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Review

Permanent underground repositories for radioactive waste

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Abstract

Solid radioactive waste first entered a deep geologic repository in 1959. Liquid radioactive waste has been injected into confined underground reservoirs since 1963. Solid wastes containing chemically toxic constituents with infinite half lives have been isolated underground since 1972. Performance to date of these and other repositories has not caused any of their owners and operators to transfer or contemplate transferring the waste confined in them to presumably safer locations. Natural and engineered analogues offer sound evidence that deep geologic isolation is effective, safe, and compatible with responsible environmental stewardship. Underground isolation of dangerous, including radioactive, wastes is therefore increasingly being used as a safe and reliable method of final disposal.
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Keywords: Radioactive waste; Permanent isolation; Underground repositories; Analogues; Disposal experience

1. Introduction

This brief technical review highlights actual underground repositories for radioactive waste in several countries. Their mission is permanent disposal, not just temporary or easily retrievable storage or research. Facility descriptions are set against the background of past and current disposal practices for dangerous (chemotoxic or radiotoxic, or both) wastes and of natural and engineered analogues. The discussion continues with sketches of projects currently under development and expected to start operating in the near future. The most-studied repository to date (WIPP) serves as a brief case study on evaluating actual and perceived risks to permanent isolation of dangerous waste. The review concludes that past and current performance of analogues and actual repositories justify confidence in the future application of underground disposal as an effective and safe technology for permanent isolation of radioactive waste from our environment. Internet sources at the end of this article provide easy gateways to more comprehensive information (Appendix).

In accordance with the policy of this journal, the text uses SI units consistently. Bequerel (Bq) is the SI unit equivalent to Curie (Ci) still in widespread use in USA. 1 Ci = 37 GBq (37E9 Bq) or 1 Bq = 27 pCi (27E−12 Ci).

Distinctions between low-, intermediate-, and high-level waste categories are not clear and consistent internationally. Classification schemes may be based on half-life, activity, origin or source, degree of isolation required, etc. In general, low-level waste contains radionuclides with low activities and short half lives and generates no heat. Intermediate waste may contain radionuclides with low to intermediate activities and short to long half lives, generating no

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to negligible heat. High-level waste contains radionuclides with high activities, long or short half lives or both, and generates heat.

2. Past and current uses of engineered underground space relevant to deep geologic waste isolation

Underground space can be a valuable commodity. Underground openings, whether large individually engineered cavities or the small but multitudinous natural voids in reservoir rocks, have temporarily or permanently accommodated water, brine, liquid and gaseous hydrocarbons, compressed air, and dangerous materials.

Excavations in low-permeability crystalline basement rocks, e.g., gneiss and granite, are currently being used to dispose of some categories of radioactive waste. Former limestone and uranium mines are serving the same purpose. Other media that may host radioactive waste in the future include claystone (argillite) and welded volcanic tuff.

Thick, geologically old rock salt is another confinement medium suitable for permanent waste isolation. Its enduring presence is evidence of long-term, in practical terms indefinite, regional stability. Salt is impermeable and easy and safe to mine. Deep excavations in salt close gradually by viscoplastic deformation (creep), encapsulating and isolating anything placed inside. Mined spaces in rock salt and its close relative, potash, have hosted chemotoxic and radiotoxic wastes for several decades.

The variety of host rocks that has been used and is being considered for future repositories indicates that in reality no particular material is necessarily ideal or best; however, several media are considered to perform quite satisfactorily, whether for low- to intermediate- or high-level radioactive wastes (Witherspoon and Bodvarsson, 2001).

3. Analogues for underground isolation – natural and engineered

Acceptance of the concept of permanent deep geologic waste isolation depends fundamentally on our ability to identify, study, and correctly interpret repository analogues. A multitude of suitable analogues is available.

Hydrocarbon reservoirs, for example, prove that natural geologic formations, even without any human assistance, can be perfectly capable of isolating highly volatile and flammable fluids underground for hundreds of millions of years.

