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Deep-Mined Geological Disposal of Radioactive Waste

Guest Editors: Bruce W.D. Yardley, Rodney C. Ewing, and Robert A. Whittleston

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NUCLEAR WASTE DISPOSAL, CLIMATE CHANGE, AND BREXIT: THE IMPORTANCE OF AN EDUCATED PUBLIC

Modern society faces a variety of major challenges that will impact the quality of our lives. Of these, 15 have been singled out as “Global Challenges” by the Millennium Project (2014) (see figure below). One of the greatest of these challenges is the availability of sufficient clean water. Another is sustainable development and climate change. Much of the US public now accepts that the rapidly increasing levels of CO₂ in the atmosphere are caused by human activity, including the burning of fossil fuels. However, there is little consensus among US scientists, engineers, politicians, and the public about how to reduce atmospheric CO₂ levels, especially at a time when developing countries are seeking the same standard of living enjoyed by the world’s most industrialized countries. Yet another challenge, which is related both to the burning of fossil fuels and to climate change, is adequate energy to power our global society. As the World Nuclear Association (WNA) has shown, nuclear energy is an attractive option: for example, France derives over 75% of its electricity from nuclear fission (WNA 2015). One of the major societal concerns limiting the widespread use of nuclear power, however, is safe disposal of nuclear waste, which is the topic of this issue of Elements. Other societal concerns about nuclear energy include the possibility of releasing into the environment radioactive material from a nuclear power plant. Such an event happened in March 2011 during the partial meltdown of the cores of three reactors at the Fukushima Daiichi nuclear power plant in Japan, the effects of which continue to this day through the interaction of groundwater with the melted cores (see the June 2012 issue of Elements). The Fukushima Daiichi event resulted in shifts in public opinion about the safety of nuclear energy and contributed to Germany’s decision to eliminate nuclear power by 2022 (Appuhn 2015). One result of this decision is the continued reliance by Germany on coal-fired power plants and by an increased reliance on wind and solar for electricity generation.

After reading the six articles in this issue, I am reminded of the complexity of the nuclear waste disposal problem, a complexity that has delayed final choices of waste disposal sites in most countries that have nuclear waste inventories. As pointed out in the introductory article of this issue “… there are, at present, no operating nuclear waste repositories for spent nuclear fuel from commercial nuclear power plants or for the high-level waste from the reprocessing of spent fuel” (Ewing et al. 2016).

I remember well a lecture I gave on radioactive waste on March 3, 2010 in an environmental geochemistry course I teach at Stanford University (California, USA). Earlier that morning, the US Department of Energy Secretary Steven Chu had announced the creation of a Blue Ribbon Commission on America’s Nuclear Future. This effectively marked the cessation of the Yucca Mountain Project. I modified my lecture and told my class that Yucca Mountain was no longer the choice for nuclear waste disposal in the US. The final report from the Blue Ribbon Commission (BRC 2012) recommended a process whereby an alternative site might be selected. One of the main conclusions of this report was that “no state, tribe, or community should be forced to store spent nuclear fuel or high level waste without its consent.”

The challenge of nuclear waste disposal has interesting parallels with other major societal challenges such as climate change as well as with political issues such as Brexit (“British Exit”—the 2016 UK referendum to leave the European Union). In all three cases, an educated public is essential for casting informed votes on major political issues and influencing government policy makers to legislate national and international policies that benefit humankind in the long-term while minimizing negative impacts. I happened to be in London (England) and Cardiff (Wales) three days after the exit decision by UK voters and had a chance to talk about this decision with a number of Brits, ranging from taxi drivers, bar tenders, and hotel employees to the academic elite of the EU. Some who voted for exit felt they didn’t have sufficient information to make an informed decision and would like another referendum, which is unlikely to happen. Others who voted in favor of...
For over 70 years, in the local community where the Elements editorial office is located, the residents have been living in the shadow of the Hanford nuclear production complex (eastern Washington, USA). During its heyday (1943–1987), this US government facility was responsible for producing 67.4 metric tons of plutonium for nuclear weapons from its 9 nuclear reactors and 5 processing plants. This was an inefficient process that generated ~53 million gallons of solid and liquid radioactive waste, which is stored in 177 large underground tanks, and ~450 billion gallons of liquids from the nuclear reactors which was discharged to soil disposal sites. This nuclear legacy remains today at the Hanford site. For the past 35 years, the US government has spent billions of dollars to monitor, characterize, contain, and clean up the waste at Hanford. Not only is this a complex and difficult process, but exactly where that waste will be permanently stored has yet to be decided as pointed out in this issue of Elements. Moreover, since 1984, the region has also been home to a commercial nuclear energy facility (Columbia Generating Station) that generates about 10% of all the electricity in the state of Washington—enough to power the city of Seattle. The spent nuclear fuel from this facility also needs a final, permanent resting place. While federal and regional governments tussle with the how and where to store hazardous nuclear waste, the local residents live with a nuclear legacy. We are all fortunate to have scientists, such as those who contributed to this issue of Elements, helping to advance the waste removal and repository processes.

Elements has now published three issues related to our shared global nuclear legacy. The December 2006 (v2n6) issue is a primer on the environmental aspects of the nuclear fuel cycle, and our June 2012 (v8n3) issue focuses on the Fukushima Daiichi nuclear accident following the catastrophic earthquake and tsunami that hit Japan in March 2011. With the addition of this third issue on geological repositories for nuclear waste, Elements readers now have an excellent set of resources on nuclear waste at their disposal (no pun intended!). We encourage you to read all three of these issues to increase your awareness of this global nuclear legacy. Also, use them in your classrooms to educate your students about this important subject … it is one that will have an impact on future generations. Members can access all three of these issues at the Elements website.

Jodi Rosso

exit did so because they felt marginalized by their government and by the power structure of their country. The EU academics I spoke with were stunned by the exit decision. One thing that became clear to me after my limited exposure to UK public opinion was that the UK policy makers on both sides of the Brexit issue did not adequately educate the public, and some distorted the facts. The ultimate impact of this decision on UK and EU citizens is very difficult to predict.

Returning to the nuclear-waste disposal challenge, one issue that has become abundantly clear after 50 years of investigating potential nuclear-waste disposal schemes is that the site(s) selected must be both technically and socially acceptable (Metlay 2016). However, in order to convince the public that a proposed site (and its disposal technique) is acceptable, the public—as well as their representatives in local, state, and federal governments—must be educated. An excellent example of a successful public education campaign is the one that preceded the environmental cleanup of Rocky Flats (Colorado, USA), a US Environmental Protection Agency (EPA) Superfund site located 16 miles from downtown Denver where, from 1952 to 1989, plutonium (Pu) pits for US nuclear weapons were manufactured. The buildings and soil at the Rocky Flats site became contaminated by Pu after a number of fires and leaks. A group of scientists from Los Alamos National Laboratory (New Mexico, USA) held public forums that incorporated scientific debate and stakeholder education about the best cleanup solutions. Extensive scientific studies showed that physical mechanisms, particularly colloid transport, dominated the transport of Pu at the site, and it was this knowledge that allowed the most extensive cleanup in the history of EPA Superfund legislation, with billions of dollars in taxpayer savings (Clark et al. 2006).

In closing, I recommend that those interested in some of the early thinking about geological disposal of nuclear waste read the book by Konrad Krauskopf (1988), my late Stanford colleague who was one of the clearest thinkers on this complex topic.

Gordon E. Brown, Jr., Principal Editor

REFERENCES


Gordon Brown, Bernard Wood, Friedhelm von Blanckenburg, and Jodi Rosso

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FROM THE EDITORS

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Gordon Brown, Bernard Wood, Friedhelm von Blanckenburg, and Jodi Rosso

EDITORIAL Cont’d from page 227
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Thilo von Berlepsch received a Diploma in Mechanical Engineering at the University of Hannover (Germany) and a PhD from the Ruhr-University of Bochum (Germany) on nuclear safety. After working in nuclear safety and nuclear regulation at an electricity utility that operated several nuclear power plants, he moved to DBE TECHNOLOGY GmbH (the German Company for Construction and Operation of Waste Repositories) where he heads the International Cooperation Department. He has been involved in many radioactive waste disposal projects. In addition, Thilo is an active member of several international working groups organized within the International Atomic Energy Authority (IAEA).

Evaristo J. Bonano is a senior manager at Sandia National Laboratories (SNL), a US National Nuclear Security Administration facility. He received his PhD in chemical radiochemistry, nuclear waste disposal, and decision analysis for nuclear waste management. He was SNL’s Lead Laboratory licensing manager during the preparation of the license application for the proposed geologic repository at Yucca Mountain (Nevada, USA) and assumed the senior program manager role following submittal to and docketing of the license application by the US Nuclear Regulatory Commission.

Rodney C. Ewing is the Frank Stanton Professor in Nuclear Security in the Center for International Security and Cooperation in the Freeman Spogli Institute for International Studies at Stanford University (California, USA) and is also a professor in the Department of Geological Sciences in the School of Earth, Energy & Environmental Sciences at Stanford. Ewing’s research focuses mainly on nuclear materials and the geochemistry of radionuclides applied to permanent geologic disposal. Rod has written extensively on nuclear waste management. In 2006, he received the Lomonosov Medal of the Russian Academy of Sciences, and, in 2015, he received the Roehling Medal of the Mineralogical Society of America.

Bernd Grambow graduated from the Freie Universität Berlin (Germany), and is currently a professor (at “excellence” grade) at the École des Mines de Nantes (France). He holds the Chair on nuclear waste disposal in Nantes and is head of the Subatech laboratory in Nantes: Subatech is a French laboratory working on high-energy nuclear physics, on nuclear medicine, and on radiochemistry. Grambow is a former director of France’s CNRS academic/industrial research network NEEDS (nuclear, environment, energy, waste, society), and his areas of expertise include radiochemistry, nuclear waste disposal, and radionuclide migration. In 2008, he received the Grand Prix Ivan Pechès of the French Academy of Science, and, in 2013, he became Chevalier of the Ordre des Palmes Académiques.

Bernt Haverkamp has been the Deputy Head of the Department for International Cooperation at DBE TECHNOLOGY (Germany) since 2004. He received a Diploma and a PhD in geophysics from the Ruhr-University of Bochum (Germany). Before joining DBE TECHNOLOGY in 2002, he worked for 10 years for its parent company DBE, the German company for construction and operation of repositories for radioactive waste, where he was mainly involved in the geoscientific surface and underground investigation of repository sites. In his current position, Bernt has participated in several international projects on the management of radioactive waste and the evaluation of repository concepts for different host rocks.

Allan Hedin is a senior company specialist in post-closure safety assessments at the Swedish Nuclear Fuel and Waste Management Co. (SKB). He was the manager for the safety assessment known as SR-Site, which formed the basis for SKB’s license application to build a final repository for spent nuclear fuel at the Forsmark site in south-central Sweden. Allan Hedin received his MS in engineering physics from the University of Uppsala in 1983 and his PhD in ion physics from the same university in 1987. He has been employed by SKB since 1994.

Boris T. Kochkin is a principal scientist at the Institute of Geology of Ore Deposits, Petrography, Mineralogy, and Geochemistry of the Russian Academy of Sciences (IGEM RAS), Moscow. He received his PhD on the geology of sandstone-hosted uranium deposits in 1988 (IGEM RAS) and a DSc degree in 2002 (IGEM RAS). Since 1990, he has been studying the geological disposal of radioactive waste. He participated in evaluating the long-term isolation of radioactive wastes at both the Mayak Production Association site (aka PA “Mayak”, South Urals) and at the Verinskie site (Siberia). He was a member of a working group for the Russian regulation of geologically disposing of radioactive waste.

Nikolai P. Laverov has been an Academician of the Russian Academy of Sciences since 1987 and is a specialist in the fields of ore deposits, radiogeology, radiogeoecology, waste forms development and the geological disposal of radioactive waste. He is a scientific leader of the Institute of Geology of Ore Deposits, Petrography, Mineralogy, and Geochemistry of the Russian Academy of Sciences. Laverov has authored or coauthored some 500 papers, has been Vice President of the Russian Academy of Sciences, and is currently a member of the Presidium of the Russian Academy of Sciences.

Victor I. Malkovsky is principal scientist in the Laboratory of Radiogeology and Radiogeoecology at the Institute of Geology of Ore Deposits, Petrography, Mineralogy, and Geochemistry of the Russian Academy of Sciences and is Professor in Mathematical Modeling at Moscow’s D. Mendeleev University of Chemical Technology of Russia. He received his PhD in thermophysics in 1980. His research focuses on theoretical and experimental studies of how elements migrate and accumulate in geological media, including how radionuclides from radioactive wastes migrate from underground repositories. He is a member of scientific and technical council of Russia’s Rosatom Energy State Corporation.

Daniel S. Metlay is a member of the Senior Professional Staff of the US Nuclear Waste Technical Review Board (NWTRB). Daniel Metlay received his BS degrees from the California Institute of Technology (USA) in molecular biology and medieval history. He received his Masters and Doctoral degrees in political science from the University of California, Berkeley. He taught political science at Indiana University and at the Massachusetts Institute of Technology (USA). Dr. Metlay has authored numerous publications dealing with technology policy, regulation, organization behavior, and radioactive waste. In June 2012, he testified before the Senate Environment and Public Works Committee on consent-based siting processes from radioactive waste repositories.
Olle Olsson received his PhD in applied geophysics from the University of Luleå (Sweden) in 1978 and, after working in Sweden’s nuclear waste program since the 1980s, he recently retired from the position of Vice President of the Swedish Nuclear Fuel and Waste Management Co. (SKB). From 1995 to 2001, he was the director of SKB’s underground research facility, the Åspö Hard Rock Laboratory. Starting in 2002, he managed the investigations of two potential Swedish repository sites and was responsible for preparation of the license application for the proposed Forsmark nuclear waste site, located ~150 km north of Stockholm. He has been a member of the Royal Swedish Academy of Engineering Sciences since 2003.

Peter N. Swift is a senior scientist at Sandia National Laboratories in Albuquerque (New Mexico, USA). He received his PhD in geosciences from the University of Arizona in 1987, and he has had leading roles in evaluating the potential for long-term isolation of radioactive wastes at both the Waste Isolation Pilot Plant in New Mexico and the proposed Yucca Mountain repository in Nevada (USA). He is currently the National Technical Director of the US Department of Energy’s Used Nuclear Fuel Disposition R&D Campaign, providing technical leadership on secure storage, transportation, and disposal of spent nuclear fuel and high-level radioactive wastes.

Robert A. Whittleston received his PhD in geochemistry from the University of Leeds (UK) in 2011. From 2012 to 2015, he was a research manager at Radioactive Waste Management Limited, a wholly owned subsidiary of the UK Nuclear Decommissioning Authority. He was responsible for providing the science that underpins the UK’s geological disposal program. Prior to his current position as a Policy Lead at the Department of Transport (UK), Rob was a senior research manager at Hitachi Europe Ltd., establishing and managing collaborative R&D projects with UK institutions and government in support of the UK Advanced Boiling Water Reactor (new build) and the Fukushima Nuclear Power Plant (Japan) decommissioning programs.

Bruce W.D. Yardley is currently Chief Geologist for Radioactive Waste Management Limited, the UK body tasked with geological disposal, and he recently retired as Professor of Metamorphic Geochemistry in the School of Earth and Environment at the University of Leeds. His research concerns fluid–rock interactions in the crust and has embraced a range of settings and approaches. These include metal transport in hydrothermal ores, the effect of carbon sequestration on rock properties, and the controls on retrograde reactions between crystalline rocks and introduced water, as well as studies of deeper processes. His recent publications include the special Geochemical Perspectives issue “Fluids in the Continental Crust” (2014, with Robert Bodnar).

Sergey V. Yudintsev obtained his PhD in 1989 and is a specialist in the scientific basis for managing radioactive waste derived from the nuclear fuel cycle. He is Head of the Laboratory of Radiogeology and Radiogeocology at the Institute of Geology of Ore Deposits, Petrography, Mineralogy, and Geochemistry of the Russian Academy of Sciences where he researches the geochemical and mineralogical aspects of radioactive waste disposal problems, including the search for new matrices in which to place long-lived radionuclides (actinides and technetium). In his career, he has worked as a researcher and principal scientist studying how to make nuclear energy both safe and sustainable.

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Geological Disposal of Nuclear Waste: a Primer

Rodney C. Ewing¹, Robert A. Whittleston², and Bruce W.D. Yardley³

The back-end of the nuclear fuel cycle has become the Achilles Heel of nuclear power. After more than 50 years of effort, there are, at present, no operating nuclear waste repositories for the spent nuclear fuel from commercial nuclear power plants or for the high-level waste from the reprocessing of spent fuel. The articles in this issue of Elements describe the status of geological disposal in salt, crystalline rock, clay, and tuff, as presently developed in five countries.

