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Nuclear Waste Disposal in Underground Mined Space, Promise – Problems/Challenges – Solutions?

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Over fifty years ago, the U.S. National Academy of Sciences promulgated the concept of emplacing high level radioactive waste deep underground, thus providing a secure permanent disposal facility for these highly toxic materials. Decades of scientific and engineering investigations followed. The road towards permanent disposal has been a bumpy one indeed! While some success has been achieved, notably for the disposal of some transuranic wastes (WIPP, New Mexico), in several countries (e.g. the U.K., Canada, Germany, and most recently the U.S.) high level waste disposal programs have run into major, almost if not yet completely terminal difficulties.

It appears that the greatest obstacle to the implementation of programs for the underground disposal of high level nuclear waste has been strong, vehement, public opposition. Notwithstanding tremendous scientific and engineering efforts, convincing the public at large, the environmental communities, and the politicians has remained elusive. What lessons can be learned from the histories of these programs? Why did they fail? How can we do better in the future?

The waste problem obviously remains. High level radioactive waste is generated every day, at several hundred nuclear power plants around the world. All indications are that the number of such plants will increase, possibly increase sharply, in the foreseeable future, probably the relatively near future. (e.g. NAS (2008a), opening sentence of executive summary: *"The so-called nuclear renaissance has increased worldwide interest in nuclear power."*; NAS (2008b), opening statement of executive summary: *"There has been a substantial resurgence of interest in nuclear power in the united States over the past few years."*)

In the absence of starting up permanent disposal facilities, the only option for now clearly appears to be temporary storage. The "temporary" storage (50 years? 100 years? 300 years?) currently envisioned in multiple countries clearly is not a "permanent" solution, and certainly has considerable potential safety, cost, and security implications? Will the physicists succeed in eliminating or at least greatly reducing long term disposal requirements?

While high level radioactive waste unquestionably has generated the most demanding requirements for waste disposal, it is worthwhile noting, even though it is rather obvious, that modern societies generate vast amounts of waste, of a wide range of varieties, e.g. chemical industry wastes, mine wastes, municipal wastes. Hence the waste disposal issue is rather broad, affects all societies, and remains in need of solutions.

Promise: disposal of waste in underground mined space has attractive benefits, and deserves further investigation and implementation.

Problems/Challenges: a broad array of technical and scientific challenges need to be overcome in order to demonstrate that disposal of waste in underground mined excavations is feasible without undue harm or risk to society or to the environment. Technical problems include construction of waste facilities, but this certainly in this case

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is only the beginning. Of particular importance is to convincingly demonstrate that any emplaced waste can be contained and isolated for a very long period of time. Major directly involved sciences that need to be invoked in order to contribute to the demonstration that containment and isolation are possible are rock mechanics, hydrology, geophysics, structural geology, and geochemistry. Given the context of the present presentation, emphasis will be placed on rock mechanics and geological engineering aspects of underground waste disposal.

Solutions? Are there approaches we can implement in order to obtain acceptance? What might such approaches be??

Introduction – some history

Although the use of underground space for a variety of purposes has been practiced for millennia, formal and explicit recognition of underground space as a third dimension, with the potential for numerous applications and associated benefits has been boosted greatly over the last few decades. During the 1970's a series of meetings took place aimed at clarifying the numerous issues associated with underground space use, and aimed at promoting a more widespread understanding of the potential and benefits of underground space use (e.g. Baker et al, 1972; U.S. National Committee on Tunneling, 1974; Casey, 1975), culminating in Rockstore 77 (Bergman, 1978), the *First International Symposium* on "Storage in Rock Caverns." One of the subjects addressed in all these meetings and workshops was the potential for underground waste disposal, at the time virtually unanimously perceived as a very promising approach, with numerous benefits. Although it certainly was recognized that considerable research would be required to convincingly demonstrate that underground waste could be emplaced safely, and that waste could be permanently isolated, there clearly was considerable optimism about the practical feasibility of such demonstrations. Since those days, a proliferation of conferences, meetings, journals, and, most importantly, a wide range of practical implementations of underground space have taken place, and continue to occur, worldwide (e.g. Erdem and Solak, 2005; Barták et al, 2007). Although waste disposal usually is addressed in these more recent meetings, typically it is a minor component of the presentations and discussions. Waste disposal has taken on such a scope that it more likely is focused on in meetings specifically addressing waste disposal (e.g. Côme et al, 1985, Saeb and Francke, 1999). But for some applications, notably the underground disposal of high level radioactive waste, severe difficulties have been encountered, to the point where several such programs have been canceled, delayed greatly, started over again, replace by long term conventional on surface storage, etc... Although some lower level waste disposal programs have been successful, success can not be claimed for high level waste disposal. Given that high level waste exists, is being generated daily, around the world, and in all probability will continue to be generated at an increasing rate, it is worthwhile to try to identify the cause of the difficulties encountered, and possible solutions, approaches to overcome such difficulties.

Waste disposal underground

The opening statement of the Executive Summary of a major review of high-level radioactive waste disposal by the National Research Council of the U.S. National Academy of Sciences summarizes succinctly the promise and conflict of underground waste disposal: *"There has been, for decades, a worldwide consensus in the nuclear technical community for disposal through geological isolation of high-level waste (HLW), including spent nuclear fuel (SNF). However, none of the national programs established to implement geological disposal has yet succeeded in establishing a geological repository and emplacing HLW in it."* (National Research Council, 2001).

Since that time, the promise of a near term implementation of such a facility has further faded away, if anything, in most countries where such programs were pursued actively and vigorously ten and twenty years ago (with the notable exceptions of Sweden and Finland, where progress appears to continue steadily). As highlighted in the title of the just cited NRC (National Research Council) report, *"Disposition of high-level waste and spent nuclear fuel: the continuing societal and technical challenges"*, societal issues have come evermore to the foreground, and may have an overriding influence on the lack of success of these programs. While unquestionably difficult technical and scientific problems have been encountered – and these difficulties almost certainly were underestimated, severely, decades ago, when the initial proposals for deep underground emplacement were made – considerable progress has been made towards the resolution of technical challenges – but clearly not sufficiently so to convince the decision makers at large.

"Today, there is strong international consensus that a deep geologic repository used to dispose of high-activity, long-lived radioactive waste "provides a unique level and duration of protection" of public health and safety and the environment. Such a system "takes advantage of the capabilities of both the local geology and the engineered materials to fulfill specific safety functions in a complementary fashion providing multiple and diverse barrier roles." *Further, the international waste management community broadly agrees that developing a deep geologic repository is "technically feasible." However, the route and pace in moving toward deep underground disposition of high-activity, long-lived radioactive waste vary considerably among countries with nuclear programs."* (NWTRB, 2009, pp. 1-2; quotations in this citation are from NEA, 2008).

