenance. Long-term risk of tailings spill, increasing as structure weathers and erodes. Increases land area impacted by mining. Airborne and waterborne dispersal of contaminants possible following erosion, etc.	Change of pore pressures from rainfall and snowmelt. Long-term risk associated with dam stability and containment capabilities. Freeze/thaw cycling may cause cracks, channelling and exposure of surface below the cover. Cycling can accelerate weathering and leaching of materials.
Below-ground: in pit	Very long-term containment. Unlikely to require frequent maintenance. Whole tailings can be contained. Pit preparation costs unlikely to be as high as above-ground options. Airborne dispersal of contaminants effectively impossible. Structural failure of containment virtually impossible.	May need pervious-surround work to minimize ground water contamination risk. Construction cost of impermeable containment could be high if suitable pit not available. Not normally possible to operate simultaneously with mining at the same location. Requires a suitable pit to be available pre-mining or all ore to be extracted prior to milling (e.g. Nabarlek). May involve double-handing of tailings if no pit is available at commencement. Re-claiming of tailings, if required, for further treatment will be difficult owing to depth.	Infiltration zones from the walls of the pit must be sealed. Slurry tailings can be discharged into a water-/ice-filled open pit. Slope instability of open pit walls due to increased precipitation and ice.
Below-ground: underground mine workings	Very long-term containment. Unlikely to require frequent maintenance. Can possibly incorporate whole tailings. Can be operated simultaneously with mining. Airborne dispersal of contaminants effectively impossible. Structural failure of containment virtually impossible.	Slimes may need to be contained separately. Requires suitable groundwater conditions. Mine waste water management system needs to be able to cope with evaporation requirements. Tailings not available for reprocessing.	Water management difficult due to freezing problems. High cost for the transportation of cement or other mixtures in remote Arctic locations.

Disposal option	**Advantages**	**Disadvantages**	**Cold weather considerations**
Below-ground: purpose-built containment (underground void or surface pit)	Very long-term containment. Unlikely to require frequent maintenance. Whole tailings can be contained. Can be operated simultaneously with mining. Airborne dispersal of contaminants effectively impossible. Structural failure of containment virtually impossible. Site can be selected in low-permeability country rock. Benign rock available for unrestricted use in construction.	Construction required before milling commences. Mine waste water management system needs to be able to cope with evaporation requirements. Suitable site may be remote from mill and increase slurry/paste transport & infrastructure costs. Paste stabilization normally necessary for underground and optional/preferable for pit.	Water management difficult due to freezing problems.
Disposal option	Advantages	Disadvantages	Cold weather considerations
Deep lake	Can operate simultaneously with mining. Cheap to establish. Whole tailings can be contained. Very long-term containment possible. Unlikely to require frequent maintenance. Whole tailings can be contained. Airborne dispersal of contaminants effectively impossible. Structural failure of containment virtually impossible.	Authorities may not allow this approach to tailings disposal. Requires nearby water body which is not used for social or economic benefit (i.e. fishery, water supply, recreation). Risk of water contamination and tailings redistribution from disturbance by major flood of changed climatic conditions.	Water and pipeline can freeze up. Difficult to dispose beneath winter ice. Freeze/thaw cycling. Frozen water in the lake peripheries can be transported by wind. The water depth should ensure that tailings do not freeze.

A comparison of the advantages and disadvantages of methods for stabilizing and isolating uranium mill tailings (compiled by S. Needham) taken from IAEA (2004) (continued).

Methods	**Advantages**	**Disadvantages**	**Cold weather**
Containment preparation:			
Low-permeability membrane	High short-medium term security against seepage; easily applied to floor and walls of surface containments.	High cost; prone to accidental damage; difficult to repair after tailings discharge commenced; unknown long-term performance; application limited to above-ground containments; cannot be retrofitted.	Long-term performance in Arctic environment should be tested. Some membranes are not recommended for use at temperatures below 5°C.
Clay seal	Permeability decreases with overloading; low cost if local material available.	High cost if local materials unavailable; application limited to above-ground and in-pit containments; cannot be retrofitted.	Weather sensibility. Conditioning and placement during winter can be difficult. Subject to freeze/thaw cycles.
Grout	Targets known weak zones; ease of application.	Misses unknown zones of weakness; grouting compound may degrade on interaction with tailings pore water, cannot be retrofitted; possible high drilling costs involving specialist equipment.	Epoxy and concrete grouts are affected by lower temperatures.
Permeable surround	Potential long-term high security around entire containment against groundwater contamination; low maintenance.	Suitable high-permeability material needed; may clog; application limited to below-ground containments; cannot be retrofitted. High cost (but distributed through operational phase).	Used in Rabbit Lake mine in Canada.
Under-drain/basal filter bed	Aids settlement.	May clog; cannot be retrofitted; water disposal must be accounted for.	
Tailings preparation:			
Neutralization	Reduces acid producing potential and mobility of U and other heavy metals.	Availability and cost may affect viability.	Transportation of reagents can be expensive.
Thickening	Reduces water content of tailings; useful in low evaporation regions to achieve water loss.	Increased pumping costs; or alternative placement techniques.	Thickened tailings will freeze faster than slurry tailings. Shifting discharge location more often.
Paste	Allows addition of compounds to significantly improve chemical and physical stability of tailings pile and containment.	Present use limited to underground containments; longevity unknown; tailings probably not recoverable.	Same as thickening.
Cycloning	High stability product; provides sand-grade material for construction; removes main contaminants.	Slimes disposal.	Cyclone operations will likely not be possible for a portion of the year due to freezing temperatures in the winter months.