KEYWORDS: nuclear waste, nuclear power, spent nuclear fuel, vitrified high-level nuclear waste, geological disposal, multiple barriers

For the past 50 years there has been an international effort to develop deep-mined geological repositories for the disposal of nuclear waste. This issue of Elements presents the reader with selected examples of the approaches that have been developed for different rock types—clay, salt, crystalline rock, and volcanic tuff. For each rock type, the scientific and engineering strategies are different and driven by the properties of the different geological formations, the types of waste to be disposed of, and the regulatory requirements of each country.

The earliest discussions of solutions for the disposal of nuclear waste date from the mid-1950s and the first US National Academy of Sciences (NAS) Committee on Waste Disposal report (NAS–NRC 1957). The basic principles were reaffirmed 20 years later (NAS–NRC 1978). Because radioactive waste retains potentially harmful levels of radioactivity for hundreds of thousands of years, geological disposal has been preferred from the outset. The first thoughtful scientific review by Earth scientists of what would be required was by John Bredehoeft and colleagues in 1978. This prescient paper recognized the importance of different waste types, the challenges of site characterization, the perturbations that the emplaced waste would impose on geological formations, and the time frames over which geological isolation would be required. Many ingenious, alternative ways of disposing of some, or all, of the nuclear waste inventory have been proposed, but geological disposal remains the only one that appears to offer safe, long-term disposal of all waste types. The report by the UK’s Committee on Radioactive Waste Management (CoRWM 2006) provides a comprehensive analysis of alternatives. Nuclear nations in western Europe and elsewhere had also begun to plan for geological disposal during the late 1970s and 1980s. Most countries have interacted through the International Atomic Energy Authority, which has established safety requirements for the disposal of radioactive waste (IAEA 2011a) and guidance on how geological disposal facilities should be developed (IAEA 2011b). A history of ten national programs was published recently by the Nuclear Waste Technical Review Board (2015) and, in part, is summarized in the article by Metlay (2016 this issue).

By combining these articles on different repository types into a single issue of Elements, the reader has the opportunity to compare and reflect on the different strategies. The good news is that there are a number of very different strategies, some of which seem close to coming to fruition. The bad news is that, after 50 years of effort, there is no geological repository receiving highly radioactive waste. Some countries with small nuclear programs have moved forward, and Finland has recent approval for the construction of a repository. In many countries with larger nuclear programs, such as the United States and Germany, the process appears to have stalled, although France continues to make progress. With this issue of Elements, we now have the opportunity to compare and evaluate the technical basis for the different strategies.

RADIOACTIVE WASTE TYPES

The types of waste intended for geological disposal in each country depend on both the nuclear fuel cycle adopted by that country and the national decisions about how to classify different radioactive materials. Waste types are discussed in more detail in the Box. For the purposes of this discussion, nuclear waste falls into three broad categories: 1) highly radioactive, heat-producing waste, mainly spent nuclear fuel and high-level waste from reprocessing of spent nuclear fuel; 2) less radioactive waste materials contaminated by long-lived nuclides, such as plutonium, which is generally termed “long-lived intermediate-level waste” in Europe or “transuranic waste” in the US; 3) low-level waste, mainly contaminated by short-lived radionuclides generated by medical procedures and reactor operations and suitable for shallow disposal. The first two categories are generally destined for deep, mined geological disposal.

From the perspective of geological disposal, the four critical issues for developing a repository are: 1) the radionuclide inventory; 2) how this inventory changes over time;
The radioactive content of different waste types determines the strategy for handling them, e.g. shallow disposal versus deep geological disposal. The largest volume of radioactive waste is low-level waste (LLW) and very-low-level waste (VLLW). How this is defined varies between countries, and the vast majority of these waste types will be disposed of in shallow, near-surface repositories, rather than by geological disposal.

The most radioactive wastes are spent fuel (SF) or the high-level waste (HLW) that is derived from SF reprocessing. When spent fuel is removed from a reactor it contains fission products, plutonium, traces of other actinides, and uranium. If fuel is reprocessed, the fission products are present in the resulting high-level waste, which is most commonly vitrified for geological disposal. Some of the fission products are radioactive, have relatively short half-lives, and generate significant heat. These wastes have to be kept in interim storage for several decades while the short-lived fission products undergo decay and the waste cools down, but they will continue to produce heat for hundreds of years. Spent fuel and HLW typically contain over 95% of the radioactivity in national radioactive waste inventories from nuclear power, despite making up only a few percent of the volume. Because the volumes are small, it is possible to package these types of heat-producing wastes in very resistant containers that will outlast most of the radioactivity, meaning that the waste does not interact with groundwater until after all but long-lived radionuclides remain. This strategy is the one used in the Swedish KBS-3 concept.

For countries that have reprocessed spent fuel, much of the waste volume for geological disposal consists of, in European parlance, long-lived intermediate-level waste (ILW), which includes scraps and waste generated during reprocessing as well as in reactor operation and decommissioning. For example, after the metal holders of fuel rods have been dismantled for reprocessing, scraps of spent fuel still adhere to them. This material can present particular challenges because it is longer-lived than SF and HLW, yet cannot be packaged in such durable containers because of the greater volumes.

FIGURES 1 AND 2 show the projected wastes that the United Kingdom currently considers in planning for geological disposal, assuming an additional generation of reactors is built, and that eventually all stockpiles of uranium (U) and plutonium (Pu) are treated as waste. FIGURE 1 shows the volumes of the package wastes and the masses of the waste. Clearly, ILW and U predominate, with relatively small amounts of the highly radioactive, heat-producing wastes (SF, HLW, and Pu). FIGURE 2 shows the contributions of the different waste types to the activity of the inventory at the projected time of opening of a geological repository in 2040 and onwards, with the area of the circles scaled to the total activity. The major source of radioactivity is spent fuel (much from reactors that have not yet been constructed), but eventually the contribution from uranium becomes important. The voluminous ILW is never a major contributor to the total activity, and when timescales reach hundreds of thousands of years, then uranium becomes an increasingly dominant source of activity because its long half-life means that it undergoes very little decay over this period.
3) some sense of the geochemical mobility and radiotoxicity of the radionuclides; 4) the thermal output of the waste. The challenge for geoscientists is to understand how the evolving conditions of a repository affect the geochemistry and mobility of the radionuclide inventory that is also changing over time. The decay of one radionuclide often leads to the accumulation of another: for example, $^{239}$Pu, which has a half-life of 24,100 years, decays to $^{235}$U, which has a half-life of 700 million years.

Many proposed deep-mined geological repositories are for the disposal of heat-generating spent fuel or high-level waste. But within each of these waste types there are important variations. For spent nuclear fuel, the type of fuel, burnup, and age since removal from the reactor all have an impact on the radionuclide inventory and the thermal output (Hedin 1997; Ewing 2015). For high-level radioactive waste, the type of chemical processing and the age of the waste are important. Reprocessing lowers the content of long-lived actinides, but leaves high concentrations of shorter-lived fission products, such as $^{137}$Cs and $^{90}$Sr, which have half-lives of approximately 30 years and hence a large thermal output. This heat in turn determines how long the waste must be stored at the surface before disposal. These complexities mean that countries with a long history of developing nuclear power plants and weapons programs have a wide variety of waste that requires different treatments and handling. By contrast, countries with waste from a limited range of commercial nuclear power plants have much less diverse waste streams.

MULTIPLE BARRIER CONTAINMENT STRATEGIES

A major tenet of radioactive waste management is the concept of multiple barriers. This “belt and suspenders/braces” approach envisions a series of barriers, each with a capacity to prevent, or lower, the release of radionuclides to the environment. The concept reflects a prudent approach in the face of the huge uncertainties that result from projections of physical and chemical processes over large scales, both spatial (tens of kilometers) and temporal (hundreds of thousands of years). If one barrier is less effective than expected, other barriers will provide a margin of safety. The barriers are of two types: engineered and geological.

Engineered Barriers

Engineered barriers include the waste form, the waste package, and the surrounding backfill. Most of the engineered barriers are physical in that they delay the access to water of the waste package (e.g. the Ti-drip shields proposed at Yucca Mountain, Nevada, USA) or they delay the release of radionuclides from a breached canister (e.g. the bentonite buffer in the KBS-3 concept for granite repositories [see Hedin and Olsson 2016 this issue]). In some cases, the engineered barrier has a chemical function, affecting the geochemical environment around the waste. For example, MgO is emplaced with the transuranic waste in the bedded salt repository at the Waste Isolation Pilot Plant (WIPP) in New Mexico, and high-ph cement was developed in the UK to encapsulate intermediate-level waste. In both cases, the intention is to remove CO$_2$ and provide an environment in which the solubility of actinides is lowered.

Waste Form

Although the most common waste forms for highly radioactive materials are spent nuclear fuel and vitrified high-level waste, there are many other types of waste forms (Lutze and Ewing 1988; Weber and Ewing 2013). A previous issue of Elements (2006 v2n6, “The Nuclear Fuel Cycle: Environmental Aspects”) has articles on spent nuclear fuel, borosilicate glass waste form, and crystalline ceramic waste forms. The properties of the waste form can be of critical importance for the simple reason that the waste form initially contains all of the radioactivity. To the extent that the waste form is durable and the release of radioactivity is low, the remainder of the safety analysis is easier. One approach is to tailor the properties of the waste form to match either the composition of the waste stream or the geological conditions of the waste form in the repository. As an example, the UO$_2$ in spent nuclear fuel is unstable under oxidizing conditions, but much more stable under reducing conditions. Also, the corrosion rate of the borosilicate glass is slower when the silica concentration in the groundwater is higher, although other chemical components can lead to accelerated corrosion. The properties of the waste form change as the temperature and radiation field evolve with time (Ewing 2015). Radiation damage produced mainly from the alpha-decay of actinides can lead to a radiation-induced phase transformation from the crystalline to the amorphous state (Ewing and Weber 2010).

Waste Package

The waste form is typically placed in a metal canister, which may consist of steel, copper, or more advanced corrosion-resistant alloys. In many countries, the waste producers (i.e. utilities) are required to package the waste into standard packages that the repository is designed to accommodate. Some countries intend to follow the KBS-3 concept, developed in Sweden: here, spent fuel is placed in iron holders which are then encapsulated in copper containers, and these containers are then inserted into holes that will be drilled into crystalline rock and lined with bentonite. Intermediate-level wastes are commonly encapsulated within stainless steel or iron canisters, with or without added cement.

Backfill or overpack

In order to control water movement through a repository at closure and buffer its composition, the remaining void space must be filled with a material compatible with the engineered and geological barriers. Bentonite backfill for heat-producing waste canisters has been investigated extensively. For larger waste volumes, host rock materials and cement are likely to be important. Repositories in salt will employ crushed salt, which will gradually be compacted as the excavated rooms close. Uniquely, the proposed repository at Yucca Mountain does not utilize a backfill (Swift and Bonano 2016 this issue).

Geological Barriers

Geological barriers exploit the properties of the rock and hydrologic system around the repository and are intended to extend the travel time for radionuclides to return to the biosphere. The movement of fluid through the rock is controlled by its hydraulic conductivity, which depends on matrix permeability and the presence or absence of fracture systems. Irrespective of the movement of groundwater, the mobility of the radionuclides in solution may be further retarded by dilution, sorption onto mineral surfaces, precipitation of secondary phases that contain radionuclides, and matrix diffusion.

All the proposed repository sites (to date) are located below the water table—with the exception of the Yucca Mountain site in Nevada where the proposed repository is in the unsaturated zone (Swift and Bonano 2016 this issue). The apparent “dryness” of the unsaturated zone is complicated by a high infiltration rate, the large volume of water that is held in the porosity, and rapid flow along fractures. These uncertainties, and their consequences in the oxidizing environment, have been an issue in judging the technical suitability of the site (Ewing and Macfarlane 2002). For disposal below the water table, the host rock must have a low permeability to limit the access of groundwater to the waste containers. Three types of host rock are
widely recognized as having the potential to provide a sufficiently low permeability to meet this safety requirement: 1) strong rocks with very low porosity and very few fractures, including igneous, metamorphic, and certain types of sedimentary rocks (see Hedlin and Olsson 2016 this issue); 2) relatively weak mudrocks or clays, which will not sustain open fractures for extended periods of time (Grambow 2016 this issue); 3) rock salt, which is also self-sealing (Berlepsch and Haverkamp 2016 this issue). The rock must also have appropriate physical properties to construct a repository within it. In some cases, as in granite, high mechanical strength favors construction, but the presence of fracture systems may increase the hydraulic conductivity to an unacceptable degree. In other cases, such as salt, a medium level of mechanical strength may be advantageous because plastic deformation and flow will seal the rock around the waste packages.

Thus, the petrophysical, geochemical, and hydrological properties of the geological formation have an important impact on the strategy that is adopted with the engineered barriers. Further, there are important interactions between the engineered and geological barriers. The geochemistry of the groundwater at the repository horizon may buffer its geochemical properties, which, in turn, will affect the rate of canisterister and waste-form corrosion. The physics and chemistry of the safety assessment is essentially an evaluation of how effective the barrier systems are going to be over time, a problem complicated by the coupled and evolving thermal, hydrologic, and geochemical conditions of the repository. The strategy for handling the heat of the spent nuclear fuel and high-level waste will also dictate the disposal strategy and the choice of barriers. Aged-waste in smaller packages can reduce the thermal pulse in the repository, which is important to avoid breakdown of clays if these are used in the backfill. On the other hand, larger packages and a larger thermal pulse might be used to drive water away from the surface of the waste package. Very high heat, however, can affect the condition of fuel cladding: this is a thin metal alloy wrapped around the fuel pins and in some concepts, is also considered a barrier. Also, the safety assessment has to consider regional aspects of the geology, such as seismicity, volcanism, and even climate change and glaciation. The presence of natural resources in a region must also be considered because the exploitation and extraction of resources can compromise a geological repository.

Depth of burial is obviously an important contribution to safety for geological disposal, and some have suggested that, instead of depositing waste canisters in mined cavities at depths of hundreds of meters, they might instead be lowered down boreholes to depths of up to five kilometers: “deep borehole disposal”. Others are skeptical about both the technical feasibility of such an approach, and the proportion of waste that would be suitable for borehole disposal. At present in the US, field tests are planned but have not yet begun. We have not included a paper on deep borehole disposal in this issue because it represents a fundamentally different strategy from a mined geological repository for the disposal of nuclear waste.

**REGULATORY FRAMEWORK**

Once engineers have designed the repository and scientists have studied the performance of all of the processes that affect the barrier systems, then the performance of the system of engineered and geological barriers has to be placed into a regulatory framework. The critical parameters that are measures of the success of the repository strategy may vary. In the US, early regulations specified fractional release for the different engineered barriers as compared to the inventory at some time, say 1,000 years after emplacement. For geological barriers, minimum travel times were defined for the groundwater system. These early requirements lead to subsystem requirements on each barrier that were finally judged to be suboptimal, and the early regulation with subsystem requirements was replaced by a risk-based approach. The risk-based approach requires a total system performance analysis that probabilistically provides a quantitative estimate of the dose to a person or population at a certain place and time, usually extending to one million years (the so-called “compliance period”). Although one certainly wants to understand anticipated doses to the affected public, this calculation adds the exposure pathways in the biosphere to the risk calculation. The biosphere’s complexity increases the uncertainty of the safety analysis.

While most countries extend their safety analysis to one million years, the level of the quantitative requirement varies. The Swedish KBS-3 concept is intended to provide containment of radioactivity within the engineered barriers until it has decayed to the level of the original uranium ore from which the waste was derived. Safety analyses may be based on quantitative deterministic models early in the disposal period and then be replaced by more qualitative arguments for the very long periods involved. Thus, the safety analysis itself becomes a major subject of research (Ewing et al. 1999).

Nearly as important as the compliance period is the position of the compliance boundary, i.e. the point at which calculations are made to show the level of exposure to the public. The point of compliance can vary dramatically, even within a single country. In the United States, the compliance boundary for Waste Isolation Pilot Plant (WIPP) is a square, four miles on an edge around the repository. At Yucca Mountain, the compliance boundary was a long rectangle, the long axis parallel to the expected movement of groundwater, 17 miles in length. This has the effect of including the dilution and sorption processes along this transport path as part of the barrier systems of the repository. Of course, all of these calculations require some confidence in our understanding of where people will live and their daily habits far into the future.