The challenges are daunting indeed. Undoubtedly, from an engineering point of view, a major basic challenge is the time frame that needs to be dealt with: hundreds of thousands to millions of years, a timeframe obviously totally outside any other engineering practice or even concept. A variety of disciplines have to be invoked in order to address the waste containment and isolation issues. Foremost among these is hydrology, as it is widely accepted that the most likely mode of release of radionuclides from a repository is through water flow. Geochemistry is important, because it affects how radionuclides might be released, and how they might travel, or become restricted in travel, e.g. as a result of adsorption on rock formations favoring such mechanisms. In locations where seismic stability might be of concern, a deep understanding of structural geology and geophysics will be critical. Rock mechanics and rock engineering are important from a number of points of view, obviously initially during construction, and later for example to establish the longevity of underground emplacement facilities, and eventual failure modes, and their consequences for waste package loading. Understanding the corrosion of the waste containers will be essential in estimating the radionuclide release rates. Typically, the overall performance of repositories is investigated and assessed through the use of performance analysis studies, complex comprehensive assessments of all the events and conditions that affect radionuclide containment and isolation, models that allow the study of the influence of the numerous uncertainties that affect performance, and hence can assist in narrowing down remaining uncertainties that have been identified as critical for performance.

Waste

The primary focus of waste and spent fuel geological disposal will be on relatively high level waste. For example, in the Safety Requirements specified in IAEA No. WS-R-4 (IAEA, 2006, p. 6), following an explanation that the requirements apply to all radioactive waste disposed of in a repository, it is clarified that *"The focus, however, is on the disposal of spent nuclear fuel, HLW from the reprocessing of nuclear fuel, other heat generating waste and waste containing high concentrations of long lived radionuclides."* This document refers to IAEA (1994) for a more detailed classification of nuclear wastes.

Examples of underground repositories that deviate from this focus include WIPP (Waste Isolation Pilot Plant), an American repository for transuranic defense wastes, and Konrad and Morsleben, German intermediate and low level radioactive waste repositories. All three are briefly introduced later.

Repository performance objectives: mission to be achieved, goals to be accomplished:

Containment

Most if not all repositories rely on the "multiple barrier" concept: the functions to be accomplished will rely on a combination of engineered and of natural barriers. The first line of defense against the release of radioactivity is the engineered barrier, typically the waste package, the engineered containment structure in which the spent fuel, or waste, is emplaced. Typically the engineered barrier is designed to contain radioactivity for hundreds to thousands of years, although some waste disposal programs (e.g. the Swedish one) rely on the waste package (with, in this example, a bentonitic overpack) to contain radioactivity for a much longer time.

Isolation

The natural barrier, i.e. the geological host rock mass is selected so as to assure that any releases from the containment structure are slowed down in their travel towards the accessible environment to an extent sufficient to assure that any impacts on humans and on the environment remain within acceptable limits.

Retrievability

As pointed out by IAEA (International Atomic Energy Agency) Director General Dr. Mohamed ElBaradei (2003): *"Another identifiable trend is the increasing general acceptance of the idea that retrievability and reversibility should be built into repository designs, to increase flexibility by keeping options open for future societies, and to enable countries to make use of subsequent technical advances in waste management and materials technologies."* The Director General, in the same address, also expressed his concern about the likelihood, now virtual certainty, that extended surface storage, for up to 100 years and more, may become the norm and practice at many power plants: *"If the new initiative for 'very long term storage' persist, they will require more advanced storage technologies, new assessments of their safety implications, considerable extension of storage licences for existing facilities, and long term institutional frameworks."* In sum, the implications of further delays in starting up repository emplacement operations will be quite drastic, significant, and expensive.

As pointed out in the introduction to a recent NEA bibliography on reversibility and retrievability, *"Reversibility and retrievability are not new concepts. In 1969, the United States National Academy of sciences, in its report to Congress Technology: Processes of Assessment and Choice, observed that: "Other things being equal, those technological projects or developments should be favored that leave maximum room for maneuver in the future. The reversibility of an action should thus be counted as a major benefit; its irreversibility, a major cost."* (NEA, 2010)

The U.S. Nuclear Regulatory Commission has long required that the retrieval option be guaranteed for up to at least fifty years after emplacement, primarily in order to allow, through in situ performance confirmation testing and monitoring, to give confidence that performance is as expected and predicted.

The U.S. Department of Energy has considered planning, design and construction of a Yucca Mountain HLW repository with a 300 hundred year retrievability option, primarily from the point of view that spent fuel at some point in the future might become a potential energy resource, and hence that its recovery might be desirable.

Bredehoeft (2003) has argued, from a hydrological model calibration point of view, that it would be highly desirable to change the Yucca Mountain repository concept to one of a monitored retrievable storage facility, for at least 300 to 1,000 years, and , preferably, indefinitely. Given that water transport is widely accepted as the most likely escape mechanism for radionuclides from repositories, the opinions of a leading hydrologist certainly deserve close attention, especially as they are backed up by several related publications questioning, for example, the feasibility of validating hydrological models (Konikow and Bredehoeft, 1992).

A number of international guidelines have been developed to assist with the setting of safety requirements for repositories. For example, the International Atomic Energy Agency, in its safety series, has published *"Safety Principles and Technical Criteria for the Underground Disposal of High Level Radioactive Wastes"* (IAEA, 1989). It deserves copying parts of the table of contents of this document, because it presents a crisp clean clear summary of the major considerations in repository planning, design, operations, and

closure:

"SAFETY PRINCIPLES

1. *Responsibility to future generations*

   Principle No. 1: Burden on future generations

   Principle No. 2: Independence of safety from institutional control

   Principle No. 3: Effects in the future

   Principle No. 4: Transboundary considerations

2. *Radiological safety*

   Principle No. 5: Dose upper bound

   Principle No. 6: Risk upper bound

   Principle No. 7: Additional radiological safety

TECHNICAL CRITERIA

Criterion No. 1: Overall systems approach

The waste

Criterion No. 2: Radionuclide content

Criterion No. 3: The waste form

The repository

Criterion No. 4: Initial period of isolation

Criterion No. 5: Repository design and construction

Criterion No. 6: Nuclear criticality

The site

Criterion No. 7: Site geology

Criterion No. 8: Consideration of natural resources

ASSURANCE OF COMPLIANCE WITH THE SAFETY OBJECTIVES

Criterion No. 9: Safety assessment

Criterion No. 10: Quality assurance"

I recognize that his IAEA (1989) safety series document has been superseded by IAEA (2006). However, the table of contents of the outdated version presents a very clean crisp presentation of the major safety issues of concern with regard to underground disposal of radioactive waste, and remains eminently relevant and applicable. The new version has a clear summary of the main types of safety standards issued by IAEA:

Safety Fundamentals: *objectives, concepts and principles of protection and safety; basis for the safety requirements*

Safety Requirements: *'shall' statements: must be met*

Safety Guides: *recommendations and guidance; 'should' statements; good practices to best practices.*

The fundamental principles of radioactive waste management, including repository planning, design, operations, and closure, are governed by *"The objective of radioactive waste management is to deal with radioactive waste in a manner that protects human health and the environment now and in the future without imposing undue burdens on future generations."* (IAEA, 2006, p.8, quoted from IAEA, 1995, p. 3, paragraph 201). *"Many of the basic principles and concepts of protection adopted in these standards ... are derived from the recommendations of the International Commission on Radiological Protection (ICRP)"*, (IAEA, 2006, p. 1), which references specifically ICRP 1991, 1997 (Radiological Protection Policy for the Disposal of Radioactive Waste), and 2000 (Radiation Protection Recommendations as Applied to the Disposal of Long Lived Solid Radioactive Waste). (ICRP (1991) has been superseded by ICRP (2007)).