Carbon dioxide, liberated from magma and then trapped under high pressure in intercrystalline voids next to vertical igneous dikes that intruded 30 million years ago into horizontal 250+ million year-old salt and potash seams in Germany and the US, demonstrates the impermeability of rock salt even to gas for several tens of millions of years (Knipping, 1989).

Intracrystalline inclusions and intercrystalline pockets in undisturbed rock salt contain saturated brines, each with a different chemical composition, a unique isotopic ratio, and a distinct and specific pressure. These discrete brine occurrences constitute convincing evidence for the tightness of the salt: what little formation fluid it contains has not become homogenized by internal or external force and has therefore remained isolated for tens to hundreds of millions of years (Stein and Krumhansl, 1984).

By demonstrating the long-term lack of migration of fluids through, and away from, geologic formations considered or actually used as host rocks for underground waste repositories, natural analogues eliminate any reasonable doubt in the ability of the same rocks to permanently confine solid waste. Adding to this confidence is the knowledge that very little, if any, dangerous materials migrated from other well-studied natural analogues. They include many concentrations of otherwise mostly dissipated minerals and ores. Especially relevant to repositories of radioactive waste is, of course, the geologically (many hundreds of millions of years) long confinement of concentrated uranium deposits, e.g., Cigar Lake, Canada, and of natural nuclear reactors and their fission products, i.e., Oklo/Gabon in West Africa (Janeczek, 1999).

While natural analogues instill confidence in long-term repository safety over geologic spans of time, our confidence in satisfactory short-term operational and intermediate-term post-closure performance is bolstered by engineered analogues.

Examples include geologic repositories in salt in Germany for chemically hazardous waste, e.g., Herfa (since 1972) (Boraiko, 1985), Heilbronn (since 1992), and Zielitz (since 1995) – compiling a successful operating record of several decades – and artifact preservation in ancient salt mines, e.g., Wieliczka, Poland, and Hallstatt, Austria, with records spanning hundreds to thousands of years.

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We gain additional confidence in the long-term isolation capability of geologic media by comparing the miniscule hypothetical release potential of radioactive waste repositories with the negligible actual consequences of worst-case engineered analogues such as underground nuclear detonations, e.g., Project Gnome, a Plowshare Series experiment to test the civilian application of nuclear explosives (Rempe, 1998).

In combination, the lessons learned from natural and engineered analogues give every indication that permanent underground disposal can provide excellent isolation from the accessible environment for a variety of dangerous materials.

4. Currently and previously active underground repositories isolating radioactive waste

Underground isolation of dangerous wastes has been practiced safely for about half a century. A few examples are fairly well-known in the international peer community, while others are virtually unknown (Table 1). Past and current repositories for radioactive waste have thus far been limited to accepting low- and intermediate-level waste categories. They are described in the order of their opening dates, beginning with the earliest. After almost 50 years of disposal experience, none of their initial essentially qualitative assessments of satisfactory future performance have been disproved. Performance to date of these repositories has not caused any of their operators to move the waste contained in them to presumptively safer locations.

4.1. 1959-Hostim

Czechoslovakia used two chambers with a total volume of about 1600 m^3 in a limestone mine dating from the 1940s near the village of Hostim in central Bohemia to dispose of approximately 400 m^3 of low- and intermediate-level waste about 30 m below the surface. Operations lasted from 1959 to 1965, after which both chambers were backfilled with specially formulated concrete. Total activity was less than 0.1 TBq (SUJB, 2005). The repository was decommissioned in 1997.

4.2. 1963-Russian deep well injection of liquid waste

The Soviet Union injected close to 50 million m^3 of radioactively contaminated liquids, much of it reprocessing waste, mostly into confined sandstone layers several 100 m below the surface in three locations. Physical and chemical interactions between waste fluids and host rocks contribute to radionuclide isolation. Extensive networks of monitoring wells document effective confinement in areas and volumes of limited extent (Rybal'chenko et al., 1998). Disposal operations at these Russian sites continue and appear feasible for several additional years or possibly decades.