**PUBLIC ACCEPTANCE**

Even when there is a strong scientific basis for the safety analysis and when a regulatory agency has declared that a geological repository is safe, public acceptance is key to success. Public acceptance does not come at the end of the process, but rather is earned throughout the process from the initial site selection through license approval. In this regard, the experience in different countries has been met with different levels of success (see Metlay 2016 this issue). There is, however, one aspect of the technical strategy that has a direct bearing on communication with the public: whether the analysis of different repository strategies is simple or complex. All things being equal, a robust strategy based on simple physical and chemical principles that are readily understood is probably more useful when communicating with the public and politicians than a very sophisticated, probabilistic analysis that is less transparent. In fact, every safety analysis requires both a simple, accurate description and a more complex analysis. An important responsibility for scientists is to be sure that the simple analysis is not a “fig leaf” for the more complicated processes that are so common in geological systems. As guest editors, we hope that we have given you enough guidance so that as you read each article you can appreciate the waste disposal strategy and identify the role and efficacy of the different barrier systems. And now imagine if you had the responsibility for developing a geological repository for nuclear waste, which strategy would you adopt? ☘
REFERENCES


The CAMECA instruments use complementary analytical techniques to deliver high sensitivity, high precision analyses allowing the study of corrosion and other alteration mechanisms in glass used for the disposal of radioactive waste.

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High sensitivity ion microprobe with 50nm resolution

**LEAP® Atom Probe**
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Characterization of SON68 glass used for nuclear waste vitrification after leaching experiment. Corrosion mechanisms are measured over several microns through chemical mappings of surface cross-sections extracted by FIB-SEM and analyzed with the NanoSIMS. The different layers (PG: pristine glass, HGL: hydrated glass layer, GL: gel layer, CPL: crystalline phase layer) are revealed, allowing a better understanding of glass corrosion processes.

Atom Probe Tomography enables unprecedented ability to characterize many of the mechanisms operating on the boroalumino-silicate glass such as dissolution (the very sharp boron and sodium profiles) and ion exchange (the counter-correlated hydrogen/alkali profiles).

Analysis conducted on a LEAP 4000X HR at PNNL, USA.

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Keeping future generations safe from today’s nuclear waste relies on this waste being effectively isolated for all time. Clay rocks, or rocks with a high clay content, offer promising isolation properties over time periods that are as long as the age of their host geological formations. Constructing a repository in such material does not significantly change the clay’s isolation properties, which is a great advantage. Isolation is a function of the interplay between the slow release of radionuclides from the waste, the diffusion-controlled radionuclide migration, the establishment of a reducing geochemical environment, and the weak solubility and strong retention of the most toxic radionuclides on clay minerals and on additional engineered barrier materials.

**Keywords:** clay rock, geological disposal, nuclear waste, long term safety, radionuclides

**INTRODUCTION: THE ISOLATION PROPERTIES OF CLAY ROCK**

Since the mid 1980s, France, Switzerland, and Belgium have all initiated projects by which to dispose of high-level radioactive waste in clay rock. The French project has focused on disposing vitrified waste derived from reprocessing spent fuel; the Swiss and Belgian projects cover, to a roughly equal extent, the direct disposal of spent fuel and nuclear waste glass. The principal attractions of using clay rock as a repository are its low hydraulic conductivity (up to about 10,000 times lower than sandstone, see Table 1) – allowing only very slow diffusion-controlled radionuclide migration – its high retention properties to hold radionuclides, and its omnipresence in the form of large geological formations.

Potential disposal sites in clay rock can be found in many locations worldwide (some specific examples are mentioned below). They all exhibit tectonic stability over extended areas, have low rates of uplift or erosion, and demonstrate optimal hydrological settings over geological time periods. The degree of homogeneity, fissuring, and faulting is assessed through site characterization. One of the great advantages of clay-rock is that it is generally not going to be attractive for mining of resources, assuming that such rocks do not contain a gas or petroleum resource or that they show no geothermal advantages over other areas.

There are three principal clay-based repository projects ongoing in Europe: using the Opalinus clay rock (Early Jurassic) in Switzerland; using the Callovian–Oxfordian clay rocks of the Middle to Late Jurassic in France; and using the Boom clay rock (Early Oligocene) in Belgium. Although there has been less mining experience of clay rock as compared to hard rock or salt, a number of underground research laboratories have been constructed to address this lack of experience. These are the Mont Terri rock laboratory in Switzerland, started in 1987; the Tournemire site in France, started in 1996; the Centre de Meuse-Haute-Marne site in Bure, France, started in 2004; and the Hades, Mol site in Belgium, started in 1980. Table 1 lists some principal properties of clay rock at these underground research laboratories with some generic data for sand and limestone for comparison.

Let’s first consider the Jurassic Callovian–Oxfordian clay formation of the Paris Basin, which is the target of the CIGEO project (ANDRA 2013) and is in the districts of Meuse and Haute Marne. There is clear evidence that this 155–165 My old geological formation has been isolated effectively from the biosphere for millions of years with...
respect to groundwater movement and ion exchange on clay minerals (using Sr data). Moreover, since its deposition there has been little or no isotopic exchange and the major minerals comprising this formation, such as carbonates and silicates, are stable (Lerouge et al. 2011). This formation is covered by a 300 m thick 150 My old Oxfordian limestone and is underlain by the 250 m thick Upper Dogger limestone. The estimated age of the groundwater within these adjacent formations is about 1 Ma (Fourré et al. 2011), and hydraulic conductivities in both formations are low (about $10^{-9}$ m/s). There have been observations of anomalously high hydraulic heads within the clay formation at the Meuse/Haute Marne site (Delay et al. 2007) that exceed those of adjacent formations, as well as anomalously low hydraulic pressures in other clay formations. These characteristics have been interpreted as being analogous to large-scale natural permeability “experiments” that have run for tens of millennia, and the results allow us to rule out the presence of water-conducting fractures (Neuzil 2013). The presence of fossils, such as ammonites, and the conservation of mineral structures formed during early diagenesis (Lerouge et al. 2011) further indicate that the clay rock has been effectively isolated from the biosphere.

Clay-rock repositories may experience tectonic events. However, tectonic fissures in clay rocks (e.g. the French Callovian–Oxfordian or the Swiss Opalinus clay formations) can seal rapidly (weeks to years) due to the presence of clay minerals that swell when exposed to water. Sealing of clay formations (e.g. the Belgium Boom clay) (Bastaens et al. 2007) than for indurated clay rock. Sooner or later, the intrinsic permeability of fractured clay rock is expected to return to that of the intact non-fractured rock (Bock et al. 2010). Indeed, natural trace element concentration profiles in pore water across clay formations show that faults are hydrologically insignificant (Mazurek et al. 2011). For example, in the Swiss Opalinus clay there are visible tectonic features, such as the ~1 m thick structures associated with the main fault, that have hydraulic conductivities similar to the bulk rock (Bock et al. 2010). The scarcity of veins demonstrates the high self-sealing capacity of this formation, which helps to explain why, despite seismic activity, there are no fast water pathways for millions of years.

**CLAY-ROCK REPOSITORY DESIGN AND OPERATION**

The design of the French repository (CIGEO project, Fig. 1) makes it the world’s largest and most advanced repository in clay rock formations. CIGEO is intended to be in operation for more than 100 years and be capable of hosting about 10,000 m$^3$ of high-level waste (HLW) (~60,000 waste packages) and about 70,000 m$^3$ of intermediate-level waste (ILW) that is long-lived (~180,000 waste packages) (ANDRA 2013). This inventory covers the waste produced up to the end-of-life by the existing reactors 1 EPR and ITER. Typical HLW packages consist of a cast-iron disposal cask, with walls ~55 mm thick, that contains a stainless steel canister capable of holding ~190 L in volume (and with walls 5 mm thick) that in turn can contain ~400 kg of HLW glass. Such glass, even after 150 years, will still generate a large amount of heat.

In the center of the 130 m thick Callovian–Oxfordian clay rock formation, at a depth of ~500 m, a repository will be excavated horizontally, leaving sufficient rock thickness above and beneath (>50 m) to ensure isolation of the waste from the Oxfordian and Dogger limestones, respectively. Over its lifespan of approximately 100 years of operation, the overall footprint of the repository is expected to be ~15 km$^2$, with several million cubic metres of clay rock

**Table 1**

<table>
<thead>
<tr>
<th>Property</th>
<th>Boom Clay Rock</th>
<th>COX* Clay Rock (clay unit)</th>
<th>Opalinus Clay Rock</th>
<th>Typical Limestone</th>
<th>Typical Sandstone</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Geological Age</strong></td>
<td>Oligocene</td>
<td>Jurassic</td>
<td>Jurassic</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Absolute Age (Ma)</strong></td>
<td>32–20</td>
<td>163–158</td>
<td>180–176</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Depth (m)</strong></td>
<td>186</td>
<td>490</td>
<td>650</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Thickness of Clay Layer (m)</strong></td>
<td>100</td>
<td>153±6</td>
<td>110</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Degree of Induration</strong></td>
<td>Low</td>
<td>Slight</td>
<td>Moderate</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Unconfined Compressive Strength (MPa)</strong></td>
<td>2</td>
<td>25±7</td>
<td>6–28</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Clay Minerals (%dry wt)</strong></td>
<td>53±4</td>
<td>49±10</td>
<td>51±4</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Quartz (%dry wt)</strong></td>
<td>41±4</td>
<td>18 (10–36)</td>
<td>23±6</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Carbonates (%dry wt)</strong></td>
<td>1±1</td>
<td>28 (15–53)</td>
<td>10±2</td>
<td>84–94</td>
<td>0–7</td>
</tr>
<tr>
<td><strong>Pyrite (%dry wt)</strong></td>
<td>2±1</td>
<td>1 (0–4)</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Organic Carbon (%dry wt)</strong></td>
<td>2.4±0.4</td>
<td>1 (0–2)</td>
<td>0.6±0.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Porosity Anion / Cation Accessible (%)vol</strong></td>
<td>16 / 37</td>
<td>8.5 / 30±4</td>
<td>6 / 12</td>
<td>3–40</td>
<td>10–25</td>
</tr>
<tr>
<td><strong>Pore Size Range (µm)</strong></td>
<td>207±17</td>
<td>165±53</td>
<td>125±16</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Specific Surface Area (m$^2$/g)</strong></td>
<td>207±17</td>
<td>165±53</td>
<td>125±16</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Pore Water pH / Eh (mV)</strong></td>
<td>8.2 / ~250</td>
<td>7.2 / ~200</td>
<td>7.24 / ~167</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Pore Water Ionic Strength / log pCO$_2$</strong></td>
<td>0.02 / ~2.44</td>
<td>0.08 / ~2</td>
<td>0.23 / ~2.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Hydraulic Conductivity Parallel / Perpendicular Bedding</strong></td>
<td>1×10$^{-12}$ / 3×10$^{-13}$</td>
<td>1×10$^{-14}$ / 2×10$^{-14}$</td>
<td>1×10$^{-14}$ &gt; 1×10$^{-12}$</td>
<td>1×10$^{-8}$ / 4×10$^{-10}$</td>
<td></td>
</tr>
<tr>
<td><strong>Hydraulic Gradient Over Clay Formation</strong></td>
<td>0.02–0.04</td>
<td>0.2</td>
<td>0.05</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Effective Diffusion Coefficient Cations / Anions (m$^2$/s)</strong></td>
<td>4×10$^{-10}$ / 4×10$^{-11}$</td>
<td>2.5×10$^{-10}$ / 4.5×10$^{-12}$</td>
<td>1×10$^{-12}$ &lt; 2×10$^{-10}$</td>
<td>1×10$^{-12}$ / 2×10$^{-10}$</td>
<td></td>
</tr>
<tr>
<td><strong>Inventory Glass Canisters /Spent Fuel (t)</strong></td>
<td>390 / 4,330</td>
<td>61,410 / 5,460</td>
<td>730 / 3,217</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* COX = Callovian–Oxfordian clay rock
In the HLW disposal area, a number of long concrete-lined galleries will allow access to the horizontal micro-tunnels (ANDRA 2013) that will ultimately host the HLW packages. The micro-tunnels will be lined by cast-iron tubing (with walls several cm thick) that will allow the 2 ton HLW waste packages to be retrieved if necessary. The separation distances between any two exothermic HLW packages will be designed to limit the temperature of the adjacent rock to a maximum of 90°C. In contrast, ILW packages are planned to be hosted in large excavated ILW cells that will be lined with concrete.

Disposal compartments for HLW and ILW — and for different types of ILW — will be separated, so limiting any chemical interactions between these different waste types. Such compartmentalization will also be beneficial during the operational phase to limit the impact of accidental situations such as fire, or water inflow by failure of groundwater isolation in access shafts. Sub-units will be separated by seals many metres long. A ventilation system will prevent the accumulation of any explosive gas (notably hydrogen) and will be used to establish a depressurization zone in the nuclear area (with respect to the non-nuclear one), and will be used to establish a depressurization zone in the nuclear area. This deep repository will be linked to surface installations by shafts for the transportation of personnel, materials, equipment, and for ventilation facilities; the waste packages themselves will be transferred by means of inclined railways along an access ramp.

After repository construction, the low hydraulic conductivity of the undisturbed original host rock is predicted to be re-established by the sealing of tunnels and shafts using plugs of compacted swelling clay, such as bentonite. The swelling pressure of this plug of clay can be adjusted to surface installations by shafts for the transportation of personnel, materials, equipment, and for ventilation facilities; the waste packages themselves will be transferred by means of inclined railways along an access ramp.

Constructing a nuclear waste repository will inevitably perturb to some extent, the host-clay-rock's properties (Tsang et al. 2012). Stress redistribution around the excavated void spaces will create an “excavation damage zone”. The extension of this zone needs to be limited by appropriate linings, boltings, steel arches, and other supports. The amount of excavation-induced damage, the amount of support work, and the character of rock damage done by tunnel excavation are closely dependent on the depth of excavation, the local rock's mass strength, the orientation of tunnels in relation to in situ stress anisotropy, and the orientations of pre-existing bedding planes. Changes in pore-water pressure also need to be taken into account (Tsang et al. 2012). In the Mont Terri and Bure underground research laboratories, immediately after excavation, the excavation damage zone exhibited an increase in permeability. However, after a few years, the hydraulic transmissivity decreased by more than four orders of magnitude due to saturation with pore water and geomechanical loading. The expected long-term hydrogeological conductivities within the excavation damage zone were in the range of $10^{-10}$ to $10^{-12}$ m/s, close to that of the adjacent undisturbed rock (Blümling et al. 2007). Due to ventilation, partial desaturation of tunnel surfaces will also occur. Mineralogical transformations, such as pyrite oxidation, the formation of Fe(III) oxides, and the precipitation of CaSO$_4$, will occur on the walls of boreholes and galleries. The swelling pressure of this plug of clay can be adjusted to surface installations by shafts for the transportation of personnel, materials, equipment, and for ventilation facilities; the waste packages themselves will be transferred by means of inclined railways along an access ramp.

Emplacement of the waste may further perturb the isolation properties of the clay-rock formation. The heat load of the HLW will lead to thermo-hydromechanical stress over some tens of metres and will increase plasticity, swelling, and creep of the host clays, which actually seems to be beneficial to the sealing of fractures and to the recovery of low permeability in the excavation damage zone, eventually producing properties for the disturbed rock that are close to that of an undisturbed clay host rock (Li 2013). Nuclear waste that has been encased in cement, and the concrete lining of galleries and the concrete plugs, will all react chemically with the clay rock, leading to mineralogical transformations that could extend to as much as a metre into the clay rock after hundreds of thousands of years (Gaucher et al. 2014). Closest to the clay/concrete interface, cement phases such as calcium silicate hydrate, ettringite, and hydrogarnet are predicted to replace

**PERTURBATIONS OF THE HOST CLAY ROCK INDUCED BY WASTE EMPLACEMENT**

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montmorillonite (Gaucher et al. 2014). Anoxic corrosion of iron-based containers will lead to hydrogen production and the release of Fe^{2+}, which then will be incorporated into the local clay minerals.

The strong gamma radiation field surrounding high-level waste may also have an effect on the host clay. For example, hydrogen gas is generated via the radiation-induced decomposition of water (radiolysis). However, due to the radiation shielding provided by the 55 mm thick cast-iron wall (French concept) of the disposal casks, only minor effects are expected.

**MASS TRANSFER IN CLAY ROCK**

To assess whether the clay-rock repository concept is safe, one needs to understand mass transfer in pristine clay rock, as well as in clay rocks perturbed by repository construction and waste emplacement. We need to know the rates by which pore water could contact the waste, how gases are transported, and how mobile radionuclides may migrate in the clay rock.