How will the goals be achieved? Examples of repositories, actual and planned.

WIPP (Waste Isolation Pilot Plant) (U.S.)

The WIPP facility has been in operation since 1999. It is used for the permanent disposal of transuranic waste (waste that contains elements with atomic numbers greater than that of uranium). The waste received was and is generated by the U.S. nuclear weapons program.

The WIPP facility is located in southern New Mexico, about 40 km East of Carlsbad, NM (New Mexico). Waste is disposed in a salt bed, at a depth of about 655 m. The waste disposal horizon is accessed by four shafts, a waste handling shaft, a salt handling shaft, and air intake and exhaust shafts. The overall layout consists of an experimental area, and of a waste disposal area. The waste disposal area is accessed through four parallel drifts, extending up to about 1.5 km from the shaft area. Perpendicular to these main drifts are disposal room access drifts, nearly 800 m long. Waste emplacement rooms typically are 4 to 5 m high and up to 10 m wide. (Sanchez, 1998) It is expected that waste disposal at WIPP will continue until about 2070.

Opening of WIPP was preceded by some twenty years of site investigations, research, and development, including geology, geophysics, hydrology, and rock mechanics. A main reason for selecting salt for waste disposal is the creep of salt, which, over time, should result in a full encapsulation of the emplaced waste. In order to provide confidence in the predictions of salt creep, extensive creep studies on WIPP salt have been performed. (e.g. Munson, 1997). Also extensively studied has been the compaction, consolidation, creep, of crushed salt, a material to be emplaced around disposed waste packages, as well as a backfill material to be used for closing rooms, drifts, and shafts, i.e. a material of which the long term permeability and stiffness is of particular interest (e.g. Zeuch, 1990).

Morsleben *(Germany) (www.dbe.de/en/sites/morsleben)*

The Morsleben repository is a waste disposal facility operated in an old salt mine, about 100 km East of Hanover, in northern Germany (when started, in the German Democratic Republic). The disposal horizons are accessed by two shafts, one of which was sunk to a depth of somewhat more than 500 m. Mining left relatively large open cavities, up to 120 m long, and up to 40 m wide and high. Waste emplacement in some of these cavities started in 1978, continued until 1991, when they were suspended until 1994, and then resumed until final termination in 1998. Nearly 37,000 m³ of radioactive waste has been disposed in the facility. In 2000 backfilling of the remaining void space has started, in order to prevent collapse of the excavations, and in order to maintain the isolating capability of the salt host rock. Backfilling is being done with a concrete designed to be compatible with the saline environment. Final closure of the site is planned to commence in 2011.

Backfill and sealing design has relied heavily on extensive rock mechanics site investigations, monitoring, and modeling. (e.g. Preuss et al, 2002; Rothfuchs et al, 2010).

The official name of the Morsleben repository is ERAM (Endlager für radioactive Abfälle Morsleben – Repository for radioactive wastes Morsleben), name used for example to identify the facility in many web pages related to it.

Konrad *(Germany)* *(www.endlager-konrad.de/cln_162/)*

The disused iron ore mine Konrad is being considered for the disposal of low and intermediate level radioactive waste. The site is in northern Germany. Iron ore was mined at depths ranging from 800 to 1300 m, from 1967 until 1976. Investigations of the site, with the purpose of evaluating its suitability for a radioactive waste repository, started in 1975. In 2007 the highest courts in the land confirmed the repository planning approval that had been granted in 2002, thus opening the way to pursue the main operational plan, approved in 2008.

Main investigations conducted from 1975 through 1982 included geology, hydrogeology, rock mechanics, seismology, geochemistry, and the safety of the planned repository.

The ore formation does not outcrop, the thick overburden is not penetrated by faults, and has an extremely low permeability, and the site is seismically very stable : a promising geological barrier is present (e.g. Langer, 1991). The site meets the criteria established by AkEnd (Arbeitskreis Auswahlverfahren Endlagerstandort – Committee on Selection Procedures for Repository Sites), a critically important committee appointed by the German government to establish site selection criteria for nuclear waste repositories.

Initial site characterization at Konrad included measurement of surface subsidence, of drop in roof level in the main levels, of convergence in main levels and exploratory drifts, of rock mass deformation above former workings, and of rock stress (Langer, 1991). During early site characterization studies numerical modeling was done using the ADINA finite element code (Diekmann et al, 1986). (It continues to be the practice that numerical modeling for geomechanical studies of nuclear waste repositories tend to be very much state-of-the-art, if not driving the state-of-the-art, e.g. Damjanac et al, 2007). Even at that time considerable attention was paid to damage around excavations: *"The average depth of the deconsolidated zone, or plasticized zone, was determined as 5 m into the side walls of the rooms."* (Langer, 1991).

At Konrad horizontal storage drifts (galleries) will be driven, 7 m wide and 6 m high. Pillars inbetween the galleries will be 28 m. Initial waste disposal will be at a depth of 800 to 850 m, in the iron ore formation. The iron ore formation is covered by a 400 m thick clayey rock with extremely low permeability. The initial subfield, to be started in 2014, is planned for disposal of 63,000 cubic meters of radioactive waste. Total waste emplaced could reach over 300,000 cubic meters, according to plan by 2040. At that time all remaining cavities will be filled with a special concrete, and the repository will be sealed.

Rock mechanics for underground waste disposal

The last several decades have seen major rock mechanics programs in support of nuclear waste disposal programs. It is fair to say that these programs have been a major driving force for rock mechanics progress for several decades. These programs have involved a variety of rock types, some with fundamentally different rock mechanical behavior. The Swedish and Canadian programs have investigated granitic rock masses. The German program has focused primarily on rock salt. Swiss and French programs have focused on shaley sedimentary formations, the Belgian program on even softer clay. The US high level waste program has been dominated for several decades by an investigation of volcanic ash flow tuffs. Japan is investigating both soft sedimentary and hard granitic rock formations.

Most of these programs have followed a classical rock engineering approach: site selection, site characterization, and determination of the rock and rock mass characteristics of importance to the facility to be build. In addition to these 'standard' components, all of these nuclear waste programs have included extensive research aspects, going well beyond the typical basic requirements for most civil or mining underground facilities. Research aspects of such programs have included large scale in situ room tests of the effects of heating on rock mass behavior and response, studies of the long term deformation aspects of rock subjected to high stresses and temperatures, extensive investigations of water flow around simulated emplacement rooms, and comparisons with numerical simulations of the in situ mechanical behavior.

Of particular importance in this context has been the growing emphasis on the need to fully account for the combined fully coupled thermo-hydro-mechanical behavior, of the recognition of the need to account for chemical effects, and possibly biological effects. The growing sophistication and complexity of the resulting models will be self-evident, in principle, as well of the difficulty of coping with such multidisciplinary complexities.