4.2.1. Zheleznogorsk (also referred to as Krasnoyarsk-26, Mining and Chemical Combine, MCC, or Severny)

Deep well injection of liquid radioactive waste started at Zheleznogorsk, north of Kransnoyarsk, in 1967. Two aquifers consisting of weakly cemented quartz–feldspar gravels, sands, and sandstones, separated by impermeable clays, serve as disposal media. Low-level waste was injected 180–280 m deep, intermediate- and high-level waste 355–500 m deep. Monitoring wells delineate the lateral extent of the aquifers affected by the injection to be about

Table 1
Currently and previously active deep geologic repositories for radioactive waste

Repository	Host rock	Operation
Hostim (CZ)	Limestone mine	1959–1965
Russian injection (RUS)	Clastic sediments	Since 1963
Richard (CZ)	Limestone mine	Since 1964
Asse (D)	Salt/potash mine	1967–1978
Bratrstvi (CZ)	Uranium mine	Since 1974
Morsleben (D)	Salt/potash mine	1978–1998
Forsmark (S)	Crystalline basement	Since 1998
Olkiluoto and Loviisa (FIN)	Crystalline basement	Since 1992/1997
WIPP (USA)	Salt	Since 1999

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3 km^2. Independent experts, including western scientists, investigated the site and concluded that the disposal system is performing well, i.e., waste is very unlikely to reach the surface before constituents of concern are reduced to concentrations far below those acceptable for drinking water (Compton et al., 2000).

4.2.2. Tomsk (also referred to as Siberian Chemical Combine, SCC, or Seversk)

Two horizons have been used at three injection locations and depths (349–386 m, 314–341 m, and 270–320 m below the surface) since 1963.

4.2.3. 1966-Dimitrovgrad (also referred to as NIIAR or Scientific and Research Institute of Nuclear Reactors)

This is the deepest of the three deep well injection sites. Relatively small volumes were disposed of 1440–1550 m deep and 1130–1410 m deep since 1966.

4.3. 1964-Richard

Czechoslovakia commenced underground disposal of radioactive waste in 1964 in the Richard former limestone mine, up to 70 m below the surface near the northern Bohemian town of Litomerice. A 5-m thick limestone bed, enclosed in a 50-m thick layer of impermeable marl, hosts the repository. Limestone extraction at the site had started in the mid-19th century. About 2700 m^3 consisting of 25 000 waste packages containing 10^{15} Bq have been filled, which leave about 3800 m^3 for future needs (Haverkamp et al., 2005). Capacity could be expanded another 2800 m^3 (Laciok et al., 1996). The repository accepts so-called institutional waste, derived from medical, industrial, research, and agricultural applications. Waste forms include radioactive sources and contaminated clothing, paper, and instruments. Projecting current trends into the future, the repository may continue operating until about 2070.

4.4. 1967-Asse

While the former salt mine Asse in north-central Germany is not a de-jure radioactive waste repository for political and historical reasons, it fulfills the de-facto technical criteria. Salt mining since the early part of the 20th century left behind huge underground chambers, some of which were filled with low- and intermediate-level radioactive waste between 1967 and 1978. In total, the repository contains about 125 000 drums of low-level waste 725 m and 750 m below the surface, and about 1300 drums of intermediate-level waste 511 m below the surface (Brewitz and Rothfuchs, 2007). The gross container volume is about 47 000 m^3, with a mass of about 90 000 tons. The total activity inventory at the time of disposal was about 7.8E15 Bq.

Still open chambers are gradually being backfilled with mined salt, an effort that began 1995. Current expectations are that the Asse will be decommissioned by 2013.

4.5. 1974-Bratrstvi

In 1974, Czechoslovakia began to dispose of waste containing naturally occurring radionuclides in five chambers of an abandoned underground uranium mine near the northern Bohemian town of Jachymov. Almost 1000 m^3 of space excavated in metamorphic rocks was originally available. In 2001, the repository was reported to contain 700 drums (IAEA, 2001). It may continue to operate until about 2030.