Tailings discharge and deposition:			
Slurry beaching	Increase stability of embankment walls; easier ponding and collection of decant water.	Not applicable underground.	Constant wetting required to prevent dust. Slurry may freeze on the beach before reaching the pond.
Thickened tails placement	Improved immediate surface stability and access; improved control of placement (e.g. layering).	Higher transport costs (pumping or trucking).	Tried in other countries with cold weather http://www.review-board.ca/upload/project_document/EA0809-004_Co-disposal_Case_Histories_1328896840.PDF
Dry cake placement	High immediate surface stability.	Higher transport costs (i.e. trucking).	Prevents pipes from freezing. Prevents frosting problems associated with conventional impoundments. Not appropriate for acid generating tailings.
Barrier/reactive layers	High control over design and placement; permits tailoring to address variations within tailings pile, etc.; potential wide range of treatments available.	Suits only paste or dry cake deposition of tailings; high placement costs (pumping or trucking), largely untested technology.	May work in cold conditions if the layers can be maintained frozen all year.
Tailings dewatering at discharge:			
Thickened tailings	Reduce water content problems, especially in low evaporation areas. Reduced use of clean water.	Higher transport costs (pumping or trucking) compared to slurry.	Tried in other countries with cold weather http://www.review-board.ca/upload/project_document/EA0809-004_Co-disposal_Case_Histories_1328896840.PDF
Paste tailings	Reduce water content problems, especially in low evaporation areas; allows addition of chemical and physical stabilisers.	Long-term performance and effects on diagenesis unknown.	Long-term performance in cold weather unknown.
Dry cake	Removes water removal and stability problems, significant reduction in leaching and groundwater contamination risks; potential for seismically active, cold, arid regions. Reduced use of clean water.	Untested in uranium mill tailings.	Untested in uranium mill tailings. Potential for use in cold regions.

Tailings dewatering in-situ:			
Under-drains	Improves settlement density, reduces instability and chemical contamination.	Cannot be retrofitted; may clog.	In permafrost conditions any under-drain installed with a pumping system in host rock risks freeze off. Possible options to implement a drainage system in a permafrost environment would include a bottom drain pumping/extraction system located in the centre of the thawed tailings and/or vertical drains installed through the tailings.
Horizontal drains	High improvement to settlement density; reduces instability and chemical contamination; design may be modified during operation.	Cannot be retrofitted; may clog.	Risk of freezing.
Wells/jet pumps/electro-osmosis	Improves settlement density; reduces instability and chemical contamination; can be targeted to specific sites. Suitable for ex-post treatment.	May require closely spaced grid of wells with attendant higher costs.	
Evapo-transpiration	Some improvement to settlement density; reduces instability, inexpensive.	Restricts access to tailings surface; of limited benefit once supernatant liquid evaporated unless used in conjunction with wells or wicks; no removal of contaminant load.	
Sand drains/wicks	Some improvement to settlement density; reduces instability; inexpensive and low maintenance. Suitable for ex-post treatment.	May take many years to reach dewatering capacity. Surface loading speeds it up.	
Tailings surface treatment:			
Water cover	Limits radon flux; dust.	Negates dewatering as an option to improve settlement density. Must be removed and followed by dewatering/settlement works prior to remediation.	May freeze.
Wetting	Reduces dust and radon flux; assists in evaporative water loss.	Components need regular inspection, maintenance and switching/moving.	Difficult during winter.
Sealants	Reduces dust, infiltration, improves access to tailings surface; good temporary protection between depositional or remedial stages.	Suitable only for short-term protection.	Subject to weather sensibility.
Decant water treatment:			
Recirculation to mill	Reduces clean water uptake, low cost.	Possible build-up of agents may decrease mill circuit efficiency.	Reduces evaporative surface.
Treat and release	Contains contaminants within the mine system.	Public perception of uncontrolled environmental harm; probable environmental impacts in event of system failure.	