Site Selection

Different countries have pursued different approaches to site selection for HLW repositories, using a variety of criteria, and with mixed results. One example, of a program that continues to look very promising, is that of Finland (Teollisuuden Voima Oy, 1992). The site selection program lasted for nearly twenty years. Preliminary investigations of five sites started with general geological studies, followed by regional studies: satellite photos, geological and geophysical maps, resulting in the identification of promising bedrock blocks (of the order of 100 to 200 km^2). Environmental factors taken into account in the next step included population density, transportation facilities, conservation areas, groundwater basins and land use plans. Field mapping was started at this point, and assisted in identifying fracture zones, considered less suitable. Based on geological classification and more in depth studies of the environmental factors, now including land ownership, the areas deemed suitable for further detailed study were reduced to 101. At this point the information gathered was submitted to the authorities, a number of government agencies and interested parties. This resulted in the elimination of a small number of candidates. From the 85 remaining potential candidate sites, based on geological variation characteristics and environmental factors five sites were selected for detailed characterization.

Several of the objectives and guiding principles of the Finnish site selection program deserve highlighting. A site suitable for high level waste disposal should provide mechanical protection against erosion and human intrusion, chemically stable conditions, little and slow water flow, and properties that retard radionuclide transport. Also, "*... it is not necessary when looking for a disposal site to hit upon one with the "best possible bedrock properties"; it is quite enough if the above conditions are met in an acceptable manner.*" (Teollisuuden Voima Oy, 1992, p. 8). These general criteria are spelled out in somewhat more detail on the next page of the referenced document, where it is stated that the formation at the site should be of an extent sufficient to allow repository strength at a depth to eliminate human interference and effects from erosion. Also considered desirable is that the rock be of a type highly unlikely to be considered for exploitation at any time in the future. The bedrock should be tectonically stable, i.e. free of fracture structures along which appreciable movements might occur in the future. Moreover, the fracture zones should be sufficiently rare so as not to compromise construction methods and safety. It is preferred that the surface topography be gentle and smooth, in order to minimize hydraulic gradients and waterflow. And it is desirable that the rock type be such that it will retard the movement of dissolved substances. Also desirable is that the rock mass be as simple as possible, be homogeneous, and be observable in outcrops. With variations, very similar site selection criteria have been developed for most HLW programs.

While in Finland (as well as in Sweden) only one rock type (granite) was considered for repository waste disposal, in others the initial site selection considered several potential rock type candidates. France has considered a sedimentary shale type formation, now its prime candidate, as well as rock salt and granite. In the US, where the initial focus was on rock salt, sites in granitic, sedimentary (shale), volcanic (basalt and tuff) rock masses as well as rock salt have been considered, with an eventual selection of the Yucca Mountain site (Nevada) for mostly civilian high level waste and spent fuel, in volcanic tuff beds, and the WIPP (Waste Isolation Pilot Plant) (New Mexico) site in rock salt for the disposal of transuranic defense wastes.

It has become very obvious that site selection for repositories is one of the major challenges involved in implementing nuclear waste disposal programs. Examples of programs that appear to have most successfully proceeded through the site selection process are the Swedish and Finnish programs. The German program has reformulated a site selection strategy, in the hope that it might lead to a credible solution, acceptable to the public. The US site selection procedure, ending in a highly politically influenced site designation step may well be an unfortunate example of how the site designation process can result in vigorous, eventually fatal, opposition to a site.

Site Characterization

Site characterization for nuclear waste repository sites typically has followed the strategies implemented for most large underground construction or mining projects, but typically has been implemented in considerably more detail. Initial site selection largely has been driven by considerations of requirements for nuclear waste isolation: low permeability formations, sufficient depth to minimize the risk of disturbances induced from the surface (e.g. potential, over the long time periods considered, usually on the scale of a million years, for glaciation, or surface erosion – risk of excessive geomorphological changes) seismic stability, rock formations that will tend to minimize the risk of radionuclide travel, e.g. as a result of geochemically favorable control aspects.

Probably all nuclear waste repository site characterization projects have involved extensive geophysical characterization, e.g. to confirm formation homogeneity and uniformity, to detect potentially major faults, etc.. (e.g. Emsley et al, 2008)

Vira (2006) describes the site investigations in Finland. The central core of the site investigations is the geological model, supported in turn by geochemical, hydrogeological, and rock mechanics models. These in turn are integrated into performance analyses, safety assessments, repository planning and design, and eventual implementation. Input data for the models is collected through a variety of field activities: geophysical, geological mapping, geohydraulic measurements, and deep drilling with associated rock and groundwater sampling. In addition, an extensive monitoring network has been emplaced, e.g. to study evolving changes in the ground conditions. Considerable emphasis is placed by this author on the emphasis the Finnish program is placing on *"the purpose ... to coordinate and combine the expertise in different disciplines in such a way that a coherent picture of the site can be produced."*

Delay et al (2007) give a comprehensive overview of the studies performed in deep boreholes drilled to characterize the potential Bure French repository site. This included detailed geological characterization as well as extensive hydrogeological testing. Measurements included piezometric head measurements and a variety of packer tests. Water samples were collected for geochemical characterization. Geophysical logging was including to characterize the lithology and the porosity of formations, and seismic profiling was performed to assess the spatial variability of the most porous facies. Some of the exploration holes drilled were used during shaft sinking to monitor the drawdown that took place during the sinking operations. Some of the holes were angled, with the specific objective of giving a better chance of detecting vertical or near-vertical structural features. Extensive suites of hydraulic fracturing stress measurements have been performed in some of the holes, giving a good understanding of the stress field at the site.

Rock Testing

There is no doubt but the research in support of HLW repository programs has resulted in major advances in rock mechanics, has been a driving force in rock mechanics developments for several decades now. Examples include the work on rock salt in support of WIPP (Waste Isolation Pilot Plant, New Mexico, USA) and in Germany, the very extensive studies on argillite and shale in France and Switzerland, the comprehensive investigations on granite in Sweden and Canada, creep testing of salt, in the broadest sense, i.e. including a variety of loading paths, a wide range of "sample" sizes and in situ monitoring configurations, a range of temperatures and humidity conditions, etc..

The challenge of dealing with argicalleous rocks is well recognized (e.g. Seedsman, 1993: *"Clay shales are often considered difficult materials with which to engineer."*)

An example, among many, of contributions made by the French nuclear waste program to develop a better understanding of the behavior of these complex materials is the indenter studies reported by Gratier et al (2004). Lebon et al (2006) give a brief introductory overview of additional work on rock mechanics testing at the French program (in addition to numerous other research topics addressed by the program), including further references. A comprehensive and most instructive report on the behavior of fractures in argillaceous formations, especially the long term behavior, has recently been published by NEA, the Nuclear Energy Agency of OECD, the Organization for Economic Co-Operation and Development (Bock et al, 2010).

Pusch (1994, 1995) has summarized the early work in the Swedish program, while Popov and Pusch (2006) address a broader range of issues associated with waste disposal in general (i.e. not focused exclusively or even primarily on nuclear waste) in mines.

Saeb and Francke (1999) give introductory overviews of the type of testing that has supported many repository programs.

In situ rock mass testing

A common feature of all major HLW disposal programs has been the implementation of extensive in situ test facilities. Such "laboratories" have been operational in Sweden, Belgium, France, Germany, Canada, Japan, Russia, Korea, and the US. (Brief overviews of these test programs are given for example in Witherspoon and Bodvarsson, 2006, even briefer ones in

NWTRB, 2009). They have been operated in a variety of rock mass types, including granite, clay, shale, rock salt, and volcanic tuffs.