To understand and to quantify the mass transfer properties of water in the clay rock, natural tracer profiles (Cl, I, Br, ^{18}O, ^{3}H, He) and radionuclides in undisturbed clay rock have been reported across different clay-rock formations (Mazurek et al. 2011). The data consistently show that diffusive transport (i.e. transport driven by chemical potential gradients) is the dominant transport mechanism for water. The diffusion profiles for soluble ions are controlled by the exchange between the layers of clay rock and the bounding aquifers above and beneath the clay-rock formation. No case of dominant advective transport in clay rocks (i.e. transport driven by pressure gradients) has been identified. Diffusion times of anions and water tracers across clay-rock layers were all in the range of millions of years, even for the Boom clay, which has the highest effective diffusion coefficients for anions among all the proposed clay-rock repository sites in Europe (Table 1). These diffusion times are probably sufficient for isolation of even the most mobile anionic radionuclides, but they are much shorter than the depositional age of the clay formations. Cation mobility is much lower than that of anions, indicating effective isolation until radioactive decay.

Ion diffusion is related to accessible porosity (Archies law), while hydraulic conductivity is related to pore size (Boving and Grathwohl 2001). When compared to sandstone or limestone, for example, this explains why hydraulic conductivity and associated advective water flow in clay rock is ~1,000–10,000 times slower than in sandstone. It also explains why diffusion is the dominant transport mechanism for clay-rocks with similar hydraulic gradients.

From molecular to macro scales, diffusion is well understood for non-sorbing species (Altmann et al. 2012). Effective diffusion rates are related to the micro-structure, the water content, the water composition, the ionic strength, the temperature, the total clay content, the accessible porosity, the mineralogy, and the pore-size distribution. For nuclear waste repositories, we need to scale up to heterogeneous clay-rock variability over tens of meters (Altmann et al. 2012). Cations can diffuse within the clay sheet interlayers as well as in the pores between mineral grains. Anions, on the other hand, can only diffuse through the centre of the pores due to anion exclusion as they approach the negatively charged clay surfaces.

In consequence, cations have higher effective diffusion coefficients than anions (see Table 1), but this does not mean that cations move faster. In fact, adsorption of cations on clay surfaces leads to a strong reduction of the apparent diffusion coefficient. For a typical retention coefficient (K_d) of cationic nuclides of, for example, 1 L/g, only 4 out of every 100,000 radioactive atoms in a given rock volume are transportable at any given time step: the others are fixed on the solid until atoms in solution are transported away. Some typical experimental retention coefficients for clays are given in Figure 2, and these show that the highest values are for tetravalent nuclides, followed by trivalent ones, divalent ones, and finally by heptavalent ones. Adsorption onto clays, essentially by inner-sphere surface complexation of the radionuclides to clay edges, is strong for highly charged cations like tri- or tetravalent actinides and tetravalent technetium, but also for ions that participate in ion exchange in clay interlayers – Cs⁺ adsorption, for example, is moderately strong (Grambow et al. 2014a). Sorption capacity decreases with decreasing clay content in the rock. Despite strong cation retention and associated low apparent diffusion coefficients, effective diffusion coefficients of the few cations remaining in the pore water are often higher than that of tritium (Robinet et al. 2011; Altmann et al. 2012).

In situ diffusion tests in underground research laboratories confirm laboratory studies. For example, after 4 years, underground test results show the expected sequence of penetration distances of the tracers (tritiated water HTO > Br >> I >> SeO_4^{2-} > Ba^{2+} > Cs > Cs^{+} > ^{137}CsX: ^{60}Co > Eu^{3+}) with >20 cm for HTO and < 1 cm for ^{137}CsEu (Gimmi et al. 2014).

The safety of nuclear waste isolation in clay rock relies strongly on ensuring the low mobility of the most toxic actinides and ^{99}Tc within the proposed host clay rock. This is achieved by making sure that there is an effective interplay between slow diffusion, strong retention, and a low solubility caused by the reducing geochemical environment. Figure 2 shows that for Tc at a typical neutral pH, the reduced form (Tc(VI)) is about 10,000 times more strongly retained on the clay than Tc(IV). This leads to migration distances of less than a meter for these nuclides (Grambow et al. 2014a), indicating that the most toxic radionuclides contribute little to the long-term radiological risk of a clay-rock repository. Reducing conditions in the natural clay formations are inferred from the stability of pyrite and the low Eh (Table 1). Repository construction will, of course, introduce oxygen: but the large amounts of iron from the waste packages and liners will ensure that the overall redox effect from repository construction will be that of reduction.

Natural organic matter of varying molecular weight exists in all clay rocks. This organic material can modify adsorption onto clay minerals. Organic matter adsorption on clay rock is partially irreversible, suggesting low mobilization (Durse et al. 2014). In case of the French Callavian–Oxfordian clay rock, less than 1% of the total organic matter is mobile in the form of small molecules like simple organic acids (Huclier et al. 2009). Some of these small molecules (e.g. suberic, sorbic, and tiglic acids) may increase rather than decrease radionuclide retention (e.g. for Eu^{3+}) on clay rock (Vu-Do 2013).

Finally, one might ask whether the radionuclides from the nuclear waste will become integrated in the natural geochemical cycle of the element in question or its...
homologues. For example, will $^{41}$Ca become incorporated irreversibly by recrystallization into the large quantities of calcite present, removing it from the migration path (Suzuki-Muresan et al. 2014)? Nickle incorporated onto Callovian–Oxfordian clay rock was counterbalanced by competitive sorption of ions of the natural pore-water system (Grangeon et al. 2015). On the other hand, $\text{Sr}^{87}/\text{Sr}^{86}$ analyses show that the main carbonate minerals (calcite, dolomite, siderite) of the French Callovian–Oxfordian clays have remained unaltered since the time of their sedimentation and early diagenesis, some 150 My ago. This observation indicates that metal ions have, for the most part, not been incorporated into carbonates beyond the near-surface region. Only the exchangeable Sr on clay surfaces and some late-precipitated celestite are in equilibrium with the present-day pore water (Lerouge et al. 2011). Hence, irreversible entrapment might be limited to a few mono layers.

**SCENARIOS CHALLENGING LONG-TERM RADIONUCLIDE ISOLATION**

In order to assess whether a repository concept is safe in the long term, one needs to analyze the performance of each of the barriers that will isolate the radioactive waste. Will they fulfill their safety functions under any type of evolution scenario? And if a barrier fails, will there be another redundant barrier that still ensures long-term safety? The answer lies in analyzing different “what-if” radiological scenarios. Taking the French vitrified waste example, a typical long-term evolution of the isolation properties of a repository in clay formations may develop in 5 sequential phases as follows:

1) **Water access to the waste container and corrosion:** Vitrified waste in its cast-iron disposal cask is surrounded by a small void space in sealed emplacement tunnels: this will result in heating of the repository. The relative humidity is close to 100%. Driven by hydraulic gradients between the clay rock and the disposal cell, but limited by the low hydraulic conductivity of the rock, clay pore-water will flow very slowly into the void space. Anoxic corrosion of the metallic iron of the disposal cask will lead to hydrogen gas production and pressure buildup. The gas pressure may slow down the arrival rate of water, but, sooner or later, water will accumulate in the disposal cell. Due to thickness reduction by corrosion of the cast-iron disposal cask, the stainless steel canister will finally breach because of lithostatic pressure. This chain of events is expected to take many thousands of years (Grambow et al. 2014b).

2) **Glass corrosion:** After container failure as outlined in phase 1 above, vapour (Neeway et al. 2012), and later water, will alter the waste glass by hydrating it, forming surface layers that incorporate sparingly soluble radionuclides (actinides, $^{99}$Tc, and others), while soluble radionuclides will dissolve. Container corrosion products, such as magnetite or siderite, will act as sinks for many radionuclides. Soluble anions like iodide become released to the extent that the waste containment glass starts to alter. Depending on the glass type, complete alteration of glass under these confined conditions in clay rock may take many hundreds of thousands to millions of years. Even after this period, solubility constraints mean that the radionuclides of highest long-term radiotoxicity (the actinides and technetium) remain largely immobilized in solid glass alteration products. In this way, the glass strongly contributes to the isolation potential of the repository system even if water comes into contact with the waste more rapidly than expected (Grambow 2006).

3) **Retention:** Water contaminated by radionuclides from the waste will come in contact with the different minerals along the migration path in the porous clay rock. Anions, such as iodide and selenide, show only little adsorption, but cations like the actinides will adsorb so strongly onto the clay rock that for any transportable atom in the pore water, 1,000 to 100,000 atoms will remain fixed on the solid phase. This will retard cation transport until complete decay in a few meters of clay rock.

4) **Migration:** The non-sorbed quantities of radionuclides, essentially anionic species like $^{129}$I, $^{36}$Cl, $^{79}$Se or, in some scenarios, organic-bound $^{14}$C, can diffuse out of the clay formation and may slowly migrate by advection through adjacent geological formations. Radionuclides may also migrate through excavated and backfilled disposal galleries, but migration paths are very long and, therefore, slower than direct diffusion through the clay rock.

5) **Dose of radiation:** Some fractions of the anionic radionuclides released during phase 4 above may eventually migrate to the biosphere where they may become diluted in fast-flowing waters and possibly contaminate deep aquifers used for irrigation. Both situations could then lead to radionuclide uptake in the food chain and the possibility of humans – if we still exist by that stage – and other animals receiving a dose of radiation. The chain of processes outlined in phases 1–5 above could form part of an expected evolution scenario. But one should remember that the whole transport path from waste emplacement to the biosphere may take many hundreds of thousands to millions of years. An alternative evolution might occur if water enters the emplacement tunnels during the operational phase prior to sealing. This could happen if shafts are not adequately isolated and they intersect groundwater-carrying formations, or by sabotage, or if decision makers hundreds of years in the future do not close the repository as planned (discussed in Grambow et al. 2014b). Such a scenario may lead to a higher release of radionuclides via galleries and shafts and needs to be avoided.

**ASSESSMENT OF THE LONG-TERM SAFETY**

The detailed spatial and temporal representations of the various repository architectures have been looked into, including performance of engineered and natural barriers,
Calculated times for breakthrough of radionuclides in the French case. Variations in thickness of clay take iodine retention on clay into account, which has been considered for the first 10,000 years in the Swiss and the French disposal concepts in clay. For much longer timescales, maximum dose values that are hundreds to a million times less than the French dose threshold of 0.25 mSv/y are predicted to occur after about 200,000 years in the Safir 2 case, 400,000 years in the French case, and 1,000,000 years in the Swiss case (dose values for the case of vitrified waste). Key dose contributing nuclides are in all cases $^{36}$Cl, $^{129}$I, and $^{79}$Se. In the Swiss case, there is also a dose contribution from organic $^{14}$C. Maximum dose contributions from nuclide release from either glass or spent fuel under “normal evolution” conditions are between ~500 to 5,000 times lower in the Swiss case than in the French case. This difference can be explained to a large extent by (1) the roughly 50 times lower inventory of glass, or 5 times lower inventory of spent fuel in the Swiss repository (2) a 5 times lower diffusion coefficient for $^{129}$I in the Opalinus clay rock as opposed to Callovian–Oxfordian clay (see Table 1); (3) the choice by the Swiss to take iodine retention on clay into account, which has been ignored in the French case. Variations in thickness of clay formation and in migration paths to the biosphere account for the remaining differences. In general, $^{129}$I contributes more to the calculated overall dose in safety assessments in clay than, for example, in granite. This is probably due to the fact that radionuclide retention barriers in granite are shorter (using bentonite backfill) or have lower retention capacity (pores of granite) per unit volume of the rock so that other radionuclides ($^{137}$Cs, U-decay series etc.) may migrate over longer distances in granite than in clay. Groundwater flow rates and associated dilution factors are, however, much higher in granite over clay rocks, resulting in potential dose contributions from $^{137}$Cs, while dosage from U-decay series nuclides will remain acceptable and dosage from $^{129}$I or $^{36}$Cl will become insignificant.

Due to the unprecedented long assessment period and the high complexity of a coupled natural and man-made barrier system, uncertainties are large when considering all possible failure scenarios, environmental boundary conditions, model parameters, model validity, data interpretation, and missing knowledge on detailed process couplings. That is why the assessment of the safety case and its uncertainties do not invoke predictions of future doses but only an assessment of the degree of certainty of not exceeding the dose thresholds (for whatever realistic scenario). Uncertainties in safety margins relative to dose thresholds can be assessed by comparing a reference situation with one or more perturbed scenarios, by performing sensitivity analyses, and by choosing alternative models and more pessimistic choices for data and modeled scenarios. In probabilistic assessments, sensitivity analyses can be used to identify the most sensitive parameters, and uncertainty analyses allow one to assess the modeled results. However, uncertainties in models, data, and scenarios are not always known for such long time periods. Large uncertainties in data do not always imply equally large uncertainties in calculated dose. Uncertainties in solubility of tetravalent actinides of as much as 7 orders of magnitude, for example, have only a small impact on the safety case due to the effective isolation of these most toxic waste constituents, even under worst-case conditions (see discussion in Grambow et al. 2014a).

Despite the encouraging safety margins that have been calculated relative to dose thresholds, the almost certain complete retention of actinides and $^{99}$Tc, and a regular peer review process by the OECD–NEA (e.g. OECD 2006), public confidence for disposing of waste nuclear material in clay is still far from being gained. Problems in credibility of safety assessments are described in Grambow et al. (2014b). Safety assessment is often considered as a purely technical compliance issue with respect to regulatory criteria. However, without offering an understanding to stakeholders, safety analyses for hundreds of thousands of years remain of little credibility to people beyond the circle of those who have performed or reviewed similar analyses. Nagra (2002b) proposed simplified “insight models” to make safety analyses understandable. The challenge is to reproduce the order of magnitude of results by simpler, easy to understand “back-of-the envelope” calculations, and to provide more qualitative supporting evidence to gain credibility.

One may, for example, simply calculate the effect of diffusion and retardation on transport by applying Ficks law and a $K_d$ value for retention, including breakthrough times (‘breakthrough’ being defined as the time at which the flux of contaminant from the contaminated sediment layer starts to become noticeable) as a function of thickness of the clay-rock formation, as illustrated in Figure 1. Anionic species such as $^{129}$I have the fastest breakthrough, which is ~200,000 years for a diffusive transport distance of 60 m (and ignoring any retention). This example corresponds well to the order of magnitude of the safety analyses results quoted above. The simple Ficks law model is sufficient to illustrate the impact of a retardation factor for iodine: Nagra (2002a) used a $K_d$ value of 0.03 L/kg, whereas ANDRA used a value of zero. Taking a retention factor of 0.07 L/kg, then the mean measured value (Montavon et al. 2014) will result in strong retardation of breakthrough to 800,000 years. A more qualitative argument for the validity of these long migration times stems from the above-mentioned mobility data of natural anionic tracers in all argillaceous formations. Figure 3 confirms that trivalent and tetravalent actinides (Np, Pu, Am, Cm, U, Th) and tetravalent $^{99}$Tc have a much stronger retention in clay rock. These elements will move through the Paris Basin (France) Callovian–Oxfordian clay rock formation as a function of depth. $K_d$ values are given in units of L/g. The dashed line marks 50 m of thickness of the clay rock barrier.

FIGURE 3 Calculated times for breakthrough of radionuclides through the Paris Basin (France) Callovian–Oxfordian clay rock formation as a function of depth. $K_d$ values are given in units of L/g. The dashed line marks 50 m of thickness of the clay rock barrier.
only a few metres into the clay rock without ever being able to leave the host formation prior to radioactive decay. That is why they do not contribute to future human dose. On the other hand, if the geochemical conditions of the repository were oxidizing, $^{99}$Tc would be in its mobile heptavalent state, Np would be pentavalent, and U hexavalent. This means that $^{99}$Tc would not be retained in the clay rock and would move out as fast as $^{129}$I. Also, actinide ions like $^{237}$NpO$_2^-$ would become rather mobile. Thus, having reducing conditions in a repository constitutes an important safety factor.

**SUMMARY**

All practical and theoretical data suggest that clay rock formations make suitable hosts for the geological containment of nuclear waste. The principal factors that ensure isolation of the waste are low water permeability, low ionic mobility, and the very significant retention of radionuclides that occur under reducing geochemical environments. A strong engineered barrier system, consisting of the nuclear waste glass and a thick cast-iron disposal cask, will further increase the isolation potential of the repository system due to slow dissolution rates of the waste glass and the strongly reducing geochemical environments that will provide very small migration distances (metres) of the most toxic radionuclides, the actinides, and technetium. The credibility of the safety case can be improved by simple “back-of-the-envelope” calculations, which can reproduce the much more sophisticated overall safety analyses to the nearest order of magnitude.