Seepage control:			
Seepage detectors	Provides early warning and allows early intervention in event of significant seepage.	Costly; in themselves do not treat the problem; difficult and expensive to retrofit.	
Collector wells	Targets known confined seepage zones.	Limited sphere of influence; unlikely to collect seepage from unknown/new seepage points; requires monitoring wells to validate performance.	Expensive. Effectiveness will depend on the local aquifer characteristics.
Interception drains	Minimizes transfer of contaminants to groundwater or surface water systems; can extend around perimeter to provide high levels of assurance; essential backup for all operating tailings facilities.	Requires monitoring wells to validate performance.	
Return to containment	As for decant water treatment.	Essential.	
Treat and release	As for decant water treatment.	Essential.	
Recirculate to mill	As for decant water treatment.	Essential.	
Groundwater monitoring	Provides essential information for effective water management during operational phase.	Not practical for long-term management/stewardship post closure.	
Capping:			
Engineered design	High security short term (<1,000 years); well-known technology; extensive experience, guidelines, geotechnical expertise.	Unknown long-term (1,000–50,000 years) performance; probable high future maintenance costs; incompatible with natural processes, forces and systems; poor aesthetics.	Climate change performance unknown.
Ecological design	Caters for/conforms with natural processes; enhances prospects for long-term security against environmental harm; probable low future maintenance costs.	Unknown technology and costs; possible long lead time for research to deliver sufficient site-specific knowledge to factor into design.	Site-specific knowledge required.

Appendix J

Examples of ionizing radiation, units, decay series, nuclear fuel cycle, etc.

Examples of ionizing radiation - the three common types of radiation.

Types of radiation	Symbol	Description
Alpha	α	A helium-4 nucleus composed of two protons and two neutrons, mass is approximately 4 Da; charge +2; no spin
Beta	β	An electron; mass ~1/1822 Da; charge −1 or +1; spin 1/2
Gamma	γ	Electromagnetic radiation; no mass; no charge

Ionizing radiation is radiation that has enough energy to remove electrons from atoms or molecules when it passes through or collides with some material. The loss of an electron with its negative charge causes the atom or molecule to become positively charged. The loss of an electron is called ionization and a charged atom or molecule is called an ion.

Units of radioactivity and radiation dose

Quantity	SI unit and symbol	Non-SI unit	Conversion factor
Radioactivity	becquerel, Bq	curie, Ci	1 Ci = 3.7 x 10^{10} Bq = 37 GBq = 37000 MBq 1 Bq = 27 picocurie (pCi)
Absorbed dose	gray, Gy	rad	1 rad = 0.01 Gy
'Dose' (Equivalent dose)	sievert, Sv	rem	1 rem = 0.01 Sv 1 rem = 10 mSv

1 becquerel (Bq) = 1 disintegration per second. One becquerel is a small amount of radioactivity. Commonly used multiples of the Bq unit are kBq (kilobecquerel), MBq (megabecquerel),and GBq (gigabecquerel). 1 kBq = 1000 Bq, 1 MBq = 1000 kBq, 1 GBq = 1000 MBq.

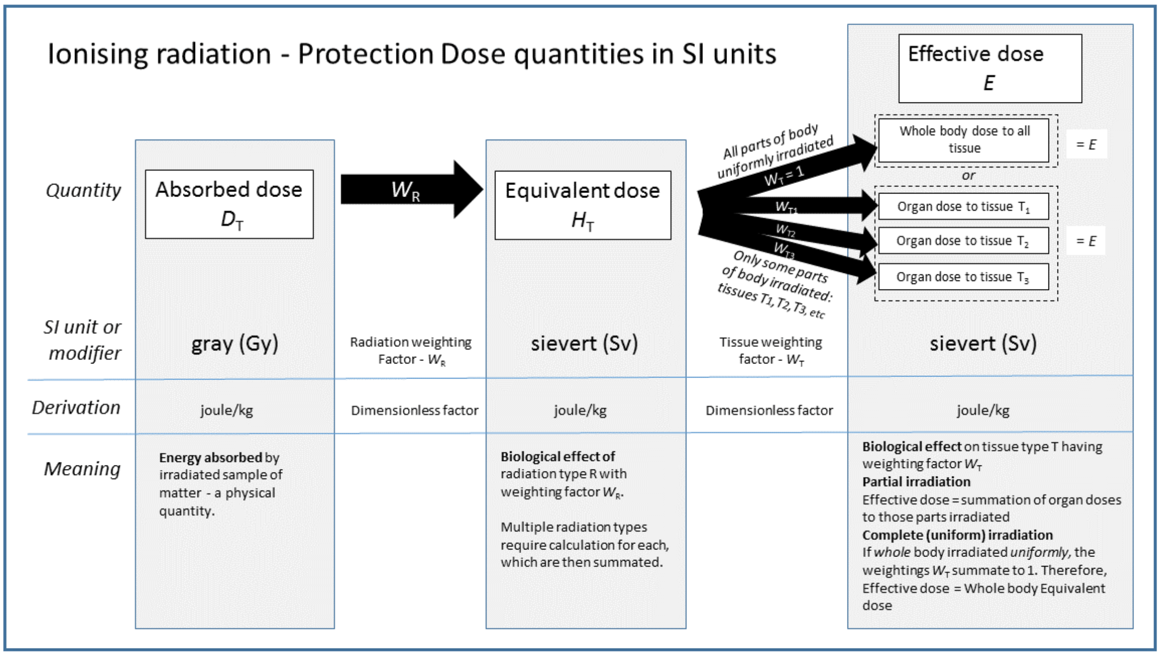
curie (Ci) - old unit of measuring radioactivity. Commonly used units are mCi (millicurie), µCi (microcurie), nCi (nanocurie) and pCi (picocurie). 1 Ci = 1000 mCi; 1 mCi = 1000 µCi; 1 µCi = 1000 nCi; 1 nCi = 1000 pCi.

grey: measure of radiation energy deposited in matter (old units 100 R(approx) = 100 rad = 1 Gy).