Waste emplacement simulations

A variety of tests have been run to study the effects of emplacing waste on the surrounding host rock. This includes in particular heater tests, in which the heat generated by decaying radioactive elements is simulated by electrical heaters. References to more detailed descriptions of such tests can be found in Saeb and Francke (1999), and in Witherspoon and Bodvarsson (2006), for example.

Numerical modeling

As for most rock engineering projects today, numerical modeling is an essential and integral component of the analysis, design, and, in particular, performance predictions of HLW repositories. In light of the fact that waterflow is generally perceived as the most likely mechanism of radionuclide transport and release, it deserves pointing out that in the hydrological community considerable skepticism has been expressed about the feasibility of validating numerical water flow models (Bredehoeft, 2003, Konikow and Bredehoeft, 1992, Bredehoeft & Konikow, 1992). While not everyone shares such (extreme?) skepticism (e.g. de Marsily et al, 1992), multiple others rather even more forcefully endorse the Konikow and Bredehoeft position (e.g. Pilkey & Pilkey-Jarvis, 2007, p. 32 – who point out that the Konikow and Bredehoeft (1992) *"paper received the Meinzer award from the Geological Society of America;* Anderson and Bates, 2001, who cite multiple additional concordant references).

The difficulties associated with predictive hydrological modeling have been discussed extensively in the literature. Far less parallel discussion appear to have taken place with regard to rock mechanics modeling. (Although Jing (2003) in a major review paper numerical modeling for rock mechanics and rock engineering states as one of his general (concluding) comments that *"Full validation of numerical models and computer codes by experiments in rock mechanics is not possible, and can at best be only partial, due to the necessary assumptions in the mathematical models and hidden nature of fractures."* Interestingly, a few sentences later, he uses "calibrated" – term strongly endorsed by Bredehoeft as well...).

It is rather self-evident that many of the problems that make hydrological modeling so problematic, heterogeneity, discontinuity, lack of comprehensive definition of the input variables needed for analysis, uncertainty about boundary conditions, as well as, possibly most important, the underlying questions as to whether validation truly is possible at all, in principle. The reservations and concerns about the concept of model validation expressed in the hydrology literature certainly deserve equal attention in the rock mechanics community as well.

Notwithstanding such fundamental concerns, modeling has been and will continue to be applied extensively for rock mechanics aspects of nuclear waste repository performance, (e.g. Dedecker et al, 2007, among many others) where frequently it has evolved in coupled thermal-hydrological-mechanical analyses (e.g. Hudson et al, 2009; Rutqvist et al, 2005, among many others).

Two of these papers deal with modeling the EDZ (Excavation Disturbed Zone), the rock directly adjacent to excavations, and hence affected by excavation, and over, the long term by stress concentration effects, rock weakening/softening, possibly water interactions, etc... This zone may constitute a preferential flowpath, of enhanced hydraulic conductivity, which might be of particular concern, for example, at locations where permanent isolation seals might be planned to be emplaced. Preferential facilitated flow through or along the EDZ could mitigate the effectiveness of seals. Hence it is important to be able to predict the long term performance of such rock zones.

Repository sealing

Sealing of the access penetrations to repositories is a critically important aspect of repository design, planning, operations, and closure. Sealing has multiple purposes: minimizing water inflow towards the emplaced radioactive materials; minimizing any outflow of (radioactively) contaminated water, reducing the risk of intentional and/or accidental human penetrations into emplaced radioactive materials, and their immediate surroundings.

Sealing has been the object of extensive research and development efforts in multiple SNF and HLW disposal programs. Very different approaches have been pursued, depending on the geological environment within which the repository will be developed. Probably the major geology types presently considered are salt (evaporite, saline formations), granitic ("crystalline") type formations, and clay/shale type formations. Different sealing materials and construction materials are considered for different geological environments. Different technologies also will be implemented depending on the type of excavations that need to be sealed: shafts, (usually horizontal) drifts and emplacement rooms, emplacement boreholes, large rather irregular emplacement stopes, exploratory and test boreholes.

Among the major sealing investigation programs have been the Swedish bentonite sealing studies, the German investigations of sealing repositories in saline environments, including crushed salt consolidation and specialty concrete sealing materials, the Canadian crystalline (granitic) bentonite seal tests, and the Swiss bentonite sealing studies in shale.

Seals often are considered as one component of the EBS (Engineered Barrier Systems) (other components being the waste package, any overpack that might be used to protect waste packages, backfill, etc..). Seal performance requirements, which govern seal design and construction, ideally are based on performance assessments, from which such major performance requirements as hydraulic conductivity and longevity/durability can be derived (e.g. Müller-Hoeppe, 2006). In earlier days it was not uncommon to state as a seal performance objective the requirement that sealed repository penetrations (e.g. shafts, boreholes) should not constitute preferential pathways, with the explicit or implicit conclusion that hydraulic conductivity of seals should not be larger than that of the host rock. Hydrological modeling studies have shown this almost certainly to an excessively and unnecessary restrictive performance target.

EDZ (Excavation Disturbed Zone)

A peculiar problem, of major interest from a rock mechanics point of view, as well as from a sealing point of view, is the damaged zone around underground excavations, especially at locations where seals are to be installed. It is expected that at these locations bypass flow along the seals, through the damage zone, could form short circuits for fluid flow, thus negating or greatly reducing the efficacy of seals.

Extensive studies, both in situ and trough numerical modeling (e.g. Dedecker et al, 2007), have greatly improved our understanding of the mechanics (as well as of hydraulics and chemistry) of what takes place in the rock immediately surrounding excavations.

A good example of how EDZ considerations come into play in repository planning and design is that of the Japanese concepts as of 2002 (Umeki), for either in tunnel emplacement or emplacement in vertical holes drilled in a tunnel floor. Of particular concern with regard to the latter option is that the emplacement holes, in this case, will penetrate tunnel EDZ, and hence that preferential flowpaths might exist, allowing flow around seals emplaced in the holes.

Buffer

Several disposal programs are considering the installation of a buffer, typically bentonite, in between waste packages/containers and the surrounding host rock. Umeki et al (2002) describe a variety of options considered at that time for the Japanese H12 repository performance assessment. At the time the Japanese program was considering both in tunnel disposal and pit disposal, the latter referring to waste emplacement in vertical boreholes drilled in the floor of the 'emplacement' tunnels. For both options provisions were included for considerable buffer amounts and thicknesses. Buffer material selected at this time was a mixture of 70% and 30% sand (as compared to the pure bentonite considered previously). The sand improves the thermal conductivity of the buffer, and strengthens it – reducing the risk of waste packages sinking or moving in the buffer. Improved thermal conductivity assists in reducing the maximum temperature to which the bentonite will be exposed (limited to 100 ºC) (as well as the maximum temperature of the steel overpack surrounding the waste package, and of the package itself). This buffer study provides an interesting example of international data exchange in order to strengthen the basis for performance assessments. Even though the Japanese program conducted extensive testing itself of the butter material, they also relied heavily on a coupled thermo-hydro-mechanical model developed as part of the international DECOVALEX projects (Tsang et al, 2009).