4.6. 1978-Morsleben

East Germany started disposal of low- and intermediate-level radioactive wastes in the Morsleben former potash and salt mine (also referred to as ERAM) in 1978. Excavation since the late 19th century had left behind a three-dimensional maze of underground space. Disposal operations about 500 m below the surface were interrupted from 1991 to 1994 to conduct a technical re-evaluation after the re-unification of Germany and ceased in 1998 (Eilers et al., 2003). The repository contains 36 752 m^3 solid and originally liquid – but solidified during disposal – waste and 6621 radiation sources. Total activity amounts to 3.8E14 Bq from beta and gamma and 2.3E11 Bq from alpha radiation.

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To enhance the stability of the mine and repository, the project backfilled some of the unused chambers (20 000 m^3) with mined salt. Twenty more chambers (about 700 000 m^3) are to be filled with a specially formulated concrete by 2010. Final closure of the repository is expected beyond 2010.

4.7. 1988-Forsmark

The Swedish Final Repository (SFR) near Forsmark in southern Sweden has operated since 1988. The facility consists of four horizontal chambers for low-level waste and one vertical silo for intermediate-level waste that were specifically excavated in metamorphic bedrock a minimum of 50 m below the Baltic Sea. Two inclined tunnels provide access from dry land nearby. Total capacity is t 63 000 m^3, which is being filled at an annual rate of about 1000 m^3 (Wikström, 1998). A second phase of excavation may add 30 000 m^3 capacity, and a third phase another 100 000 m^3.

4.8. 1992-Olkiluoto and 1997-Loviisa

Two repositories have been operating in Finland since the 1990s, both accommodating low- and intermediate-level waste. The Olkiluoto facility started first, in 1992, and the Loviisa facility followed in 1997. Both were excavated in crystalline bedrock, 70–100 m below the surface. They are accessed from the surface by both inclined tunnels and vertical shafts. Olkiluoto's design capacity is about 8000 m^3, while Loviisa's is about 4000 m^3. By the end of 2004, Olkiluoto had received 4140 m^3 and Loviisa 1234 m^3 (OECD/NEA, 2005). Both repositories are expected to operate for about 40 years.

4.9. 1999-WIPP

The Waste Isolation Pilot Plant (WIPP) near Carlsbad in southeastern New Mexico started in 1999 to dispose of intermediate-level (transuranic) radioactive waste contaminated with radionuclides that have long half lives. About 60% of the waste is so-called mixed waste, i.e., waste that, in addition to radionuclides, contains chemically toxic or hazardous constituents. The repository horizon lies in the middle of a huge rock salt formation, 655 m below the surface (USDOE/CAO, 2000). WIPP does not use a former mine but was, and continues to be, excavated exclusively for waste disposal. Design capacity is 175 000 m^3, of which more than 25% have been filled. Current law allows disposal of only defense (nuclear weapons)-related waste with negligible heat generation.

5. Underground repositories under development

Several deep geologic repositories for radioactive waste, mostly for high-level waste and spent nuclear fuel, are either in the planning stage, or under active investigation in underground research laboratories, or in various stages of realization (Table 2).

5.1. Finland

In 2001, Finland selected a repository location in Eurajoki, close to the Olkiluoto nuclear power plant, for disposing of spent nuclear fuel. Site-specific confirmatory research, started in 2004 and expected to be completed by 2010, is being conducted at the Onkalo underground laboratory at the same location (Äikäs et al., 2003). The laboratory will likely become incorporated into the eventual repository, which is planned to accommodate 6500 tons. The design uses cast-iron cylinders surrounded by oxygen-free copper, inserted into holes into the walls of underground excavations. The annuli between canisters and the walls of the holes are to be filled with bentonite. Construction of the repository is scheduled for 2010 through 2020, with first disposal operations immediately following.