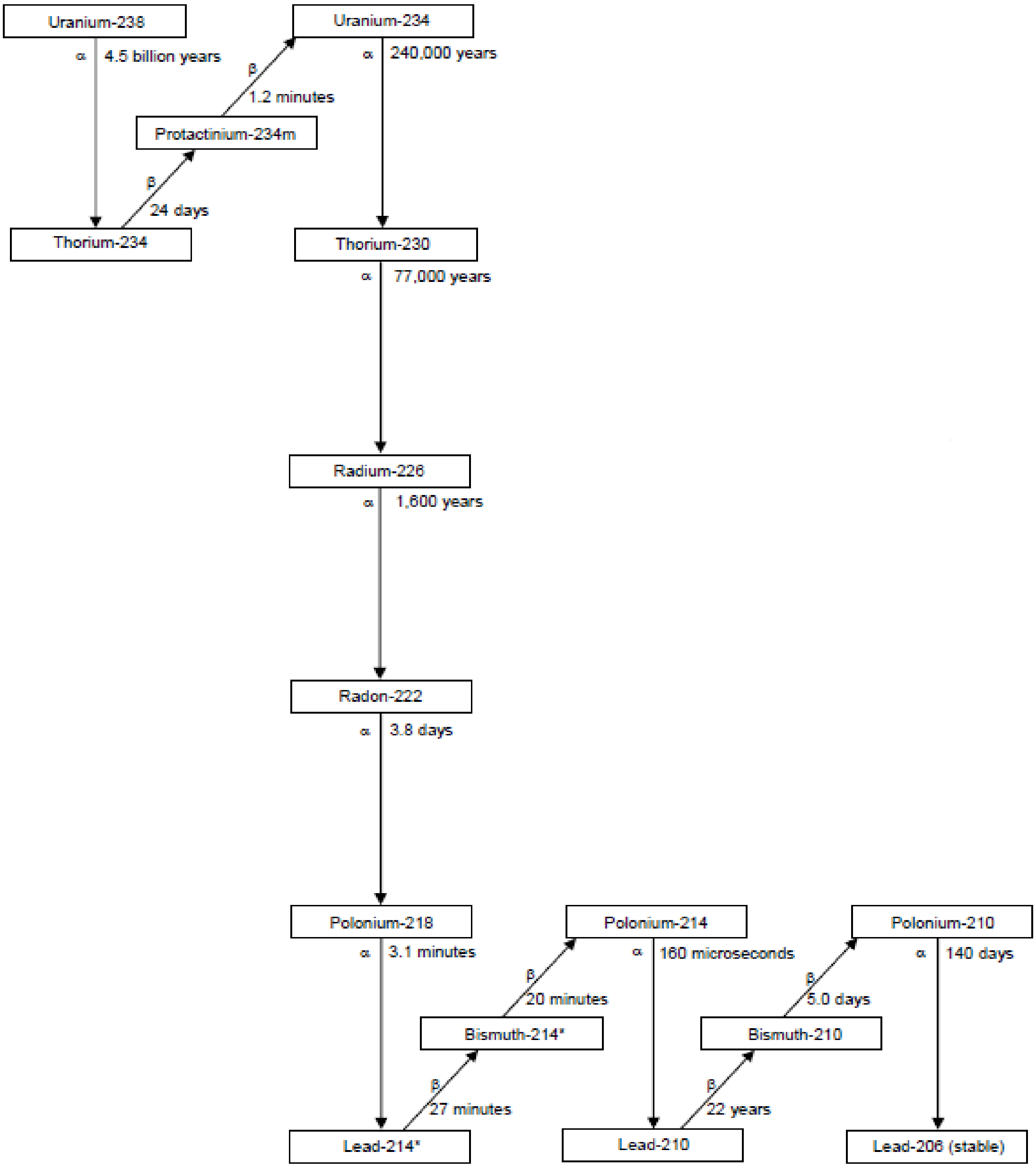
sievert: measure of biological impact of deposited radiation dose – depends on type of radiation, (1 Gy (gamma or beta) = 1 Sv (= 100 rem), 1 Gy (alpha) = 20 Sv.

dose: exposure to radiation over time; effective dose (Sv, usually reported in milli-sieverts (mSv) = 1/1000 Sievert): considers sensitivity of all body organs to radiation and is measure of total radiation impact (internal and external) – dose used in regulatory limits.