Unquestionably one of the disadvantages of bentonite, by far the preeminent candidate for buffers, is the complexity of its behavior, mechanical, thermal, hydrological, and chemical. Hence a vast amount of research has been performed over the last few decades, aimed at assuring that the understanding of the complex behavior of this material is sufficient to give adequate confidence that its behavior can be predicted, or at least can be bound reliably, over a very long time, i.e. thousands, preferably tens or even hundreds of thousands of years. Börgesson et al, 2001, for example, summarize a combination of laboratory tests and of numerical modeling, by four independent research groups to study the thermo-hydro-mechanical characteristics of a bentonite-based buffer material. At about the same time, Chijimatsu et al (2001) performed a large scale in situ experiment in the Kamaishi (Japan) mine. They installed a 1 m diameter nearly 2 m long heater in a 1.7 m diameter 5 m deep borehole in the floor of an alcove in the mine. The heater was surrounded by a granular bentonite compacted in place. Buffer and surrounding host rock were extensively instrumented (piezometers, thermocouples, strain gages strain meters, etc...), providing for a comprehensive observation of developments during the heating and cooling phases (260 days and 180 days respectively).

Backfill

Whether or not repository excavations will be backfilled completely, partially, or not at all will depend on the site specific conditions. Nevertheless, it appears the most repositories as currently planned and conceived will be backfilled to a very significant extent, quite possibly almost completely. Extensive backfilling certainly will assist in reducing the risk of intentional or accidental human intrusion. Backfilling always will provide some mechanical stabilization effect, if only by filling up otherwise void remaining space. If the backfill is designed and emplaced with reasonable care, it could provide a significant confinement effect on the host rock, thus having a corresponding strengthening effect – the primary objective and function of backfill as used in many mines. More specific performance objectives can be assigned for backfill, e.g, being part of the seal system. In such cases, using appropriate additives, e.g. clays, cementitious materials, fly ash, etc...it should be possible, for example, to greatly reduce the hydraulic conductivity of the backfill, and/or to greatly increase the sorptive capacity of the backfill (e.g.Roxburgh, 1987, Sections 5.5 and 6.7).

In this way, backfill can assist, significantly, in waste isolation and radionuclide control, even if not formally assigned such a function, e.g. in explicit performance assessments, and thus can provide a considerable extra margin of safety, at, presumably, a not excessive cost, i.e. a cost which is modest relative to overall repository costs.

URLs Underground Research Laboratories

For all practical purposes, underground research laboratories can be considered an integral, essential, dominant, aspect of all disposal programs. (e.g. Kickmaier and McKinley, 1997). Although a great deal of essential information can be gained from surface investigations, from studies in boreholes, for all practical purposes in situ characterization and testing is an essential requirement for a description of the host rock mass and of its characteristics and behavior in order to allow an adequate assessment of the waste isolation capabilities of the site, of the geological barrier. While more or less emphasis can be placed on the geological vs. the engineered barriers, depending largely on the host formation(s), all sites require an in depth understanding of the mechanical, hydrological, geochemical, thermal characteristics of the site in order to allow making an adequate evaluation of eventual barrier performance.

URLs have been constructed and implemented at potential or likely repository sites, or as "'generic" facilities in locations, rock types, deemed representative of typically much larger potential host rock formations, such that "site specific", more appropriately "rock type/mass specific" investigation results readily can be applied to a much large rock volume/area, i.e. are representative for multiple, preferably numerous, potential sites.

A common characteristic of many URLs is that often they have been used for multinational research/investigation collaborations. For example, the German *Repository Safety Research Division Company for Reactor Safety (GRS) mbH* has been involved in URL projects for crystalline rock in Åspö, Sweden, and Grimsel, Switzerland, and clay URL' at Mt. Terri, Switzerland, and Bure, France, as well as salt and other projects in Germany (Rothfuchs et al, 2010). According to these authors, *"Field testing and comparison of experimental and modeling data are important steps for the validation of process models, which are implemented in integrated PA* [Performance Assessment] codes, sometimes in a simplified manner." While, as discussed in slightly more detail elsewhere in this paper, one might quibble somewhat about the term "validating", there certainly is no doubt but that close interaction and information exchange between URL planners, designers, and operators and developers of a variety of numerical codes must be an essential aspect of and contribution to code development and improvements as well as experimental design, planning, optimization, and results interpretation and analysis.

Transportation

Although it may appear that HLW and spent fuel transportation is somewhat marginal to repository design and performance as such, it deserves pointing out that such transportation has been the focal point of strong opposition to repository operations, both in the US and in Germany. It clearly is a factor that can not be neglected in repository planning, possibly starting from site selection: certainly in the US, a major objection to the selection of the Yucca Mountain site, in the state of Nevada, Western US, was the perception of several inequities: Most of the spent fuel is generated in the East [of the US]: why locate a repository in the West? Nevada already has a fifty year history of nuclear weapons testing: why impose one more nuclear burden on this state?

Also, as a result of the requirement to transport spent fuel and HLW through multiple states, it became possible to mobilize opposition to transportation in those states, thus significantly broadening the opposition to the Nevada Yucca Mountain site. A number of technical and public transportation issues are discussed in the 2004 NWTRB (U.S. Nuclear Waste Technical Review Board) annual report. (NWTRB, 2004).

In its report on transportation in the US of SNF (Spent Nuclear Fuel) and HLW (High-Level Radioactive Waste) the Committee on Transportation of Radioactive Waste argues that " ... *there are no real fundamental technical barriers to the safe transport of spent nuclear fuel and high-level radioactive waste and the radiological risks of transport are well understood and generally low. However, there are a number of challenges that must be addressed before large-quantity shipping programs can be implemented successfully. Among these are managing "social" risks."* (National Research Council, 2006, Executive Summary)

Research

As will be clear from the previous discussions, deep underground waste disposal has been the subject of multiple very extensive research projects. Examples of publications dealing specifically with this topic include a special issue of the journals *Engineering Geology* (Delage and Cui, 2005) and *Environmental Geology* (Tsang, 2009). (The latter gives references to multiple earlier special journal issues, including in particular those of the *International Journal of Rock Mechanics and Mining Sciences.*) The special issue of Comptes Rendus Geoscience (Trouiller, 2006) presents a collection of papers, many of which are in English (and all have an English abstract, sometimes as well as an abbreviated English version), of research performed in support of the investigations for a potential French HLW repository in argillites.

International agencies and collaborations

A number of international agencies play a major role in developing strategies for implementing nuclear waste repositories (as well as for all other aspects of nuclear energy). These include in particular the IAEA (International Atomic Energy Agency, Vienna, Austria), the NEA (Nuclear Energy Agency) of the OECD (Organisation for Economic Co-operation and Development, Paris, France), and EURATOM (European Atomic Energy Community, Brussels, Belgium). All of these have published extensively on nuclear waste management, including many publications on geologic repositories, many of which are available on their respective web pages.

International collaboration has been the norm for many aspects of repository research. One example is the DECOVALEX-THMC project (e.g. Tsang, 2009, Tsang et al, 2009, Hudson et al, 2009). This project was initiated by the Swedish Nuclear Power Inspectorate, in order to address the important yet complex question of how to address the need to model coupled phenomena around geological repositories, in particular the interactions between mechanical, hydrological, thermal (and, later, chemical) effects that affect fluid migration and hence could affect radionuclide transport. Results of this extensive collaboration have been published in three special issues of the *International Journal of Rock Mechanics and Mining Sciences* (Vol. 32, No. 5, 1995; Vol. 38, No. 1, 2001; Vol. 42, Nos. 5-6, 2005) and in a special issue of *Environmental Geology* (Vol. 57, No. 6, 2009). It is fairly self-evident that this collaborative research has made major contributions to the advance of rock mechanics (as well as other disciplines, notably hydrology). A topic that has particularly drawn attention during the last cycle of this project is the modeling of the development of the damaged and disturbed zones around underground excavations (Rutqvist et al, 2009a and b; Hudson et al, 2009; Pan et al, 2009; Millard et al, 2009).