5.2. France

Near Bure in Lorraine, 45 km south of Bar-le-Duc, France investigates a claystone (argillite) formation of 130 m thickness, between 420 m and 550 m below the surface, for its potential to host high-level and long-lived

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Table 2
Radioactive waste repositories under development

Project	Host rock	Status
Finland-Onkalo	Crystalline basement	Active R&D
France	Claystone/argillite	Active R&D (Bure)
Germany-Gorleben	Salt	Suspended R&D
Germany-Konrad	Iron ore mine	Inoperative permit
Sweden	Crystalline basement	Active R&D
USA-Yucca Mountain	Volcanic tuff	Active R&D

intermediate-level radioactive waste. The underground research laboratory consists of vertical shafts and horizontal drifts, as well as experimental alcoves (Verstricht et al., 2003). Construction started in 2000, and an international peer review in 2003 revealed no ''showstoppers''. Direct experiments in the host formation itself started in early 2004. Current French regulations do not allow waste disposal in research laboratories; therefore, if the laboratory validates the concept of disposal in claystone, a separate repository must arguably be built.

5.3. Gorleben (Germany)

For two decades, the Gorleben salt dome in north-central Germany had been investigated for its suitability to host all categories of radioactive waste, prominently among them heat-generating high-level waste. This work included the sinking of two shafts and the excavation of exploratory drifts about 850 m below the surface. During all this time, no evidence had came to light that would render the site unsuitable (Lempert, 1998). In the face of that positive record, the then German (red/green) administration in 2000 suspended all further work, supposedly for three to ten years, but in effect indefinitely. The facility has since been maintained in mothballs.

5.4. Konrad (Germany)

The Konrad repository for waste with negligible heat generation was permitted in 2002 but has not yet started accepting waste because of judicial and political hurdles. Old iron ore mine workings (active 1957–1976) between 800 and 1300 m deep near Salzgitter, Germany, are isolated from groundwater horizons by impermeable claystone and marl layers. Original plans called for a capacity of 600 000 m^3, but the currently inoperative license allows the disposal of only 303 000 m^3 (Biurrun and Hartje, 2003). If Konrad receives an executable permit soon, it is expected to operate until about 2080.

5.5. Sweden

Two sites in crystalline bedrock are being studied for their suitability to host a repository for spent nuclear fuel about 500 m deep. Specific site investigations continue to be aided by research results from the Äspö Hard Rock Laboratory. The disposal concept calls for copper-clad iron canisters to be inserted into horizontal or vertical holes, with a bentonite buffer placed between the canister and the surrounding rock (Pettersson and Widing, 2003). Final site selection is currently expected by about 2010, to be followed by repository construction and the start of disposal operations by 2020. The repository is intended to accommodate about 4500 canisters and expected to accept about 200 canisters per year.

5.6. Yucca Mountain (USA)

Yucca Mountain northwest of Las Vegas, Nevada, consists of volcanic tuff. This site adjacent to the Nevada Test Site has been evaluated since 1978 for its suitability to host an underground repository for heat-generating high-level radioactive waste and spent nuclear fuel from both, civilian and military applications (MacFarlane, 2003). The proposed repository horizon differs from other planned and actual repositories worldwide by lying about 300 m above the groundwater table; however, this difference appears not to confer any general advantage or disadvantage.

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Corrosion-resistant container alloys and titanium drip shields above the emplaced containers are expected to ensure that the little water that may percolate down from the desert floor above does not compromise effective isolation of the waste.

Beginning in 1993, more than 8 km exploratory tunnels were excavated to study the underground environment. Starting at the surface, they ramp down below the surface as deep as 300 m.

The US Congress limited the capacity of the Yucca Mountain repository to 70 000 metric tons. From a purely technical perspective, Yucca Mountain's capacity could probably be expanded significantly. A current estimate is that the repository may open about 2020.