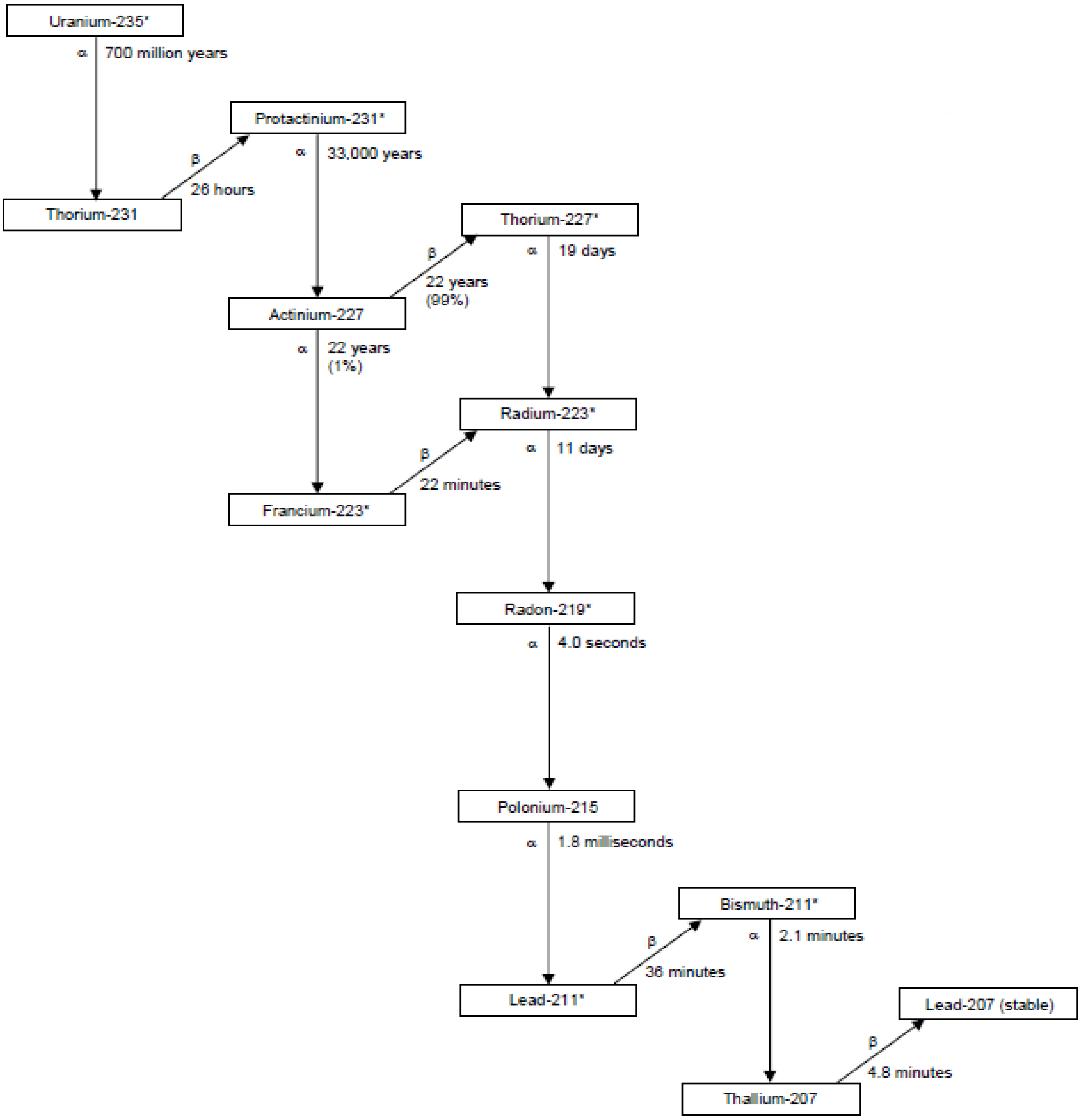
Dose quantities. Source: http://en.wikipedia.org/wiki/Sievert


Ionising radiation - Protection Dose quantities in SI units
Quantity
Absorbed dose D_T
W_R
Equivalent dose H_T
All parts of body uniformly irradiated
$W_T = 1$
W_{T1}
W_{T2}
W_{T3}
Only some parts of body irradiated: tissues T_1, T_2, T_3, etc
Effective dose E
Whole body dose to all tissue
= E
or
Organ dose to tissue T_1
Organ dose to tissue T_2
Organ dose to tissue T_3
= E
SI unit or modifier
gray (Gy)
Radiation weighting Factor - W_R
sievert (Sv)
Tissue weighting factor - W_T
sievert (Sv)
Derivation
joule/kg
Dimensionless factor
joule/kg
Dimensionless factor
joule/kg
Meaning
Energy absorbed by irradiated sample of matter - a physical quantity.
Biological effect of radiation type R with weighting factor W_R.
Multiple radiation types require calculation for each, which are then summated.
Biological effect on tissue type T having weighting factor W_T
Partial irradiation
Effective dose = summation of organ doses to those parts irradiated
Complete (uniform) irradiation
If whole body irradiated uniformly, the weightings W_T summate to 1. Therefore, Effective dose = Whole body Equivalent dose