One important aspect of international collaborations is peer review of programs. For example, the French Government requested the Nuclear Energy Agency to conduct a review of the Dossier Argile 2005, a major report on ongoing studies for a potential repository in a clayey formation produced by ANDRA, the French National Agency for Radioactive Waste Management. The review has been published as an OECD document (OECD, 2006). Similarly, *"The Belgian Government asked the OECD Nuclear Energy Agency to organize an International Review Team (IRT) to provide a peer review of the SAFIR 2 report according to agreed Terms of Reference. In particular these state that 'The peer review ought to help the Belgian Government and the institutions, organizations and companies involved in waste management to decide on the future work programme and its priorities.' The Terms of Reference focus on:*

(i) 'the long-term safety assessment methodology, the well-foundedness of its results and the quality of its scientific and technical bases';

(ii) 'the remaining key uncertainties and the RD&D programme that is proposed to deal with them in the next phase of the program.'" (OECD, 2003, p. 7)

(In the above SAFIR 2 refers to the second report summarizing research and development of the Belgian program to study the emplacement of high-level and long-lived radioactive wastes in a deep clay formation.)

The nuclear Energy Agency has published a formalized approach for such international peer reviews (NEA, 2005), which, for fairly obvious reasons, it highly recommends. *"...the Radioactive Waste Management Committee (RWMC) provides a forum for senior representatives from international agencies, regulatory authorities, policy making bodies, and research and development institutions with responsibilities in the management of radioactive waste and materials, as well as for other government-nominated specialists, to exchange information and experience on waste management policies and practices in NEA member countries, and to advance the state of the art on the technical and societal aspects of radioactive waste management."* (NEA, 2005, p. 5). An Appendix to this publication lists some fourteen international review projects, including reviews of projects in Sweden, The Netherlands, Canada, the US, the UK, Japan, Belgium, France, and Switzerland.

An extensive overview of worldwide radioactive waste disposal programs up to about 2006 is given by Witherspoon and Bodvarsson (2006). This review summarizes reports from 24 countries. For most countries it provides information about the nuclear waste and its sources, and about the approach taken in each country to mange the waste. For most countries this includes a geological disposal component, quite advanced for some (e.g. Sweden, France, Switzerland, US). For these included are discussions about rock formations considered or proposed as host formations, tentative disposal plans, e.g. repository concepts, and research in progress towards implementation of disposal options. For others the planning remains rather embryonic, but may include for example selection criteria and approaches for potential host formations and locations, site selection approaches, and assignments of responsibilities for steps to be taken towards the implementation of repository plans.

A more up-to-date but far less technical survey of multiple international programs is given by NWTRB (2009b). This overview provides information about 13 countries. For all of these are given *Institutional Arrangements* and *Technical Approaches.* Institutional arrangements notably include such aspects as the organization responsible for the implementation of repository programs, and of the regulatory and overview bodies. Typically included are the laws and regulations that govern waste disposal practices.

Young et al (2005) summarize extensive collaborative research performed by groups in several countries on seismic evaluation of thermo-mechanical modeling of rock damage induced around radioactive waste packages. This study has looked at a variety of rock types, including diorites studied in Sweden, clay investigated in Switzerland, and argillite, the primary host rock candidate in France.

Similarly, Mazurek et al (2008) give a detailed technical/scientific discussion about how date and analyses from a variety of sites in argillaceous formations can be used to support the safety analyses for repositories in such formations. They discuss in particular how one can identify similarities and differences in order to develop a scientific basis for the transferability of information between sites. This results in a summary discussion of what can be transferred, and what can not be transferred: weaknesses and strengths, benefit, values of such transfers. They illustrate transferability with examples for diffusion coefficients and for hydraulic conductivity, and also discuss the practical experience gained with such transfers. Specific examples summarized from the French nuclear waste program include the development of experimental tools and methods for in situ testing, the addressing of the always challenging scale issue: how does one transfer date from (relatively small) lab scale testing to full scale in-situ performance, and the development of conceptual models, illustrated with the case of the role of transport along brittle discontinuities.

Regulations and legal framework

Given the extreme sensitivity of nuclear waste disposal, as has become overwhelmingly self-evident, for several decades now, in many countries, it is essential that regulations be implemented, to assure that geological waste disposal is safe, and to try to convince the public at large and the politicians that indeed it can be done safely. Given the complexity of the task, and the seriousness of the issues involved, not surprisingly this already has proven to be difficult. Obviously the legal and regulatory details are likely to differ significantly between different countries and societies.

A number of publications provide extensive overviews of legal and regulatory approaches taken in different countries, noticeably the proceedings of two NEA (Nuclear Energy Agency) workshops on the topic: NEA (2008c) and NEA (1997). The NEA Regulators' Forum of the RWMC (Radioactive Waste Management Committee), formed in 1999, has published a number of comparative studies on regulatory standards in various countries (e.g. NEA, 2007). A fairly striking observation from such comparisons is the considerable differences that exist among countries in how geological disposal is regulated, as well as in the (numerical) criteria implemented.

The future: how do we move forward?

Clearly in several countries underground disposal of HLW has run into severe, overwhelming, obstacles, notwithstanding the early optimism about this approach, and notwithstanding the vast research efforts that have been devoted to the subject. However, the HLW is here. Moreover, all indications are that nuclear power generation, and hence waste generation, is likely to increase significantly in the near future, most notably in India, China, and the US.

One observation is rather clear and obvious: good science and good engineering do not suffice to implement a repository! A strong argument can be made, for example, that the German nuclear waste disposal program has made major contributions to the improvement of our understanding of salt rock mechanics. Similarly, the Canadian program has contributed superbly to improving our understanding of the development of overstressed zones around excavations in hard brittle rock under high in situ stress. Neither of these accomplishments was sufficient to convince the authorities that safe disposal of HLW was feasible with the proposed repository methods. (e.g. Walnner et al, 2006; Russell and Facella, 2006). (It is of some interest that Russell and Facella refer to "used" fuel rather than "spent" fuel – to emphasize that "spent" fuel typically is far from spent, but is considered by many to remain a potential energy resource?)

The one option that appears to become a de facto approach in the US is extended surface storage, apparently, in all probability, for many decades. *This raises serious questions about the generational equity issue which used to be a dominant driving force towards permanent underground disposal. "Returning to the overall position and considering the high level issues, all stakeholder groups seem to agree that the principle of intergenerational equity requires early disposal of HLW."* (NEA 2008a, p. 66, in Chapter 6: Discussion). *"It seems to be a generally agreed principle amongst the industry, the public and politicians that each generation that benefits from nuclear power should honour its responsibilities and should deal with its radioactive waste in a manner that protects human health and the environment, now and in the future, without imposing undue burdens on future generations. This ethical principle of "intergenerational equity" is a driver to avoid undue postponement of HLW disposal."* (First of the "Overarching Issues" listed on p. 70, in Chapter 7, Conclusions, of NEA 2008a).