6. Risk perception versus reality of disturbing underground waste repositories

Intensive studies, sophisticated models, and performance assessment calculations endeavor to demonstrate that waste repositories are unlikely to release harmful constituents in concentrations of concern for virtually indefinite periods of time – say between 10 000 and one million years. Analogues certainly indicate the feasibility of satisfactory permanent isolation, assuming no inadvertent human intrusion. Potential future exploration for, and production of, known mineral resources at or near a repository site is sometimes assumed to increase the risk of such a breach. US regulations address this issue by requiring that other favorable characteristics must outweigh the perceived weakness of a site containing known natural resources.

6.1. WIPP case study

For WIPP, inadvertent intrusion by drilling is the only barely credible scenario that could potentially cause the release from the repository of waste constituents in concentrations of regulatory concern. The facility is situated in an area rich in a variety of natural resources. These range from near-surface caliche, through potash seams 420–540 m deep, to hydrocarbon reservoirs 1400 m to more than 7000 m deep. To mitigate concerns expressed by regulators and oversight groups, any mining and drilling within the 42 km^2 area dedicated to WIPP is prohibited. The likelihood of the inadvertent human intrusion scenario becoming a reality is further reduced to an almost negligible chance by a variety of preventive administrative, institutional, and engineering measures.

Protective measures against unintentional WIPP penetration include the placement of project records into local, state, national, and international archives, as well as the construction of permanent surface markers. These will be massive monuments, engineered to last thousands of years, and inscribed with messages in symbols and several languages. Future generations will therefore be able to decipher these "Rosetta Stones" even if all knowledge of one or more of the languages used becomes lost.

6.2. Alternative mitigation possibilities

An alternative resolution to the perceived conflict between waste isolation and the potential for resource extraction might be to actually encourage carefully controlled drilling and mining before repository closure, in order to reduce the incentive for future intrusion. Oil and gas below a disposal horizon could be reached by inclined drilling from outside the disposal area footprint. Mining of ore zones above a disposal horizon concurrent with repository operation could, besides eliminating the incentive for later mining, provide underground space for emplacement of warning markers, disincentives, and possibly even obstacles to repository penetration.

6.3. Principal uncertainties

Alternative mitigation may appear an eminently rational alternative to the currently mandated approach. But neither it nor any other precautionary measures could possibly address the one characteristic that is generic to any repository site (be it located in an area of presently known natural resources or not): we are in no position to even guess the kind of materials future generations will consider as valuable natural resources. Neither hydrocarbons, nor potash, nor a variety of other naturally occurring materials were considered as natural resources as

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few as 200 years ago. Repository performance assessments, by comparison, try to look many thousands to one million years ahead.

In light of our fundamental ignorance about the material needs of our descendants, it is impossible to try to predict the lesser or greater likelihood of human intrusion into one particular site compared with any other. Besides, underground isolation is in any case much safer in the long run than storage at or near the surface. There, exposure to the elements is a virtual certainty, and the risk of human interference is very high.

7. Conclusion

In theory and practice, geologic isolation of radioactive waste is a safe, environmentally sound, and permanent solution. This conclusion is based on natural analogue performance (in some cases over billions of years) and operating experience (several decades, with no cogent case for retrieval and alternative disposal paths). Materials are recycled into the lithosphere in a carefully planned and engineered way. The range of feasible technologies is broad and international, as illuminated by two repositories near homonymous towns.

The modern nuclear age arguably started at Jachymov (formerly Joachimsthal), Bohemia (Czech Republic). Its mines provided the pitchblende uranium ore, from which Mme. Curie isolated radium. Jachymov lies a short distance north of Karlovy Vary (formerly Karlsbad). Wastes created by the nuclear age are interred in final resting places not far from the old Karlsbad (Bratrstvi) in Europe and the new Carlsbad (WIPP) in the USA.

More than half a century of actual data have shown that very different geologic and hydrologic regimes can isolate a variety of radioactive materials from natural and man-made sources. No need has been demonstrated to find alternatives to past or current underground repositories. Neither has evidence been produced to reconsider the lessons learned from analogue studies. Future applications can build on that positive record.