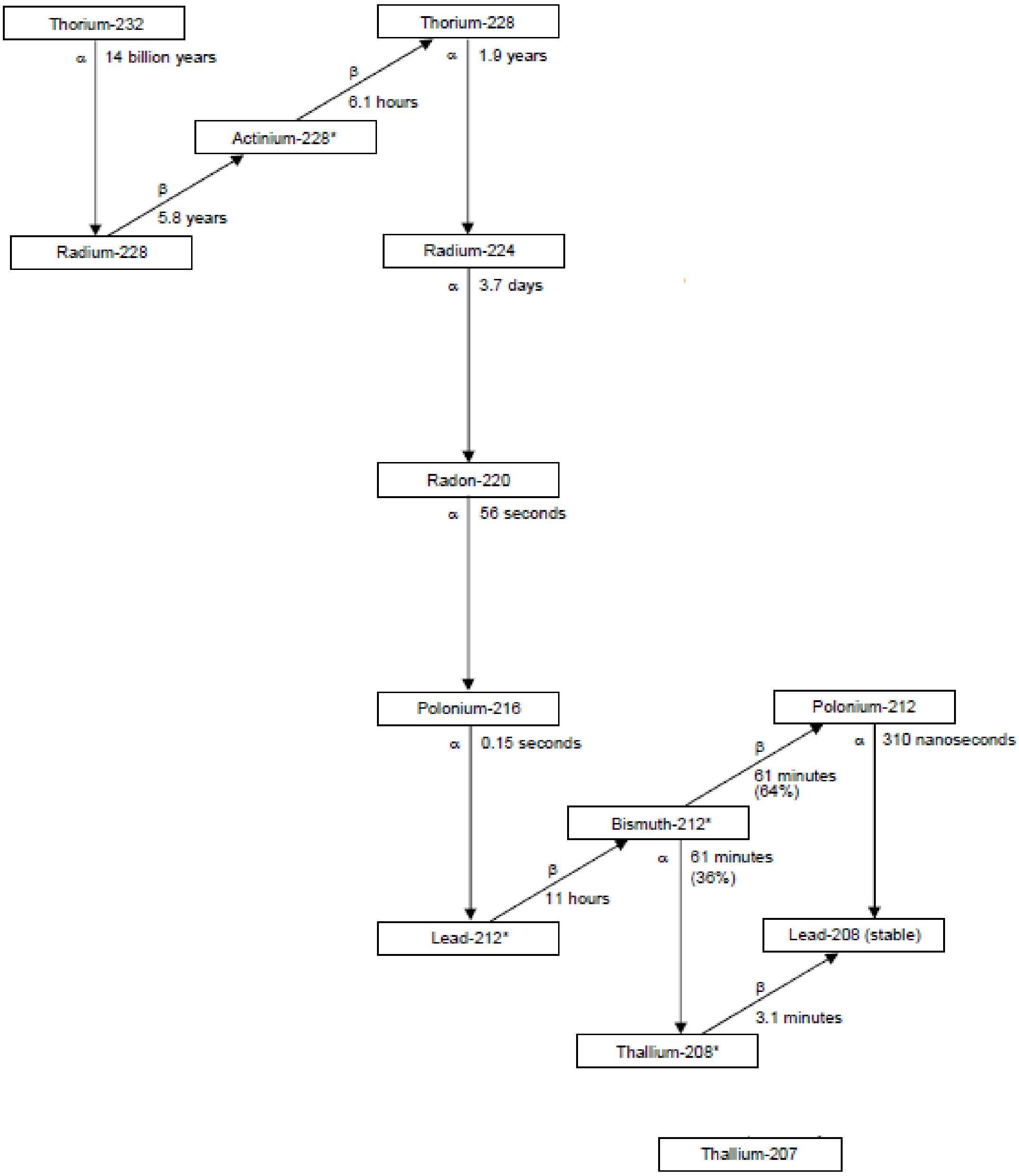
Uranium – 238 Decay Series. α and β show alpha and beta decay and the asterisk indicates that the isotope is also a significant gamma emitter. The times shown are the half-lives. Half-life is defined as the time it takes for one-half of the atoms of a radioactive material to disintegrate. Half-lives for various radioisotopes can range from a few microseconds to billions of years.