The delay in starting up repositories obviously also raises technical questions about the "temporary" surface(?) storage facilities that will contain the spent fuel and HLW for decades. The U.S. Nuclear Waste Technical Review Board (NWTRB, 2009a) has raised questions, for example, about very-long-term (defined as 120 years or more) dry storage, with the suggestion that rather more information will be needed in order to safely implement such an approach.

A number of suggestions have been made about alternate paths toward deep underground HLW disposal, and they all have in common the recommendation of building flexibility into the approach taken: rather than setting firm detailed requirements up front, allow for adjustments to be made as the programs develop, progress, evolve. (To geotechnical engineers this probably might seem somewhat self-evident: design as you go – the observational method! (Peck, 1969))

The "Committee on Principles and Operational Strategies for Staged Repository Systems" of the "Board on Radioactive Waste Management" of the US National Academies has outlined a "One Step at a Time" approach towards developing underground nuclear waste repositories (National Research Council, 2003). This seems to be very similar, totally parallel, to the step by step approach of which IAEA (2006, p. 3) suggests: *"The step by step approach, together with the consideration of a range of options for the design and operational management of a disposal facility, is expected to provide flexibility in responding to new technical information, advances in waste management and materials technologies, and in enabling social, economic and political aspects to be addressed. This approach may include options for reversing a given step in the development or even retrieving waste after its emplacement if this were to be appropriate."* One of the significant benefits of a step by step approach is that it allows the operator, regulator, and any interested party to learn from the experiences gained during operations: *"The geological disposal system (the disposal facility and the geological environment in which it is sited) is developed in a series of steps in which the scientific understanding of the disposal system and of the design of the geological disposal facility is progressively advanced."* (IAEA, 2006, p. 4). This of course, deserves being put into a much broader context: given that all indications are that it will be many decades before any HLW repository gets closed, every conceivable aspect of human knowledge and technology by that time virtually certainly will have advanced considerably.

Macfarlane (2006) raises as fundamental questions: *"Is the Earth system understood well enough to make predictions about the future behavior of radioactive waste emplaced into rock? And can the models that provide these predictions be verified or validated?* Furthermore, if the answer to these questions is no, then how can a nuclear waste repository site be valuated?" Macfarlane discusses at considerable length the large number of considerable uncertainties associated with modeling, for a variety of reasons. She concludes that it will be virtually impossible to reduce all uncertainties to what might be considered an acceptable and convincing level. She cites Swedish and German programs as examples of programs that might lead to repositories, and suggests an approach following those examples. In particular, she puts heavy emphasis on the need to have a site that is socially and politically acceptable to the community at large. In her final conclusions she strongly emphasizes that "… *a false sense of urgency surrounds nuclear waste disposal in the United States."* (One could easily argue that the nuclear power industry would disagree rather strongly with this statement – given that the legally required start date for the U.S Federal Government to start accepting spent reactor fuel is long past due, well over a decade by now).

Pilkey and Pilkey-Jarvis (2007, Chapter three, pp. 45-65) also strongly criticize the heavy reliance by the U.S. Department of Energy Yucca Mountain high level waste repository program on modeling, as rather strongly indicated by the title of their book: *"Useless arithmetic".* They quote Danish physicist Per Bak, who *"...suggests a strategy for coping with the complexities that we encounter: • Don't predict • Adapt."* This, of course, to geotechnical engineers, will be eerily reminiscent of the observational approach to deal with difficult, complex, geotechnical engineering situations.

Lopatin et al (2006), in an overview of the Russian radioactive waste disposal program, make the interesting recommendation to, in light of the importance of local public perception and acceptance, as well as that of the local authorities: *"With this in mind, the most advisable disposal solution is to locate a repository on site with, or in the immediate vicinity of, waste-generating enterprises -- i.e., the existing operations of the atomic and mining industries. This consideration of proximity could be more critical than any geological factors."* This is the approach taken in Belgium, and was one of the reasons why early on in the US program the Hanford (Washington state) received high priority. It also of course might reduce somewhat the potential opposition based on the risks associated with spent fuel transportation over long distances, a major driving force of opposition both in Germany and in the US (although the gains in this regard might be fairly marginal, if the pursuit remains for one, or a very small number of sites, so that extensive transportation still might be required).

The U.S. National Research Council (2005) has considered potential alternatives to deep geologic disposal of some types of wastes from defense activities. The Council recommends using risk assessment and a risk-informed approach to consider such alternatives, and makes a strong argument for trying to develop more flexibility and management alternatives for at least some wastes.

One approach that may contribute to improving the odds of actually implementing the geological disposal of radioactive wastes may be the growing *"Internationalization of the Nuclear Fuel Cycle"* (U.S. Committee on the Internationalization of the Civilian Nuclear Fuel Cycle, 2008). Although the focus of this study is primarily on nonproliferation concerns, generated to a significant extent by *"The so-called nuclear renaissance* [which] *has increased worldwide interest in nuclear power",* the report also addresses concerns related to storage and disposal: *The international community should help countries provide adequate capacity for safely storing spent fuel (on their own territory* *or elsewhere)..."* [Recommendation 1b]. This document also provides support for the argument that extended retrievability of spent fuel would seem desirable: *"In most cases, reprocessing is not economic under current conditions. When the world's economically recoverable uranium resources diminish compared to demand or there is widespread deployment of fast reactors, then reprocessing may become economically attractive."* [Finding 9a]. One unmistakable conclusion, following from this document, is the widespread anticipation that nuclear power almost certainly will increase, most likely increase significantly, in the relatively near future. Unavoidably associated with such a trend will be the generation of more spent fuel and of more radioactive waste, both of which will have to be managed, somehow.

In the research arena, international cooperation and collaboration has been very extensive with regard to geological disposal of radioactive waste. EURATOM (the European Atomic Energy Community) for example *"has been financing research on the broad subject of radioactive waste for many years; in the area of geological disposal of high-level radioactive waste in particular this effort stretches back for more than three decades ... Especially important in these efforts are the collaborative research activities by consortia of EU radioactive waste management organizations co-funded by the Euratom Framework Programme."* (EURATOM, undated, p.3). The vision document from which this quote is taken, based on *"A broad consultation process ... performed during summer 2009..."* states that *"Our vision is that by 2025, the first geological disposal facilities for spent fuel, high-level waste, and other long-lived radioactive waste will be operating safely in Europe."* (EURATOM, undated, p.9).

In response, at least partially, to the major difficulties encountered in trying to implement a repository, the German government, through the Ministry of the Environment, has commissioned a committee to revisit, from the very beginning, the site selection of a repository. The report resulting from this committee's work (AkEnd, 2002) provides comprehensive guidelines and strategies for approaching such a delicate and difficult task.

Recently Rosa et al (2010) have argued rather forcefully and convincingly that a critical necessity towards the implementation of HLW repositories is the development of social acceptability and the rebuilding of trust in the entities responsible for such facilities. They point out that the loss of trust in responsible agencies has been, and probably continues to be, a major stumble block on the way to actual repository implementation. Presumably this argument could readily be broadened for a great many and a wide variety of industrial and especially waste treatment and management facilities.

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