Acknowledgements

The bulk of this review is based on information available on the Internet. Colleagues contributed clarifications, details, and corrections. Remaining errors and omissions are my own.

I will always be grateful to the deep geologic waste disposal pioneers of Kali and Salz in Germany. My interest in the subject never waned since they allowed me to visit their Herfa repository in 1973.

Two fairly recent events give me great reason for optimism: The fall of the Berlin Wall and the Iron Curtain since 1989, and WIPP's opening for business in 1999. The opinions expressed in this review are mine and have not been reviewed or approved by anyone affiliated with WIPP.

Appendix. Recommended Internet information sources

US repository projects – official sites

Waste Isolation Pilot Plant (WIPP): http://www.wipp.energy.gov/
Yucca Mountain Project: http://www.ocrwm.doe.gov/ym_repository/index.shtml

Non-US repository programs

International: http://www.radwaste.org/disposal.htm
Finland: http://www.posiva.fi/englanti/index.html
France: http://www.andra.fr/publication/produit/Synthese-argile-VA.pdf
Germany: http://www.dbe.de/en/final-disposal/final-disposal-of-waste/index.php
Russia: http://www.iiasa.ac.at/Publications/Documents/RR-00-001.pdf
Sweden: http://www.skb.se/default2____16806.aspx

Commercial repositories for chemotoxic waste in salt

http://www.ks-entsorgung.com/willkommen_en.cfm
http://www.uev.de/eng/frame/frameset.html

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Natural and engineered analogues

Oklo
http://www.ocrwm.doe.gov/factsheets/doeymp0010.shtml
http://www.ans.org/pi/np/oklo/
http://www.physicscentral.org/action/2005/reactors-research.html
Strategic Petroleum Reserve
http://www.fe.doe.gov/programs/reserves/spr/spr-sites.html
Gnome/Plowshare
http://www.atomictourist.com/gnome.htm
http://www.wipp.energy.gov/science/UG_Lab/gnome/gnome.htm

Individual repositories

Asse
http://www.gsf.de/asse/index_en.phtml
http://www.umwelt.niedersachsen.de/master/C11961543_N11622631_L20_D0_I598.html
Morsleben
http://www.dbe.de/en/sites/morsleben/1/index.php
http://www.bfs.de/bfs/druck/broschueren/morsleben.html
Czech repositories
http://www.proe.cz/surao2/index.php?Lang=EN&c=86
http://www.vidivici.cz/surao2/watrp/13_concept_net.pdf
http://www-esd.lbl.gov/NW/international/wwr/wwr8.pdf
Swedish project
http://www.rhk.hu/english/quest3.htm
http://www.skb.se/templates/SKBPage___8735.aspx
http://www.nea.fr/html/ndd/reports/efc/efca04.pdf
Finnish project
http://www.world-nuclear.org/sym/2002/ryhanen.htm
http://www.posiva.fi/englanti/tutkimus_esittely.html
Russian liquid waste injection
http://www.iiasa.ac.at/Research/RAD/previous.htm?sb=4
http://www.galson-sciences.co.uk/BORIS/
Yucca Mountain
http://www.nei.org/documents/YuccaResourceBinder/index.html

References

Äikäs, T., et al., 2003. Going underground in Finland: design of Onkalo in progress. In: Proceedings of Waste Management '03, Tucson.

Biurrun, E., Hartje, B., 2003. License for the Konrad deep geological repository. In: Proceedings of Waste Management '03, Tucson.

Boraiko, A.A., 1985. Storing up trouble…hazardous waste. National Geographic Magazine 167 (3), 336, 337, and 346.

Brewitz, W., Rothfuchs, T., 2007. Concepts and technologies for radioactive waste disposal in rock salt. Acta Montanistica Slovaca 12, 67–74.