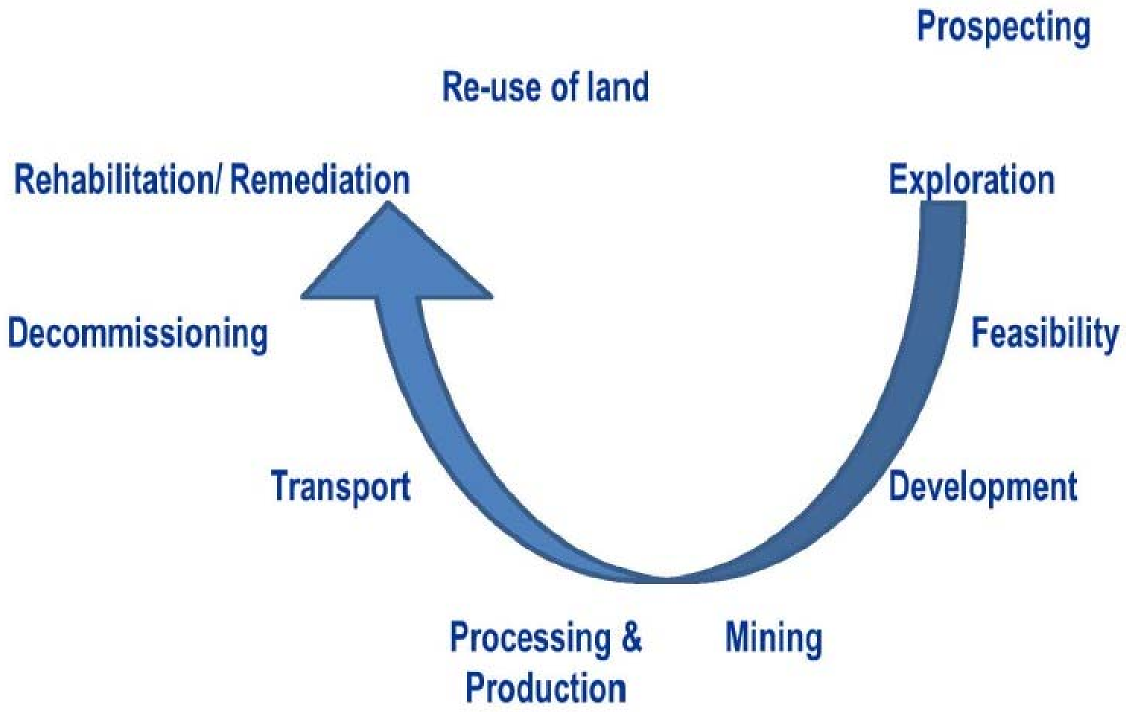
Uranium – 235 Decay Series. α and β show alpha and beta decay and the asterisk indicates that the isotope is also a significant gamma emitter. The times shown are the half-lives. Half-life is defined as the time it takes for one-half of the atoms of a radioactive material to disintegrate. Half-lives for various radioisotopes can range from a few microseconds to billions of years.