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Crystalline Rock as a Repository for Swedish Spent Nuclear Fuel

Allan Hedin1 and Olle Olsson2

INTRODUCTION

In Sweden, the power utility owners are, by law, required to safely manage and to dispose of radioactive waste from nuclear power plants. To meet this requirement, the power utilities set up the Swedish Nuclear Fuel and Waste Management Company (SKB). On 16 March 2011, SKB applied for a license to build a repository for spent nuclear fuel at Forsmark, in south central Sweden. The proposed repository uses a method in which the spent nuclear fuel is placed in iron inserts that are then placed within copper canisters and the whole package is then surrounded by bentonite clay and deposited at approximately 500 m depth in groundwater-saturated granitic rock (FIG. 1). This method has been termed the KBS-3 concept and was first described by SKB in 1983 (SKBF/KBS 1983). Around 12,000 tonnes of spent nuclear fuel, corresponding to roughly 6,000 canisters in a KBS-3 repository, are forecast to be produced from the currently approved Swedish nuclear power programme by 2045, the date when the last nuclear reactor is planned to be taken out of service. This article explains the KBS-3 repository concept, gives an account of how the Forsmark site was selected, and provides an overview of the safety assessment named SR-Site (SKB 2011) that supports SKB’s licence application.

THE KBS-3 CONCEPT

Safety Principles Behind the KBS-3 Concept

In Sweden, a final repository should meet a risk target (the risk for harm to an individual should be less than one in a million per year) and include several passive barriers. Work on the Swedish final repository project commenced at the end of the 1970s, and since then, SKB has established a number of principles for the design of a final repository in order to meet the legal requirements. These principles constitute the safety philosophy behind the KBS-3 concept, as formulated in SKB (1994, 1998). The main safety principles are summarised below.

- By placing the repository at depth in a stable geological environment, the waste is isolated from both human and near-surface environments. This means that the repository is not strongly affected by either societal changes or long-term climate change.
- By locating the repository at a site where the host rock can be assumed to be of no economic interest to future generations, the risk of human intrusion is reduced.
- The spent fuel is surrounded by several engineered and natural safety barriers.
- The primary safety function of the barriers is to contain the fuel within its canister.
- The secondary safety function of the barriers is to retard a potential release from the repository.
- Engineered barriers shall be made of naturally occurring materials that are stable over the long-term in a repository environment.
- The repository shall be designed and constructed to avoid any high temperatures that might have detrimental effects on the long-term properties of the barriers.

FIGURE 1

The KBS-3 concept for disposal of spent nuclear fuel. The spent nuclear fuel is placed in iron inserts that are then placed within copper canisters and the whole package is then surrounded by bentonite clay and deposited at approximately 500 m depth in groundwater-saturated granitic rock. FROM SKB (2011).

KEYWORDS: nuclear waste, geological repository, safety assessment

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The locations in Sweden of the sites investigated for a good geological prospects for establishing a final repository. A large body of geoscientific data was acquired showing that there are many places in Sweden with bedrock. A large body of geoscientific data was collected over the parts of Sweden with granite and gneiss. During the period 1977–1985, the SKB (and, in some cases, government organizations) carried out comprehensive investigations at eight potential sites (study sites) distributed at the foundation for the program for siting of the final repository that was developed in the early 1990s and that has since guided the siting work.

During the period 1993–2000, SKB conducted feasibility studies in eight municipalities. The purpose of these studies was to determine whether premises existed for further siting studies for a final repository in the municipality in question, while the municipality and its inhabitants were given an opportunity to form an opinion, without commitments, on the final repository project and their possible further participation. A principal task was to identify areas with bedrock that had the potential for a final repository. Geological studies, therefore, comprised a main component, but no drilling was done at this point. However, three of the municipalities had study sites in which drilling had been done earlier. Technical, environmental, and societal conditions were also studied. Within the framework of the feasibility studies, SKB also engaged in an active dialogue with private citizens, the municipality, and the county administrative board.

In 2002, two areas were prioritized for site investigations: first, Forsmark in the municipality of Östhammar; second, the Simpevarp–Laxemar area in the municipality of Oskarshamn (Fig. 2). With the consent of the municipalities, SKB initiated site investigations for a final repository in 2002. Site investigations included measuring local rock characteristics from the air, the surface, and in 1,000 m boreholes. The sizes of the investigated area at each site was approximately 10 km² and the investigations included about 20 cored boreholes down to the required 500 m repository depth or deeper. In addition, SKB made an inventory of natural and cultural values, and investigated how a repository might affect the local community. These investigations were concluded in 2008.

The strategy used by SKB for site selection put the greatest importance on the prospects for achieving long-term safety, in accordance with applicable Swedish regulations. Analyses were made of the site-related characteristics that

SITE SELECTION

The Site Selection Process

The siting process for a final repository in Sweden continued for more than 30 years. During the period 1977–1985, the SKB (and, in some cases, government organizations) carried out comprehensive investigations at eight potential sites (study sites) distributed over the parts of Sweden with granite and gneiss bedrock. A large body of geoscientific data was acquired showing that there are many places in Sweden with good geological prospects for establishing a final repository.

A principal conclusion from the study site investigations, and other studies of the bedrock, was that suitable and less suitable areas cannot be attributed to any particular part of the country, or any special geological environment within the crystalline bedrock. Instead, it was always local conditions that were of the greatest importance. Another lesson was that the siting work had to be based on the acceptance and trust of the local population. These conclusions formed the foundation for the program for siting of the final repository that was developed in the early 1990s and that has since guided the siting work.

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are of importance for long-term safety and of the prospects of executing the final repository project in a robust manner so as to take maximum advantage of the characteristics of the site.

The systematic examination of the two potential sites led SKB to conclude that Forsmark would be more suitable. In addition, it was concluded that none of the other study sites investigated provided any significant geoscientific advantages compared to Forsmark. On 3 June 2009, SKB’s Board of Directors decided that Forsmark should be the site for which SKB should apply for a license to build a final repository for spent nuclear fuel.

**The Forsmark Site**

Field data from the site investigations were interpreted and evaluated into a cross-disciplinary site-descriptive model (SKB 2008), one that involved a synthesis of geology, rock mechanics, thermal properties, hydrogeology, hydrogeochemistry, bedrock transport properties, and surface system properties. The site-descriptive model provided an understanding of the site’s properties within the different disciplines, and it also provided an assessment of the uncertainty in these properties.

Geologically, the Forsmark area consists of crystalline bedrock that belongs to the Fennoscandian Shield and that formed between 1.85 Gy and 1.89 Gy ago. The area is located on the Precambrian peneplain along the shoreline of the Baltic Sea. Forsmark contains a tectonic lens of relatively homogeneous rock surrounded by large ductile deformation zones. The rock in the tectonic lens, where the repository is to be located, is dominated by medium-grained metagranite, with a high (~20%–50%) quartz content. Subordinate rock types are pegmatitic granite, fine- to medium-grained metagranitoid and amphibolites, and other minor mafic to intermediate rocks.

The main safety-related features of the Forsmark site are as follows:

- A low frequency of water-conducting fractures at repository depth.

Three major sets of deformation zones with distinctive orientations have been recognized: 1) vertical or steeply dipping deformation zones, 2) gently south-east dipping deformation zones, and 3) gently south-dipping deformation zones. The gently dipping zones are more frequent in the south-eastern part of the site, and these have higher hydraulic transmissivities than the vertical and steeply dipping zones. The frequency of open and partly open fractures is very low below ~300 m depth. The upper 100–150 m of the bedrock that overlies the target volume contains many highly transmissive fractures in good hydraulic contact over long distances; whereas at depth, the rock has very low permeability due to very few transmissive fractures and a virtually impermeable (hydraulic conductivity of $<10^{-15}$ m/s) rock matrix (Fig. 3). At repository depth (~470 m), the average distance between subvertical transmissive fractures is more than 100 m. When taking into account the low topographic relief of the area, this results in extremely low groundwater flow at repository depth under current climatic conditions.

- Favourable chemical conditions, which include reducing conditions at repository depth and a salinity that ensures stability of the bentonite buffer.

Groundwaters in the uppermost 100–200 m of the bedrock are compositionally variable, with chloride concentrations in the range 200 to 5,000 mg/L. These values suggest the influence both of brackish marine water and of meteoric waters. At depths between 200–800 m, the salinity is fairly constant (5,000–6,000 mg/L), and, in transmissive zones, the water composition indicates remnants of water from the Littorina Sea, which covered Forsmark between 9.5 ky and 5.0 ky ago. In the sparsely fractured rock where the planned repository is to be located, Littorina water is absent below 300 m. At depths between 800 m and 1,000 m, the salinity increases to higher values. Low concentrations of sulphide, a copper-corroding agent, is another favourable property of the groundwater.

- Very low potential for any metallic or industrial mineral deposits, which reduces the risk of future human intrusion.

The rock mechanics and the other properties of importance for a safe and efficient construction of the repository are also favourable. The rock mass is stiff and strong with a deformation modulus of approximately 70 GPa and a uniaxial compressive strength of approximately 90 MPa. However, the rock stresses at Forsmark are relatively high compared to typical values of the Swedish bedrock. The maximum principal stress is estimated to be approximately 41 MPa at repository level.

The integrated conceptual model of the Forsmark site is illustrated in Figure 3. This includes groundwater flow, which occurs in the deformation zones and fractures. The repository is planned to be located in fracture domains FFM01 and FFM06 where the fracture frequency decreases significantly with depth: below 300 m it is very low, on the order of one transmissive fracture per 100 m. The groundwater at depth in the planned repository volume is old and shows no evidence of interaction with surface waters during the last 100 Ky.

**Figure 3** Three conceptual models used to assess the viability of the underground Forsmark nuclear waste repository site. In all three images, a NW–SE profile is shown. (Upper) Conceptual model for the bedrock’s fracture domains. (Middle) Conceptual model for the discrete fracture network (DFN) in the Forsmark bedrock for connected open fractures. (Lower) The present-day distribution of groundwaters in the region and their sources. Abbreviations beginning ZFM refer to rock deformation zones, FFM refer to fracture domains and RFM to rock domains. From SKB (2008) where further details are explained.
Site-adapted Repository Design

To establish a final layout for the repository’s deposition tunnels and deposition holes, a large volume of rock will have to be characterized, and this characterization can only be carried out effectively from underground excavations. This means that the characterization will develop as the construction work proceeds.

The depth for the repository will be optimised with respect to long-term safety and construction feasibility of the repository. Below 400 m, the frequency of water-conducting fractures is very low, while the rock stress is still acceptable. The approximate depth of the repository is ~470 metres.

The thermal properties of the site determine the minimum spacing of canisters to ensure that the maximum peak temperature in the buffer does not exceed 100 °C. Relatively high thermal conductivity at the site (average 3.6 W/(m.K)) facilitates closely spaced canisters and, hence, an efficient use of the rock volume. The spacing between canisters along the deposition tunnels is 6 m for most parts of the repository.

The layout is adapted to meet the requirements needed to mitigate most types of predicted earthquake hazards. This is primarily done by ensuring that all deposition holes are placed away from any local rock deformation zones that might be large enough to host future earthquakes.

THE SAFETY ASSESSMENT SR-SITE

Introduction

The safety assessment known as SR-Site forms a cornerstone of SKB’s license application for a spent nuclear fuel repository at Forsmark. The assessment took four years and involved experts internal to SKB itself and external experts from industry and academia. Reporting from the project comprised several thousand pages, including an 800-page main report (SKB 2011).

Experience from test manufacturing of the KBS-3 canisters supports the assumption that all 6,000 canisters will be tight at deposition. The key issue in the safety assessment was to assess the extent to which canisters could fail in the long-term and what the radiological consequences of such failures might be. Swedish legislation requires that the safety of the repository be analysed for one million years after closure, and a main task is, thus, to assess the extent of canister failures one million years into the future. In order to determine this, the future evolution of the repository system must be evaluated. The time perspective is given by the radioactive decay of the spent fuel which has decayed to a level roughly comparable to that of uranium ore after approximately 100,000 years.

Future states of the repository will depend on three factors: 1) the initial state of the repository; 2) the internal processes that may act on the repository (e.g. radiation, thermal, hydraulic, mechanical, chemical, and biological); 3) the external factors that may act on the repository.

Internal processes include the decay of radioactive material, which lead to the release of heat and the subsequent warming of the fuel, of the engineered barriers, and of the host rock. Groundwater movements and chemical processes might also affect both the engineered barriers and the composition of the local groundwater. External factors include the effects of future climate and climate-related processes, such as glacialations and isostatic uplift.

The initial state, the internal processes, and the external processes, as well as the way that they may interact and influence one another over many thousands of years, can never be fully described or understood. There are, therefore, unavoidable uncertainties in predicting how the repository will behave and, as a consequence, how to evaluate its long-term safety.

Repository Reference Evolution

In the assessment, a reference evolution was first analysed in detail to gain an insight into the overall evolution of the system and of the uncertainties that affect the evolution. The analysis was based on information obtained from the site investigations, and on all identified processes that could affect the system in the long-term. Focus was on the containment capacity of the system. Over relatively recent geologic time, the external conditions in the Forsmark region have been characterized by periods of temperate climate, permafrost conditions, and full glacial conditions, and in patterns that repeat in 120 Kyr cycles. In the reference evolution, the external conditions during the first 120 Kyr glacial cycle were assumed to be similar to those experienced during the most recent cycle, the Weichselian. Thereafter, seven repetitions of that cycle were assumed to cover the entire 1 My assessment period.

Much of the material presented in the reference evolution results from computer simulation studies. Initially, the evolution is characterized by transients caused by the excavation of the host rock and the construction and presence of the repository. In the longer term, the evolution is driven by changes in the external conditions.

The thermal evolution is characterized by a quick temperature increase due to the heat produced by the spent fuel, with peak temperatures in the canister, in the buffer and in the wall of the deposition hole occurring after a few tens of years. The temperature is predicted to return to the host rock’s background temperature (about 11 °C at Forsmark) in tens of thousands of years, assuming temperate climate conditions. Under glacial or, in particular, permafrost conditions, the temperature at repository depth (~470 m) will decrease, but will always be above 0 °C.

A mechanically damaged zone is expected to form during excavation, particularly below the floors of the deposition tunnels, although it is unlikely that this damage zone will form a hydraulically connected pathway. The initial thermal transients may cause limited rock spalling from the walls of the deposition holes. Over the longer term, the mechanical conditions in the repository should reflect the same structural stability that these host rocks have experienced for hundreds of millions of years. The stress regime will be influenced by the long-term build-up of tectonic stress, part of which can be released as earthquakes, notably in response to future glacial loads. Large earthquakes in major fracture zones in the vicinity of the repository are expected to be rare but cannot be fully excluded, and the layout of the repository is designed to minimize the risk of canister failures during such events.

Hydraulically, the repository is drained during construction and operation. As a consequence of the rock properties at Forsmark, the times required for resaturation of the deposition tunnel backfill and of the buffer will vary considerably between different parts of the repository and are likely to range from a few tens of years to several thousand years. In the long-term, the flow conditions in the rock are controlled by changes in the external conditions. Hydrostatic pressure at repository depth may increase from around 4.5 MPa when the climate is temperate to ~30 MPa should the thickest expected ice sheet develop during a future glaciation. Chemical variations in repository surroundings are also expected, especially during the initial phases of repository construction and operation. These include the consumption by microbes and minerals in the rock of initially entrapped oxygen in the repository, in the backfill, and the buffer. These chemical transients are expected to be followed by slowly varying conditions during the initial temperate stage and changes controlled by changing external conditions in the long-term.
Assessment of Potential Canister Failures

Three potential failure modes of the KBS-3 canisters have been identified. The first is failure due to corrosion of the copper shell. The second is failure due to shear loads on the canister should a rock fracture that intersects the deposition hole undergo shearing. The only identified cause for a fracture to shear significantly is a major earthquake in the vicinity of the repository. Such an event could induce secondary movements in the rock mass that could then cause single fractures to shear. The third failure mode is due to isostatic loads, primarily caused by high overburden pressures from future glaciers above the repository. The three canister failure modes were assessed during the reference evolution simulations. Based on that assessment, the possibility of more severe conditions for each of the failure modes was investigated.