Compton, K.L., et al., 2000. Deep Well injection of Liquid Radioactive Waste at Krasnoyarsk-26, vol. I. International Institute for Applied Systems Analysis, Laxenburg, Austria. RR-00-001.

Eilers, G., et al., 2003. Sealing of the Morsleben repository, Germany. In: Proceedings of Waste Management '03, Tucson.

Haverkamp, B., et al., 2005. Update of the safety assessment of the underground Richard repository, Litoměřice. In: Proceedings of Waste Management '05, Tucson.

IAEA, 2001. Report on the International Regulatory Review Team (IRRT) Mission to Czech Republic. IAEA. IAEA/NSNI/IRRT/01/3.

Janeczek, J., 1999. Mineralogy and geochemistry of natural fission reactors in Gabon. In: Reviews in Mineralogy, vol. 38. Mineralogical Society of America, pp. 321–392.

Knipping, B., 1989. Basalt intrusions in evaporites. In: Lecture Notes in Earth Sciences, vol. 24. Springer.

Laciok, A., et al., 1996. Geological disposal of radioactive waste in the Czech Republic. In: Witherspoon, P.A. (Ed.), Geological Challenges in Radioactive Waste Isolation – Second Worldwide Review. Lawrence Berkeley National Laboratory, pp. 77–85. LBNL-38195.

Lempert, J.P., 1998. Further development work for a future Gorleben repository. Nuclear Technology 121 (2), 221–226.

MacFarlane, A., 2003. Underlying Yucca Mountain – the interplay of geology and policy in nuclear waste disposal. Social Studies of Science 33 (5), 783–807.

Author's personal copy

OECD/NEA Committee on Radioactive Waste Management (RWMC), 2005. Radioactive Waste Management in Finland (Background Information). Available from: <http://www.stuk.fi/ydinturvallisuus/ydinjatteet/ydinjate/en_GB/ydinjate/_files/73810475841424335/default/radioactive_waste_management_in_finland.pdf> (accessed 05.04.07).

Pettersson, S., Widing, E., 2003. Development of the Swedish deep repository for spent nuclear fuel in crystalline host rock. In: Proceedings of Waste Management '03, Tucson.

Rempe, N.T., 1998. Negligible environmental consequences of confined underground nuclear detonations as positive, beyond-worst-case analogues for deep geologic waste isolation. In: Proceedings of DisTec '98, Hamburg, Germany, pp. 277–283.

Rybal'chenko, A.I., et al., 1998. Deep Injection Disposal of Liquid Radioactive Waste in Russia (translator B. Teague, US). In: Foley, M.G., Ballou, L.M.G. (Eds.). Battelle Press, Columbus.

Stein, C.L., Krumhansl, J.L., 1984. Compositions of Brines in Halite from the Lower Salado Formation, Southeastern New Mexico. SAND84–1252A. Abstracts with Programs. Geological Society of America. 99th Annual Meeting, Reno.

SUJB (State Office for Nuclear Safety), 2005. Czech Republic National Report under the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management, Revision 2.3. Available from: <http://www.sujb.cz/docs/NZ_VP_RAO_2_3_EN.pdf> (accessed 24.04.07).

US Department of Energy Carlsbad Area Office, 2000. Pioneering Nuclear Waste Disposal. US Department of Energy Carlsbad Area Office. DOE/CAO-00-3124.

Verstricht, J., et al., 2003. Repository concepts for nuclear waste disposal in clay formations. In: Proceedings of the Sixth International Symposium on Field Measurements in Geomechanics, Oslo.

Wikström, M., 1998. Radioactive Waste Management in Sweden – Experiences and Plans. Swedish Nuclear Fuel and Waste Management Co., Stockholm. Available from: <http://www.skb.se/upload/publications/pdf/wikstrom-cambridge-98.pdf> (accessed 05.04.07).

Witherspoon, P.A., Bodvarsson, G.S. (Eds.), 2001. Geological Challenges in Radioactive Waste Isolation – Third Worldwide Review. Lawrence Berkeley National Laboratory. LBNL-49767.