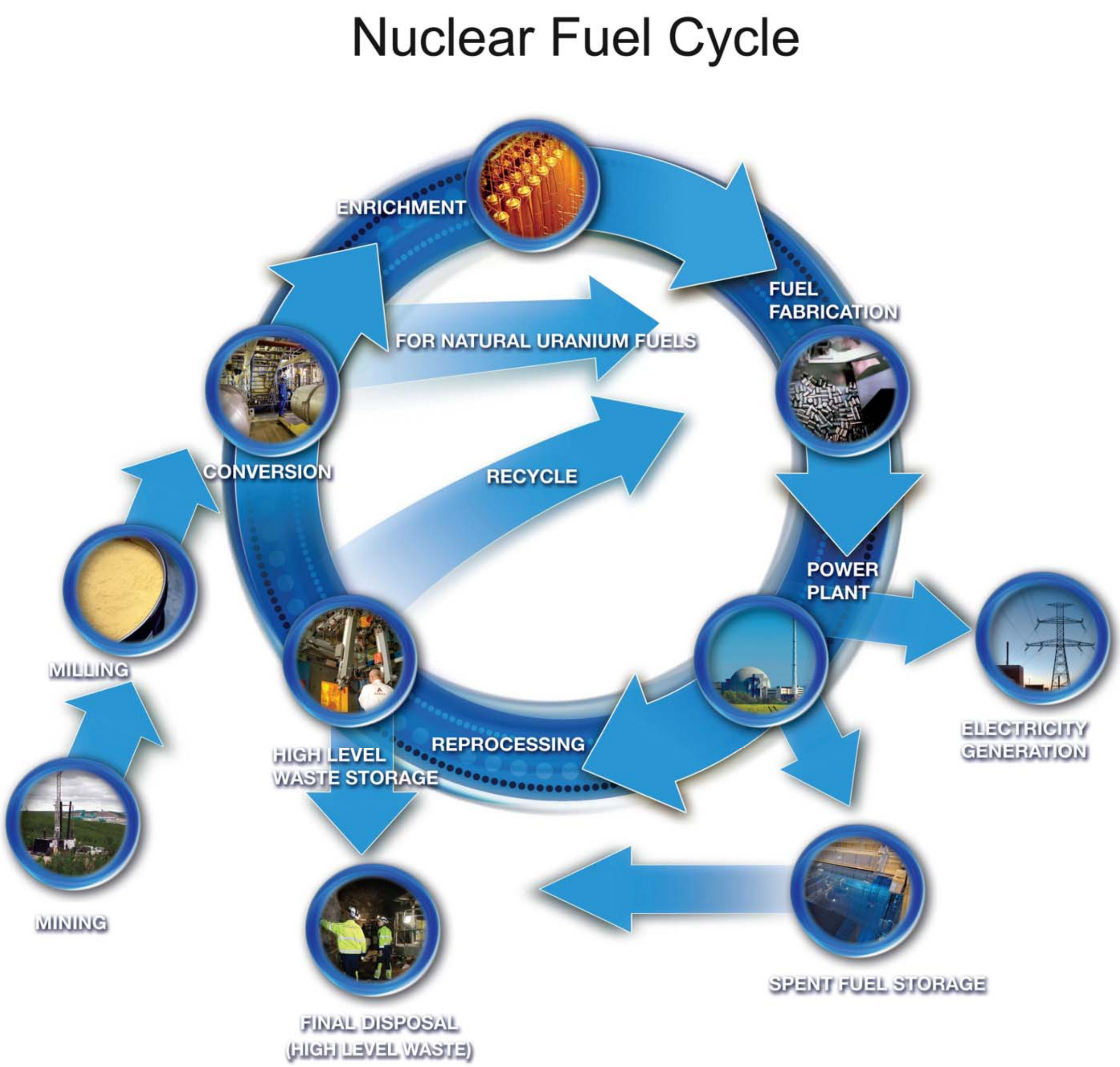


Thorium – 232 Decay Series. α and β show alpha and beta decay and the asterisk indicates that the isotope is also a significant gamma emitter. The times shown are the half-lives. Half-life is defined as the time it takes for one-half of the atoms of a radioactive material to disintegrate. Half-lives for various radioisotopes can range from a few microseconds to billions of years.



Uranium Production Cycle





Source: http://www.iaea.org/OurWork/ST/NE/NEFW/Technical-Areas/NFC/images/nfc-image-big.jpg

Appendix K

Peer review

This report was peer reviewed by:

Kevin H. Scissons

Mr. Kevin H. Scissons is a radiation / mining senior environmental scientist. Mr. Kevin H. Scissons have worked more than 21 years for the Canadian Nuclear Safety Commission, (CNSC / AECB), including 8 years as Director of the Uranium Mines and Mills Division, and in the last year at CNSC as Strategic Advisor. Duties including reviewing and proposing modifications / update to the Uranium Mines and Mills Regulations; compliance and licensing activities for operating or decommissioned uranium mines and mills in Saskatchewan, assessing the proposals for any other new uranium mines throughout Canada, public outreach and training (CNSC 101); Public Information Meetings; international training and workshops on regulating uranium mines and mills with the US NRC, and the IAEA (i.e., Texas, Vienna, Tanzania); harmonizing regulatory processes with other federal and provincial agencies.

Peter W. Waggitt

Mr. Peter W. Waggitt has over 40 years of professional experience as an environmental scientist and engineer dealing with issues of environmental protection and remediation. For the past 25+ years this activity has been in the context of regulating uranium mining, including conducting audits, field investigations and inspections dealing with issues of exploration, operations, waste management and remediation at active, rehabilitating and abandoned uranium mines; also, more recently, dealing with issues of radioactive waste management involving naturally occurring radioactive material (NORM). This experience has been accumulated in a wide range of climatic zones and cultural settings, working with colleagues and clients from many races, religions and cultures including Traditional Aboriginal landowners in Australia and local populations in Central Asia, Africa and Latin America. Considerable experience as a team leader and project manager for international studies and technical assistance programs. Periodically acted as an Assistant Secretary in the Australian Federal Environment Department, also a Government representative at national and international meetings in Australia and overseas; also worked with the International Atomic Energy Agency of the United Nations (IAEA) on document preparation and training in Vienna and overseas. For 2003 and 2004 he was elected to the Board of Chartered Professionals for Australasia and was Vice Chair of the Board for 2004. The author of more than 60 technical papers, conference presentations and major reports. A staff member at IAEA in Vienna from 2004 to 2008 as a Waste Safety Specialist dealing with decommissioning and residue safety in relation to NORM, uranium mining and depleted uranium; duty stations were in Central Asia, North and South America, Africa, the Middle East, Far East and Europe. After retirement in March 2008, he remained as a full-time consultant with the IAEA until May 2011 working on uranium production cycle issues, primarily involved in providing technical assistance and training throughout Asia, Africa and Latin America. In June 2011 he was appointed Assistant Director - Mining Environmental Compliance and Chief Mining Engineer in the Department of Resources of the Northern Territory Government, Australia managing teams regulating all environmental aspects of mining and exploration of all minerals, as well as extractive operations. Peter has also resumed duties as a member of the Board of Chartered Professionals. In July 2013 Peter was appointed Director Mining Compliance in the re-named Department of Mines and Energy.

All the comments and recommendation was considered by the authors and are included in the report.

EXPLOITATION OF RADIOACTIVE MINERALS IN GREENLAND

Management of environmental issues based on experience from uranium producing countries

This report provides an overview of the most common potential impacts associated with uranium mining and milling activities and general management strategies targeting identified environmental issues in order to protect the environment now and in the future. The report include also international best practices for environmental and radiation protection and worldwide current legislation, regulation and guidelines.

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