Under the reducing conditions expected to be restored shortly after closure of the repository, the only identified significant copper-corroding agent in Swedish granitic groundwater is hydrogen sulphide (herein, termed just ‘sulphide’): this is based on well-established thermodynamic data. The corrosion of copper by sulphide results in the formation of copper sulphide (for simplicity written as Cu₂S, even though other nonstoichiometric forms are possible) and molecular hydrogen according to the following reaction:

\[ 2Cu + HS^- + H^+ \rightarrow Cu_2S + H_2 \]

The assessment showed that failure of a canister from sulphide corrosion can be ruled out, as long as the protective clay buffer is in place around the canister. The buffer material is generally stable in Swedish groundwater. However, in low ionic strength groundwater, the clay may form colloids that can be transported away, thereby eroding the buffer. Such groundwater conditions may occur after extended periods of temperate climate or under glacial conditions. For the most exposed canister positions, a substantial part of the buffer may be lost, leaving the canister more exposed to corrosion by sulphide. Over hundreds of thousands of years, failure of a highly exposed canister due to this corrosion mode cannot be ruled out. Some aspects of the assessment were of a statistical nature: they made use of data on groundwater flows and sulphide concentrations from the site investigation. The calculated likelihood that no canister fails due to corrosion during the 1 My assessment period is about 50%, implying that the likelihood that at least one canister fails is also about 50%. It is only when the highest flow rates are combined with the highest sulphide concentrations, and when these negative conditions are assumed to prevail throughout the assessment period, that failure occurs. The canister failure calculation was based on several pessimistic assumptions regarding other aspects of this failure mode. It may be possible to replace some of these by more realistic assumptions when more is learned about the site and the mechanisms of buffer erosion and canister corrosion. An additional concern for corrosion is the potential penetration to repository depth of oxygenated groundwater that might result from increased flow rates during the passage of a glacier edge over the repository. In this situation, the near-surface oxygen-consuming microbes that today help generate reducing conditions just below the surface cannot be expected to be active because there will be a lack of degradable organic substances. Extensive calculations of worst-case conditions in the safety assessment demonstrate that biotite in the rock matrix and chlorite adjacent to fractures will have sufficient reducing capacity to preclude penetration of oxygenated water to repository depth, even for the enhanced flow rates that may occur during the passage of a glacier.

Canister failures due to shear loads may occur as a consequence of large earthquakes in the vicinity of the repository. Large earthquakes are very rare in Sweden today, but cannot be ruled out in larger fracture zones over a glacial cycle, particularly during the post-glacial phase. Such earthquakes may cause secondary shear movements in larger single fractures that intersect canister positions. Efforts will be made to avoid placing canisters in such positions, but there is a small likelihood of one being inadvertently accepted. In statistical terms, the calculated likelihood that no canister fails due to shear loads during the 1 My assessment period is about 90%, implying that the likelihood that at least one canister fails is about 10%. In the analysis of this failure mode, several aspects of the calculation were treated pessimistically.

Regarding canister failures due to isostatic loads, the key concern is the enhanced hydrostatic pressures expected when a glacier covers the site. The swelling pressure from the water-saturated buffer must also be accounted for in the assessment of this failure mode. The analyses in SR-Site showed that when the most severe glacial conditions are combined with a pessimistic assessment of the maximum buffer swelling pressure, no canister failures are expected due to isostatic loads.

In conclusion, the overwhelming majority of the 6,000 canisters are expected to remain tight even one million years into the future.

Consequences of Canister Failures

For the two failure modes that could not be ruled out, radiological consequences for future inhabitants in the vicinity of the repository must be estimated. This is done by modelling the release of radionuclides from failed canisters and the further transport of these through the buffer, the host rock, and the biosphere. Key transport-related processes include diffusion and sorption in the buffer, advective transport with flowing groundwater in the host rock, and diffusion into and sorption in stagnant matrix pores in the host rock. Also, the properties of the waste form (the spent nuclear fuel) play a crucial role in these estimates of radionuclide releases. Under reducing conditions at repository depth, the ceramic uranium oxide waste matrix (in the form of uraninite) is very stable, meaning that the radionuclides embedded in the waste matrix are released at a very slow rate. This is still true for hypothetical failures shortly after the time of deposition when oxidation by radiolysis of water would be more pronounced.

In the calculations of radiological consequences, a self-sustaining farm was typically assumed to be located where radionuclides are released to the surface. In addition to considering contaminated soil, the farm is assumed to obtain water for irrigation and for domestic needs from a contaminated well. The calculated doses to the most exposed individuals are converted to a risk for fatal effects, based on the understanding of how doses from radiation affect humans. Swedish legislation stipulates that such risks may not exceed $10^{-6}$ (one in a million) per year. In comparison, the corresponding risk from natural background radiation in Sweden is typically $10^{-4}$ (one in ten thousand) per year. Figure 4 shows the calculated risk for canister failure due to corrosion and due to shear loads. The likelihood of each failure mode, according to the preceding paragraph, is embedded in the results. As seen in the figure, the sum of these two risk contributions is below the regulatory limit throughout the 1 My assessment time. This is a key argument for the safety of a KBS-3 repository at the Forsmark site.

Confidence in the Assessment Results

The KBS-3 design and the understanding of its safety have been developed over several decades. Confidence in the KBS-3 concept and in its specific implementation at the Forsmark site has been achieved for the following reasons:
The knowledge of the Forsmark site from surface-based investigations is sufficient for the assessment of long-term safety. The site has favorable conditions for safety and neither SKB’s internal experts nor the international review panel has identified any remaining site-related issues requiring resolution in order to demonstrate safety. Confidence in the site-descriptive model and in the understanding of the site is obtained by a systematic and quality-assured program for site investigations and site modelling.

There was a well-established reference design – which incorporated specified and achievable production and control procedures – that yielded an initial state of the repository system which has properties favourable for long-term safety at the Forsmark site. The engineered parts of the repository system were based on demonstrated technology and on established quality assurance procedures to achieve the initial state of the system. Examples of important aspects of the initial state of the engineered barriers include:

- The copper canister sealing quality.
- The casting quality of the cast iron insert.
- The buffer’s properties, such as density and content of montmorillonite and impurities.
- The backfill properties, which ensures its ability to keep the buffer in place and to swell.
- The appropriate adaptation of the repository to specific underground conditions and to the quality of the excavation technique.
- The quality of the deposition technique.

There is further potential for optimizing the above factors when this reference design is developed and implemented.

The scientific understanding of issues affecting long-term safety of a KBS-3 repository is mature as a result of decades of research within Swedish and other national programs and from international collaboration projects. The R&D efforts to understand repository evolution and safety have led to an understanding of key processes such as copper corrosion, shearing of canisters, other potential causes of canister failure, and of key phenomena that control retardation of radionuclides. This knowledge is systematically documented in reports in a format suitable for the safety assessment. Some concerns regarding the stability of the barrier materials have previously been raised within the scientific community. However, it is SKB’s view that such concerns have been adequately addressed both by scientific arguments in the knowledge base that underpins the safety assessment and by the amendments requested in its review.

The SR-Site main report and its supporting documents have undergone comprehensive peer review by recognized experts in the relevant fields of science.

A complete analysis of issues identified as relevant to long-term safety has been carried out in SR-Site according to an established assessment methodology. A cautious and pessimistic approach was taken when addressing uncertainties.

Documented quality assurance routines have been applied in the assessment of the initial state, in the development of the site description and in the analysis of long-term safety.

**CONCLUDING REMARKS**

The review process for the license application under the Nuclear Activities Act and the Environmental Code is still in progress (as of August 2016). To support its decisions on license applications, the Swedish government requested that the OECD Nuclear Energy Agency organize an international peer review of the post-closure radiological safety case produced by SKB. The Nuclear Energy Agency Secretariat appointed an International Review Team (IRT) consisting of 10 international specialists in 2011. The IRT found that “SKB generally gives a convincing illustration and technical basis both for the feasibility of the future repository, according to the KBS-3 design, and for its radiological long-term safety” (OECD 2012). The statements to the Swedish government from the Land and Environmental Court and from the Swedish Radiation Safety Authority are expected in 2017.

REFERENCE


The Russian Strategy of using Crystalline Rock as a Repository for Nuclear Waste

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INTRODUCTION

In Russia today there are ten nuclear power plants (35 reactors with an installed capacity of 26 GW), which generate ~18% of Russia’s total electricity. As a consequence, a significant amount of radioactive material has accumulated in Russia over the past 70 years: this derives both from defense activities and from nuclear power generation. Currently in Russia, there are about 24,000 metric tons of heavy metal (MTHM) in the form of spent nuclear fuel (SNF) from the former USSR, present-day Russia, and from Russian-type reactors operating abroad. To date, more than 3,000 MTHM of the SNF have been reprocessed (Khaperskaya 2012).

About 800 MTHM of SNF is produced in Russia annually, including spent fuel generated by nuclear reactors of Russian design elsewhere in the world that is returned to Russia. More than 200 MTHM of this amount were reprocessed in 2015. Reprocessing of one MTHM of SNF produces 13–31 m³ of high-level liquid radioactive waste (HLW), 59–78 m³ of intermediate-level radioactive waste (ILW), and 1,552–1,875 m³ of low-level radioactive waste (LLW) (Kopyrin et al. 2006). Significant volumes of ILW and LLW are also produced by the normal operation of nuclear reactors. Discharging radioactive waste to oceans, rivers, and lakes has serious ecological consequences. For more than 50 years in Russia, liquid radioactive waste was injected into deep aquifers that are isolated from the surface by rock formations having low permeabilities (Rybalchenko et al. 1998). Yet, significant amounts of liquid and solid radioactive waste are currently stored in temporary storage facilities (OECD NEA 2014). The accepted international approach to dealing with defense-derived HLW and waste from commercial SNF processing is based on their solidification and disposal in an underground geological repository.

UNDERGROUND DISPOSAL OF SOLID RADIOACTIVE WASTE IN RUSSIA

According to a March 2012 executive order of the Russian government, handling of all nuclear waste and final disposal should be completed by the federal-state enterprise known as the National Operator for Radioactive Waste Management (FSUE NO RAO), a daughter company of the Russian Federation State Nuclear Corporation (Rosatom). The legal basis for radioactive waste disposal in Russia is the statute “NP-055-14: Disposal of radioactive waste. Principles, criteria and essential safety requirements.” This Russian statute is based on the International Atomic Energy Agency (IAEA) standard SSR-5 (IAEA 2011). Based on NP-055-14, a repository satisfies safety requirements if the dose to the population should be less than 1 mSv/y on average for any consecutive five years, but should not exceed 5 mSv/y over the entire repository lifetime (defined in “NRP-99/2009: Norms of radiation safety”). The interested reader is referred to OECD NEA (2014) for further repository regulations regarding the site design, construction, loading, and operation (e.g. see sections OSPORB-99/2010, RB-023-02, and NP-093-14). Managing radioactive waste in Russia, including the safety requirements of their burial, is regulated by the Federal Law N 190-FZ (Federal Law 2011).

A road map for the selection and licensing—including the construction, operation, and preservation—of a repository site in Russia has been developed with careful regard for international experience (Kudryavtsev et al. 2008; Lobanov et al. 2011; Polyakov et al. 2013). The road map, with dates in brackets where appropriate, includes the following:

- Site selection within the granite–gneiss Nizhnemanskii Massif, which is located close to a radiochemical enterprise that has operated from 1993 to 2005.
- Formulation of an “Announcement of Intention” (a preliminary document for consideration by executive authorities) to develop an underground repository for the final disposal of HLW (2002, 2008).
- Geological engineering survey with the drilling of deep boreholes and development of a construction plan (2009–2014).
- Start of the underground research laboratory (URL) construction (2016).
Studies of the geology and radioactive waste disposal technology in the URL to assess repository safety (2016–2029).

Preparation of the safety case and acquisition of the license (by 2029).

**GENERAL CHARACTERISTICS OF THE REPOSITORY**

The specific site, of one to two kilometers in surface dimension, that was chosen for the repository was Yeniseisky (Fig. 1A), which is in the northern part of the Archean granite–gneiss Nizhne-Russkiy Massif. The site selection was based on the hydrogeological, geochemical, and physical properties of the rock, transportation convenience, and proximity to a large radiochemical enterprise. This site was characterized as suitable for the disposal of solid HLW and ILW (Kudryavtsev et al. 2008; Lobanov et al. 2011). The HLW and ILW will be placed at a depth of 450–525 m in Archean gneisses with water conductivity of 0.0009–0.002 m/day in an area of descending groundwater flow that is weakly alkaline (pH 8.6–8.7) and has reducing properties (Eh ~100 mV).

Radioactive waste intended for disposal at the Yeniseisky site is defined as belonging to one of two classes. The first class of waste includes HLW with a high rate of heat generation (up to 2 kW/m³); the second class includes HLW with a low rate of heat generation and ILW containing long-lived radionuclides. Mined drifts (Figs. 1B, 1C) will be used for disposing wastes of the first and second classes (Polyakov et al. 2013). All of the HLW will be incorporated into a glass-like waste form, whereas the ILW will be immobilized in a cement matrix. The plan calls for the disposal of 4,500 m³ of first class HLW and 155,000 m³ of second class combined HLW and ILW. Some 2,700 m³ of vitrified HLW (6,200 t of Na–Al–P glass emitting 600 MCi, or 2.22 × 10⁷ TBq of total activity) has now accumulated at the Production Association “Mayak” (Southern Urals), which is the largest radiochemical enterprise in Russia. Vitrification of the existing liquid high-level waste, stored in 14 tanks (total volume 14,564 m³, emitting 74.3 MCI), will produce an additional 5,000–6,000 t of Na–Al–P glass in a few years (Batorshin et al. 2015). The total volume of the vitrified HLW will be close to 4,500 m³, which is the capacity limit of the planned repository.

Containers with HLW of the first class will be located between two horizontal repository levels in short (75 m) vertical boreholes (Fig. 1B). Waste of the second class will be in steel canisters (1.5 m³) and will be emplaced in mined drifts that are 15–20 m in length (Fig. 1C). Repository safety will be ensured by using an engineered barrier system (EBS) and by the properties of the geological medium. Elements of the EBS include the waste form, the holding canister, degree of overlap, the bentonite buffer used for the vitrified HLW, a backfill of crushed rocks, and concrete-lined boreholes.

Liquid radioactive waste vitrification was developed in the USSR using an Na–Al–P glass. This glass has the capacity to incorporate problematic components of the HLW (e.g. Al, Si, Cr, Mo), can be produced at temperatures below 1,000°C by a one-step process without calcination of the liquid HLW, and is relatively resistant to γ- and β-radiation. The Na–Al–P glass is the preferred waste form for most of the accumulated vitrified radioactive waste in Russia (although some ILW is incorporated into a B–Si glass at the SIA “Radon” plant). Therefore, the Na–Al–P glass should be considered as the main form of HLW in the repository. The containers of radioactive waste at Yeniseisky will not be copper canisters, such as will be used in Finland and Sweden for their SNF disposal. From the Russian perspective, the use of containers made of expensive copper leads to unjustified cost without a significant improvement in safety. In the Russian repository, containers will be made of stainless steel or carbon steel. The total thickness of the inner container (about 3 mm) and of two outer overpacks is 15 mm. The thickness of the buffer for compacted bentonite is 150–190 mm, and the concrete lining of the borehole will be 60 mm thick.

**THE UNDERGROUND RESEARCH LABORATORY (URL) AT THE YENISEISKY SITE**

There are well-advanced plans to build an underground research laboratory (URL) at the Yeniseisky site, with construction due to start in 2016 (Polyakov et al. 2013). Studies in the URL should provide necessary data for preparation of the analysis of the repository safety case, which will be consistent with Russian and international regulations. Field studies of rocks and hydrogeological conditions at Yeniseisky were performed between 2008 and 2011. Ten boreholes were drilled to a depth of 700 m and 4 boreholes to a depth of 200 m. Clearly, these ten boreholes do not provide for the comprehensive characterization required for a geological repository. The URL will be used to refine determination of characteristics of the EBS and to decrease uncertainty in the data used to model radionuclide migration from the repository should the EBS fail. At the same time as the URL is being constructed, studies will be carried out on the local granite and gneiss up to the depth of 520 m, including data collection for assessing repository safety by means of computer simulations based on 3-D...

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**FIGURE 1** (A) Location of the Yeniseisky site. Yeniseisky is located 4 km from Zheleznogorsk, 4.5 km from the Yenisei river, and 60 km from Krasnoyarsk. Inset map shows more detailed location. (B) Map of the proposed Yeniseisky repository and the location of the underground research laboratory (red color). (C) Schematic illustrating the encasement of the radioactive wastes in the repository. Abbreviations are HLW (high-level radioactive waste), ILW (intermediate level radioactive waste). After Lobanov et al. (2011) and Polyakov et al. (2013).
advection-dispersion model of radionuclide migration in the geological medium. Studies of the different radioactive waste disposal technologies will start in 2025: the results should improve the process and reveal any site-specific potential interactions of the radioactive waste with the local geological medium. The repository will then be built on the basis of the results generated at the URL.

**PROPERTIES OF THE PHOSPHATE GLASS WASTE FORM**

One of the engineered barriers of the repository is the glass-like matrix used for immobilizing HLW. With regard to the specific character of the Russian waste (high content of Al, Mo, sulfates) and the existing technologies of their immobilization (one-stage melting in a Joule-heated furnace), Na–Al–P glass has been developed in Russia for the purpose of producing a viable waste form (Vashman and Polyakov 1997). This is in contrast to the borosilicate (B–Si) glass used in other countries to contain HLW (Lutze 1988). To contain the HLW that is produced after processing one ton of SNF requires about one ton of the glass. The Na–Al–P glass, however, is less thermally stable and has a higher dissolution rate after its crystallization than the borosilicate glasses (Mukhamet-Galeev et al. 1994; Vashman and Polyakov 1997).

An increase in the temperature of the waste form (the glass) due to radioactive decay will lead to an increase in the rate of its dissolution in water. The dissolution rate rises by up to 2.5 orders of magnitude in the range 70–170 °C both for Na–Al–Pglass (Mukhamet-Galeev et al. 1994) and for B–Si glasses (Lutze 1988). Formation of an alteration zone (a gel) on the surface of the B–Si glass matrix decreases the dissolution rate; however, the dissolution rate increases again once the local waters are refreshed (Lutze 1988; Grambow 2006). The protective gel layer formed on the surface of a simulated glass has a Na–Al–P composition (mass fractions in %: 27.2 Na2O, 14.4 Al2O3, 50.4 P2O5, 2.5 CuO, 2.3 Fe2O3, 1.9 Na2O2, 2.5 UO2) occurred after it was treated for 24 hours in unsaturated water steam at 300 °C. As a result, the glass changed into an aggregate of Na–Al phosphate crystals, spheres of REE–Sr–phosphate that have a monazite structure, the white layered square-shaped crystal in the center is a phosphate of Cs and U, probably of the meta-autinite group. Transferred from the matrix into the aqueous phase. This was previously observed during the hydrothermal alteration of B–Si glasses (e.g. Pirlet 2001). Understanding the potential migration of radionuclides via colloidal transport under real conditions at the selected site is a goal of further investigation at the URL.

Although the waste form (glass) is one of the principal engineered barriers, the other engineered barriers will also be thoroughly investigated: the corrosion resistance of the canister; the interactions between all the EBS elements (canister, waste form, bentonite buffer); the mechanical properties of the cement matrix and its intermediate level waste in water; and what influence an alkaline plume derived from cement dissolution (pH 13) might have on the long-term reliability of the engineered barriers.

**MODELING RADIONUCLIDE MIGRATION**

In the event of EBS failure, the reliability of radioactive waste isolation from the biosphere depends on retardation by the geology. This may be estimated by modeling radionuclide migration for a base-case scenario (as planned and operating to specifications), its variants, and disturbance scenarios of radionuclides released from the repository. For the predictive modeling, we selected a 3-D advection-dispersion model. Input data for its application include the following 3-D distributions of transport properties of the massif: permeability (k), porosity (φ), dispersion coefficients (αL, αT), and coefficients of radionuclide migration between the rocks and the groundwater (K0). For the calculation of the spatial distribution of k, we used data from pump tests in exploratory wells at the Yeniseisky site (Ozerskiy and Karaulov 2012). An analysis of these data shows that the lengths of separate fractures are limited, and longer-scale hydraulic connection between the fractures is absent. Therefore, one can assume that the geological medium is formed from blocks with horizontal dimensions of 250 m × 250 m and 50 m thick. Permeability within a block is assumed to be equal to an average value for the block; permeabilities of different blocks are, a priori, random independent values with a log-normal distribution. Parameters of the distribution are determined from a statistical analysis of packer tests (i.e. tests determining of rock permeabilities at specified depth through pumping from corresponding intervals of a borehole which are separated from the rest of the borehole by two inflatable bladders, or packers, before the pumping). A more thorough calculation of the groundwater flow velocities calls for exploratory drilling not only at Yeniseisky but also throughout the entire modeling domain. Our prelimi-
nary model calculations show that the migration of uranium after 10,000 years, in the absence of engineered barriers, will be confined within a relatively small domain (the concentration of uranium in the groundwater decreases by two orders of magnitude at a distance of ~1 km from the repository). Distribution coefficients for Np, Pu, and Am in the modeled water–rock system are less than that of U. Therefore, one can expect that a domain of pollution by the isotopes of Np, Pu, and Am will be less than that for U. However, it should be understood that colloid-facilitated transport of actinides can substantially extend the area of their migration (Malkovsky and Pek 2009). The analysis of the actinide migration will be continued by experiments at the URL.

THE ORIGINALITY OF THE RUSSIAN APPROACH

Superficially, the Yeniseisky site seems directly analogous to other proposed repositories in similar rock types. Although there are some similarities, there are also some key differences that require the Russian site to take a different approach to handling radioactive waste.

The geological features of the Yeniseisky site have much in common with the sites at Forsmark (Sweden) (see Hedin and Olsson 2016 this issue) and at Olkiluoto (Finland) (SKB 2011; POSIVA 2012). The rock types—granites and gneisses—and the nature of these rocks are similar. However, the geological setting at the Yeniseisky site is different from the sites in Finland, Sweden, and those in Canada. These latter sites are all located on ancient cratonic shields that are tectonically stable regions with very low seismicity. But the Yeniseisky site is located in a zone of Neogene–Quaternary post-platform tectonic activity where the level of seismicity can be high (up to magnitude 8), which could lead to the failure of the EBS (Kochkin and Petrov 2015). From this point of view, the Yeniseisky site has more in common with the Scandinavian sites, as in Finland, Sweden, and Canada, those in Canada. These latter sites are all located on ancient cratonic shields that are tectonically stable regions with very low seismicity. But the Yeniseisky site is located in a zone of Neogene–Quaternary post-platform tectonic activity where the level of seismicity can be high (up to magnitude 8), which could lead to the failure of the EBS (Kochkin and Petrov 2015). From this point of view, the Yeniseisky site has more in common with the other granite-hosted underground geological repositories in the world.

Despite the relative similarity to the other granite-hosted sites, the design of the Russian repository is very different from the well-known (Swedish) KBS-3 concept. The waste types (both HLW and ILW) for the Russian design are different in their compositions and in the nature of the waste forms themselves. The Na–Al–phosphate glass is a waste form for HLW that is only used in Russia. Steel, instead of copper, will be used for the waste packages. Also, the Russian wastes do not require any consideration of retrievability. The only common feature in the Russian and KBS-3 strategies is in the use of bentonite as a buffer. An important feature of the Russian repository design is that the HLW will be emplaced to make maximum use of the mined space. The mined caverns will be filled with ILW encaiscement in cement, and the vitrified HLW will be placed into wells between horizontal galleries.

Public hearings were held on 24 July 2015 in Zheleznogorsk at the location of the proposed URL at Yeniseisky, and the plans were approved by the city residents. Construction of the URL will begin this year (2016) with the financial support of a Federal Target Program on Nuclear and Radiation Safety. Thus, as of 2016, the radioactive waste repository planned for Yeniseisky has a bright future.

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Rock salt formations can make suitable hosts for the disposal of high-level radioactive wastes. The performance of salt as a host rock for a repository over million-year timescales has been investigated for the potential site for a geological repository at Gorleben in Germany. The main threat towards the stability of a natural salt barrier is its high solubility. Hence, prevention of water access into the waste emplacement area has to be ensured. Geological factors to be assessed in this context include diapirism, the formation of (future) glacial channels, the impact of loads and stresses imposed by glaciers, hydrocarbons, and the local hydrogeology. The disadvantages of salt are, however, outweighed by its beneficial properties: high thermal conductivity, good hydro-mechanical properties, and a tendency to creep and thus seal cracks. These characteristics make rock salt a very attractive candidate to host a geological repository for essentially all kinds of radioactive waste.

KEYWORDS: radioactive waste disposal natural barriers, salt characteristics, Gorleben

INTRODUCTION

Despite substantial progress in the development of geological repositories in some countries (Metlay 2016 this issue), only two geological repositories have thus far received waste packages for disposal: the Waste Isolation Pilot Plant (WIPP) in Carlsbad (New Mexico, USA) and the Endlager für radioaktive Abfälle Morsleben (ERAM) site in Morsleben (Germany). Both are constructed in rock salt. Activities at ERAM continue to be covered by an operating license, but no waste has been accepted since 1998. Even though the ERAM facility was realised in a mine previously used as a production mine, something not allowed today, the reasons for prohibiting waste acceptance are that the license had not been obtained through a planning approval process. The WIPP facility itself halted acceptance of waste in 2014 following a safety incident, which was not related to the general safety concept of a repository in salt. Following recovery efforts and installation of new safety measures and equipment, the WIPP facility is poised to resume operations in December 2016 (WIPP 2016).

The Gorleben facility in Lower Saxony (Germany), also constructed in rock salt, is projected to be the most advanced geological repository project for high-level radioactive waste (HLW) and spent fuel (SF). Activity at this facility is currently suspended for political reasons. The main reasons put forward to stop work at the Gorleben site were insufficient public involvement and the lack of a proper site selection process rather than specific safety concerns.

Design of Geological Repositories in Salt

Safety is the overriding governing principle in the design of any nuclear waste repository. Ensuring long-term safety requires a detailed knowledge of the host geology and a full technical analysis of the proposed design. Repository design at the Gorleben site has to meet not only German national mining requirements and nuclear regulations but also specific strategic requirements that include facility lifetime, retrievability of wastes, and parameters such as...
the maximum permissible temperature for the host rock. In the case of rock salt, this is 200 °C (Bollingerfehr et al. 2013). The emplaced waste canisters have to be enclosed as quickly and as tightly as possible within the containment-providing rock zone (CPRZ) and this zone must remain intact with its barrier function unimpaired by internal or external processes and events.

The German concept for a geological repository for high-level radioactive waste disposal in salt was developed along the idea that the safe performance of a repository should mainly be ensured by the natural barrier, i.e., safety does not rely on manmade engineered barriers, but rather on the predictable behaviour of the geology at the finally chosen site. Computer modelling suggests that, over a 1 Myr period, water intrusion into the CPRZ leading to release of radionuclides will not occur and that existing interstitial water is not part of the groundwater circulation in the sense of groundwater regulation.

Designing the Gorleben repository was an iterative process. As knowledge of the site increased, the repository design was refined and adjusted to the specific site and the applicable safety requirements.

Above-ground exploration comprised mainly hydrogeological and geophysical assessments. These included seismic surveys and drilling to the surface of the salt dome, as well as deep drilling and pilot drilling for the shafts. Belowground exploration started in 1986 with the sinking of two shafts and continued until 2000 when a moratorium was imposed for 10 years. In 2012, at the beginning of a second period of suspended activity, the exploration area had been mined and the site had been extensively assessed with respect to the homogeneity of the salt dome, the presence and origin of any hydrocarbons, and the chemical and physical properties of the rock salt itself.

**Table 1**

<table>
<thead>
<tr>
<th>MAIN PROPERTIES OF SALT RELEVANT FOR NUCLEAR WASTE DISPOSAL</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Argument (BMWi 2008)</strong></td>
</tr>
<tr>
<td><strong>Mechanical Properties</strong></td>
</tr>
<tr>
<td>“Experience in mining in rock salt formations proves that stable underground structures can be constructed here. Thanks to the favorable mechanical properties of rock salt, cavities can be created without any special support and maintained for decades.”</td>
</tr>
<tr>
<td>“Rock salt reacts to mechanical load with a slow, flowing movement that is known as “creeping”. This particular property of rock salt causes cavities in the rock to be “self-sealed”. As a result, the necessary geological barrier function is guaranteed in a natural way over very long periods of time once the emplacement process is complete.”</td>
</tr>
<tr>
<td><strong>Hydraulic Properties</strong></td>
</tr>
<tr>
<td>“Under natural stratification conditions, the permeability of the rock salt toward gases and liquids is extremely low. The saline solutions found today in the Gorleben salt dome are just as old as the rock salt that formed the salt dome (solution trapped during sedimentation) – i.e. over 200 million years old. This is an indicator for the fact that rock salt can be regarded as practically impervious as a host rock.”</td>
</tr>
<tr>
<td><strong>Thermal Properties</strong></td>
</tr>
<tr>
<td>“Rock salt exhibits a high level of specific thermal conductivity. For this reason, rock salt is particularly well suited as a host rock for high-level waste since the heat can be dissipated to the surrounding rock far better than in the case of crystalline or argillaceous rock, for example.”</td>
</tr>
</tbody>
</table>

**Figure 1** Simplified cross-section of the Gorleben salt dome showing the planned repository level ~1,000 m below the surface. The inner dark blue area represents the Hauptsalz sequence of the Zechstein 2 series (z2HS). Its boundary towards the Zechstein 3 series are given by the Kaliflöz Staßfurth (z2SF – Staßfurth potassium seam – red layer) and the layers from Grauer Salzton to Hauptanhydrit (z3GT–z3HA – grey salt clay to main anhydrite – green layer). The light blue and grey areas indicate the Zechstein 3 and Zechstein 4 series, respectively. The “Go-“ and “GoHy-“ numbers assigned to the black arrows at the surface refer to exploration boreholes.
**Operation of a Geological Repository in Salt**

While long-term safety is of paramount importance for the potential suitability of a site for a geological repository, the highest risk of dose exposure both to the environment and to people is during repository operation. The most risky phase is when the radioactive waste is actually being handled and the repository is still directly connected to the surface.

The German concept for a geological repository in salt, with Gorleben as an example, is illustrated in Figure 2. Waste packages carrying HLW or SF will be transported by flatbed rail wagons to the shaft and lowered to the underground facilities. Here, the wagons will take them to emplacement chambers where they will be unloaded for final emplacement. Packages will be emplaced horizontally in drifts or vertically in underground boreholes. After emplacement, crushed salt will be used to backfill the remaining drift openings (Bollingerfehr et al. 2013).

**Closure of a Geological Repository in Salt**

The objective of the geological repository closure concept is to safely contain the radioactive waste inside the salt host rock. There should be no continuous path for liquids to advect through manmade openings between the radioactive waste canisters and the overburden. As a guiding principle, the number of pathways through the CPRZ must be at a minimum. At Gorleben, this has been done in two ways. First, the emplacement drifts are entirely within the boundaries of the homogeneous Staßfurt rock salt, which excludes the existence of potential pathways along interfaces between different salt layers within the salt stratigraphy (Fig. 3). Second, only two shafts are planned: this is the minimum to ensure safe operation of the underground facility in terms of providing escape routes and adequate ventilation.

To maintain the very low permeability of the salt and to ensure that water influx does not lead to dissolution and erosion, fracturing of the rock salt has to be minimized. Furthermore, a steady convergence of rock salt around the drifts will be ensured by backfilling with crushed salt to re-establish the original rock properties.

Crushed salt will compact under lithostatic pressure and so will close the excavations tightly in the long-term (Hansen and Leigh 2011). Besides pressure, compaction of crushed salt also depends on temperature and moisture content. In a cold drift (normal rock temperature, ~38°C), the compaction process needs about 800 years for a porosity of 0.05 to be attained, whereas the same porosity can be reached in just a few years when the emplacement drift is hot (>150°C). The same porosity of 0.05 can be reached in an access drift of reduced temperature (~100°C) after about 30 years if the moisture content of the crushed salt is increased to approximately 1% compared to the normal moisture content for crushed salt produced from the excavated material, which is typically less than 0.02%. Accordingly, backfill material with a higher moisture content will be used in the main transport drift than elsewhere in order to accelerate compaction (Müller-Hoeppe et al. 2012).

In addition to backfilling, drift seals (engineered barriers) will be located close to areas where the hoisting cages of both shafts are filled and emptied (at shaft filling stations) and at selected positions in all drifts connected to the shaft. This will ensure that potential fluid pathways to and from the shaft are sealed and that the radioactive waste is isolated to the point when the crushed salt has become sufficiently compacted to be practically impermeable. First results of a full-scale in situ experiment in the Morsleben geological salt repository (Mauke and Herbert 2013) indicated that very low permeabilities would be reached a short time after seal construction. A constant pressure was applied to the seal. The pore pressure in the sealed volume, as well as, temperature and displacement properties were measured. Only three years after sealing, an integral permeability of the order of 10⁻¹⁸ m² had already been reached (Müller-Hoeppe et al. 2012).
The shaft filling station and the infrastructure areas will be backfilled with gravel, which has negligible compaction capabilities, to form a permanent porosity area to delay the increase in brine pressure at the drift seals (Müller-Hoppe et al. 2012). Other materials selected for the seals (e.g. a Ca-bentonite called Salzdetfurth, a salt concrete known as Asse, a magnesium oxychloride concrete termed Al, and compacted crushed salt) have been successfully used in previous constructions. Organic substances (e.g. asphalt and bitumen) will not be used, because not enough is known about their long-term behavior or their biological impacts under repository conditions (Müller-Hoppe et al. 2012).

THE LONG-TERM SAFETY OF A GEOLOGICAL REPOSITORY IN SALT

The safety concept for a repository in the Gorleben salt dome is based on the safe containment of radioactive waste in the CPRZ (Bollingerfehr et al. 2013). The principle of the CPRZ has been introduced by the German government for the safety requirements needed to dispose of heat-generating radioactive wastes (BMU 2010). The CPRZ ensures the containment of the radioactive waste, though it may not necessarily follow geological boundaries. After closure of the repository, no maintenance or other intervention measures will be allowed inside the CPRZ. Bollingerfehr et al. (2013) defined the CPRZ as surrounding the mined structures to a distance of 50 m.

Long-term safety of the CPRZ has to be proven for a period of 1 million years. To do this, the extent of the CPRZ must be clearly defined in space and in time. Any water that intrudes into the CPRZ must not lead to the release of radioactive waste, and any existing interstitial water must not become part of local groundwater circulation. The latter can generally be safely assumed when advective transport rates are comparable to diffusive transport rates.

Threats to the Long-Term Stability of the Containment-Providing Rock Zone (CPRZ)

Preservation of the CPRZ depends on processes that influence both groundwater flow and erosion at the surface. Future geological evolution could include processes such as diapirism, erosion and crustal deformation, while future climate change will lead to new glacial and interglacial periods. Furthermore, the potential for waste canisters to move out of the CPRZ (e.g. by sinking due to their higher density than the rock salt) must also be examined. Below, some of these issues are examined using the Gorleben site as the example because it is the one that has been developed and assessed as a potential site for an HLW geologic repository.

Salt Dissolution

Salt is highly soluble in water. This fact poses a theoretical risk that rock salt above the CPRZ can be dissolved, causing the CPRZ to become impaired. At Gorleben, the salt dome reached ground surface during the Cretaceous and around half of the original volume was dissolved (Köthe et al 2007).

Even when the salt is covered by overburden, dissolution can occur if undersaturated groundwater is present. This process, known as “subrosion” (from “subterranean erosion”), is dependent on ambient conditions like temperature, availability of water, dissolvable rock, type of reaction system (open or closed), mineralogical composition of the rock, and water chemistry. Subrosion of the rock salt formation will generate a caprock consisting mostly of gypsum. The youngest layers thereby created by the dissolution will be at the base of the caprock, closest to the top of the remaining salt (known as the salt table), while the oldest parts are at the top of the caprock sequence (Bornemann et al. 2008).

At the Gorleben site, the same characteristic subrosion textures occur in the caprock at all locations above the salt dome. The standard sequence in the upper caprock from top (oldest) to bottom (youngest) (Köthe et al. 2007) is as follows:

- Flaser and nodular gypsum (“Flasergips and Knollengips”)
- Pinstriped gypsum (“Liniengips”)
- Spotted gypsum (“Sprenkelgips”)

These upper caprock units normally only contain isolated fissures and faults or cavities. Greater fragmentation occurs in the lowermost few metres of the spotted gypsum beds and this marks the transition to the underlying caprock breccia (“Hutgesteinsbrekzie”), a mixture of lumps of the overlying caprock types with a matrix of sandstone, and possibly some of the local Nordic glacial till.

The caprock surface has a significant relief (with highs of ~ −100 m and troughs of ~ −300 m). This is attributable to the varying thickness of the caprock and the presence of a Quaternary glacial channel that partially cuts across the salt dome below which the caprock was eroded (Bornemann et al. 2008).

How the existing caprock evolves is the basis for the long-term assessment for subrosion at the Gorleben site. It is expected that over the next million years, glacial periods will occur comparable to the Elster to Weichsel glacial periods of the Quaternary. If correct, this will imply an average subrosion rate of 0.1 to 0.2 mm/y during a glacial period, leading to erosion of 100 m to 200 m of salt, assuming no deposition or other processes occur (Köthe et al. 2007; Bornemann et al. 2008). The subrosion rate from the Elster period to the present was much lower (0.05 to 0.1 mm/y), and, assuming a continuous alteration between glacial and warm periods and concomitant uncertainty, the subrosion depth at the Gorleben site is expected to be in the range 50 m to 100 m (Mrugalla 2011). For NW Germany generally, subrosion has extended down to ~ −420 m, but below ~180 m specific conditions are necessary for significant subrosion, but those are very unlikely to occur at the Gorleben site (Wolf et al. 2012).

In view of the limited extent of subrosion, the most likely scenarios for reduction of the overburden at Gorleben are diapiric uplift and the formation of glacial channels.

Salt Diapirism

The term “diapirism” describes the process of buoyant rise of (for example) rock salt through overlying rocks. Prerequisites for diapirism are a sufficient thickness of salt (at least a few hundred metres), a sufficient overburden pressure exerted by younger and denser rocks, and weak zones in the overburden (Mrugalla 2011). The development of the salt dome at Gorleben has taken place over the past 250 My (Cramer 2005) – and some movement still continues.

During the diapiric uplift of the Gorleben salt dome, the salt traveled distances of up to 5 km laterally and 3 km vertically at flow rates of up to 0.34 mm/y. The average diapiric speed at the top of the salt dome has been estimated to be no more than 0.086 mm/year, as derived from the speed of the salt in the catchment area of the salt dome and the largest cross-sectional area of the salt dome since the Cretaceous. The fastest upward movement took place...
of the canisters. Wolf et al. (2012) concluded that sinking of containers would not affect the preservation of the CPRZ at Gorleben.

**Integrity of Rock Salt as a Geological Barrier**

Further threats to the efficacy of the geological barrier system are loads and stresses that might lead to a loss of integrity via the formation of microcracks. These microcracks might create permeable pathways between the repository and the water-bearing beds. The isolating properties of the host rock in the CPRZ must be fully evaluated. Cracks, which can be numerically modelled, may be induced by tectonic, hydraulic, or cryogenic processes. Dilatancy criteria and fluid pressure criteria for hydrofracturing must be satisfied in a sufficiently thick zone around the underground workings of the repository (Mönig et al. 2012) to preclude microcracking.

The dilatancy criterion requires that deviatoric stress does not induce crack growth or the development of interconnected pore spaces. The stress state when dilatancy gives rise to damage is called the “dilatancy limit”. In the visco-elastic–plastic model, the ratio between the slope of the volumetric strain $d\varepsilon_{vol}$ and the principal strain $d\varepsilon_1$ has to be lower than or equal to $0$.

The fluid-pressure criterion describes whether fluid pressure is sufficient to cause extensional fracturing (hydrofracturing). The minimum principal stress ($\sigma_{\text{main}}$) in the barrier, plus any tensile strength ($\sigma_t$) that may be present, must be larger than the hypothetical fluid pressure ($p_F$) throughout. The BGR uses a simplified description of this criterion in which the salt is assumed to have no tensile strength. In its simplified version, the criterion is also called the “brine pressure criterion”:

$$p_F - \sigma_{\text{min}} < 0$$

Naturally formed fissures and faults are common in rock salt, but they are usually healed and closed by salt recrystallization. In Gorleben, open fissures filled with brine were detected directly during the exploration work and indirectly inferred from the inflow of brine into boreholes. It is inferred that these fissure systems are of limited extent because the flow volumes recorded in the Gorleben salt dome were low and either greatly diminished over time or ran dry completely. No fissures were encountered in the core region of the Hauptsalz, which is the area of the planned repository (Bornemann et al. 2008).

Fissuring will not, therefore, significantly impair the integrity of the barrier system at the Gorleben site during a new ice age, even if the mechanical impact of an advancing glacier reaches a maximum depth of approximately 200 m to 300 m. Similarly, the formation of fissures caused by differential cooling of the salt and the adjoining rock during permafrost conditions is not expected at a depth of 200 m. Given the depth of the Gorleben salt dome and the planned depth of the repository, undue fracturing or fissuring would not be expected (Bornemann et al. 2008).

An important rock-dependent parameter to consider, and one that influences the development of a stress field, is the ability of the rock to creep. Nearly 1,000 samples from the different stratigraphic units of the Gorleben salt diapir show distinct and large differences in the steady-state creep rates of different rock salt types. These differences in creep rates are due to differences in the impurity distribution and are mostly related to stratigraphic position. Applying a bandwidth of average values allows robust simulations to be made.
Presence of Hydrocarbons in the Salt

Hydrocarbons are part of the natural inventory of substances in and around salt deposits, and they are present at the Gorleben site. Liquid and gaseous hydrocarbons tend to rise due to their low density (compared to water). If they reach an isolating layer they may become trapped and accumulate. Because rock salt has a very low permeability for gases and liquids, such accumulations are often trapped below salt overlies. Hydrocarbons within the salt will, thus, occur in fractures, along grain boundaries, or within salt grains (Bracke et al. 2012; Wolf et al. 2012).

Hydrocarbons in porous rock formations below the Gorleben salt dome or laterally adjacent to it are separated from the repository area by large isolating salt masses. The assessment of the hydrocarbon content in the salt was suspended in 2000 due to the moratorium on activities at the site. Hydrocarbon concentrations in Hauptsalz samples range between 0.02 ppm and 443 ppm, with a median value of 0.3–0.4 ppm (Bornemann et al. 2008; Bracke et al. 2012). Hydrocarbons are not expected to impact on safety because they occur in small amounts and salt-related processes are slow (Mrugalla 2011).

Hydrogeology of the Overburden

The Cenozoic strata that covers the Gorleben salt dome forms a system of aquifers and aquitards having a maximum thickness of 430 m. Two main aquifers are separated by forms a system of aquifers and aquitards having a maximum range between 0.02 ppm and 443 ppm, with a median value of 0.3–0.4 ppm. The lower aquifer touches the cap rock and, locally, the salt table. The ground surface in the vicinity of the Gorleben has very little relief. Groundwater flow is from SW to NE. The lower aquifer waters are very saline and, due to their higher density, flow transports brine to the syncline rim and collects at the base of the aquifer (Klinge et al. 2007).

Groundwater flow in permeable layers is expected to continue throughout the assessment period (i.e. the required time for which safety has to be shown to be ensured), but might stagnate during glacial periods. Small changes in the hydraulic gradient caused by processes during a glacial period might substantially modify the flow system (Mrugalla 2011; Wolf et al. 2012) and could even reverse the groundwater flow direction (Boulton et al. 2001).

CONCLUSION

The advantages and the disadvantages of using salt as a host rock for a nuclear waste repository have been evaluated for the Gorleben site. The most significant disadvantage is salt’s high solubility. However, the beneficial properties of salt outweigh other factors: salt’s high thermal conductivity, good hydro-mechanical properties, and tendency to creep and to seal cracks. These characteristics make rock salt a very attractive candidate to host a geological nuclear waste repository. The approach developed in Germany for salt domes to find practical solutions to the safety requirements needed to host nuclear material may be replicable to other rock types, e.g. clay, as well as to bedded salt. Indeed, a project is now underway to systematically evaluate the transferability of concepts.

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For more than three decades, the US Department of Energy has investigated the potential for permanent disposal of high-level radioactive waste and spent nuclear fuel in a deep-mined repository at Yucca Mountain, Nevada (USA). A detailed license application submitted to the US Nuclear Regulatory Commission in 2008 provides full documentation of the case for permanent disposal of nuclear waste in tuff. The aridity of the site and great depth to the water table provide a disposal environment and a design concept unique among deep-mined repositories currently or previously proposed worldwide.

**KEYWORDS**: Yucca Mountain, radioactive waste, deep geological disposal, tuff

**INTRODUCTION**

Before work on the project ceased in 2010, Yucca Mountain (Nevada, USA) (Fig. 1) had been evaluated by the US Department of Energy for more than three decades as a potential site for a deep-mined repository for a portion of the United States’ spent nuclear fuel (SNF) and high-level radioactive waste (HLW). The complex background history can be read in multiple sources including Carter (1987), Long and Ewing (2004), MacFarlane and Ewing (2006), Walker (2009), Stuckless (2012), Rechard et al. (2014), Holt (2015), and Stuckless and Levich (2007, 2016). Primary references for the technical content of this paper are given in DOE (2008a, b), which remains the DOE’s principal documents of record for the project, and in Helton et al. (2014).

**LOCATION AND MISSION**

Yucca Mountain is located in the southwestern US about 145 km northwest of Las Vegas (Nevada) in arid and sparsely inhabited desert of the Great Basin (Fig. 2). The largest component of the waste considered for disposal at the site is SNF from commercial nuclear power plants, but the repository would also have accommodated HLW and SNF from national defense programs and research reactors. The total inventory of waste that could be disposed of at Yucca Mountain is limited by law to 70,000 metric tons of initial (pre-irradiation) heavy metal contained in SNF or equivalent amounts of HLW. However, the total combined mass of HLW and SNF in the US requiring permanent disposal exceeds this limit, and, since the early 1980s, national policy has anticipated that a second geological repository will ultimately be required. Commercial reactors in the US generate a total of ~2,000 metric tons of SNF per year, and, assuming no new reactors are built, the total inventory of SNF in the US at mid-century, when the last of the existing reactors are shut down, has been estimated to be ~140,000 metric tons (DOE 2013).

**SUMMARY OF THE PRIMARY COMPONENTS OF THE DISPOSAL SYSTEM**

Like essentially all other concepts for geological disposal, the repository considered at Yucca Mountain has three primary components: the natural setting that hosts the repository, including site geography and geology; the engineered barriers that help isolate the waste, including the waste packages and other structures within the underground facility; and the waste itself. The Yucca Mountain repository shares its reliance on a combination of engineered and natural barriers with other disposal concepts worldwide, but, as discussed in the following sections, specific aspects of the disposal concept at Yucca Mountain are unique. In particular, the repository would have taken advantage of local topography and the desert environment to emplace waste in horizontal tunnels mined hundreds of meters above the water table (Fig. 2). This choice would have provided rail access to the underground workings by using inclined ramps mined into the side of the mountain, and it was believed to reduce the quantity of water that might contact the waste or its packaging in the future compared to what could be expected in repositories mined below the water table. The choice allowed for the possibility of using thermal decay heat to delay the time at which liquid water might contact the packages, but it also introduced technical challenges unlike those faced by other repository concepts, including consideration of humid oxidizing environments in the disposal region and the complexity of evaluating coupled thermal, chemical, and hydrologic processes in a system that contains both liquid and gas phases.

**Geography and Geology**

Yucca Mountain is a north–south-trending ridge with approximately 150 m of vertical relief on its steeper west face (Fig. 1). Elevations in the vicinity range from ~1,500 m above sea level on the crest of the ridge to ~1,000 m above sea level in the valleys 5 km east and west of the ridge. Land at the site is owned by the US government. The nearest resident human population is in the unincorporated rural community of Amargosa Valley (Nevada), 20–30 km south of the repository site, where 1,456 people live (based on the 2010 census).
Yucca Mountain consists of successive layers of silicic Miocene-age volcanic tuff, deposited between 14 My and 11.5 My ago as pyroclastic flows and ash falls from the eruption of now-extinct calderas 10 km and more to the north (DOE 2008a, Section G1 5.2). Rock units include welded tuffs formed from ash that was compressed and fused at high temperatures immediately following deposition and nonwelded units that were deposited at lower temperatures. Displacement on multiple north-south-trending high-angle faults after deposition of the tuffs has offset the original volcanic layering and contributes to the present topography of the region. Exploratory tunnels and the waste disposal zones are located in densely welded tuff 200–300 m below the land surface in intact rock between major block-bounding faults 1–5 km apart.

Hydrology of the region is characterized by aridity and a deep water table that is ~600 m below the crest of Yucca Mountain and more than 200 m below the disposal horizon (Note: The water table in the region has been higher during wetter Pleistocene climates; past increases in water table elevation beneath the repository are estimated to have been no greater than 50 meters [DOE 2008a, Section 2.3.9.3.4]). Mean annual precipitation varies with elevation and topography from 110 mm to 208 mm (DOE 2008a, Table 2.3.1-6). Despite the arid climate, unsaturated rocks at Yucca Mountain are not dry: core data from the tuff show average porosities of ~10–40%, with residual (i.e. post-drying) water saturations ranging from 2% to 42% (DOE 2008a, Table 2.3.2-3). Groundwater flow in the unsaturated rocks is fed by intermittent infiltration at the land surface and occurs both in the rock matrix and in fractures. At least some fraction of the flow in fractures may be rapid: samples collected in the exploratory tunnels at Yucca Mountain show the presence of $^{36}$Cl and $^3$H derived from atmospheric testing of nuclear weapons, consistent with transport times from the surface of less than 50 years (DOE 2008a, Section 2.3.2.3.4.3). Within the lower-porosity welded tuffs, models indicate that flow is dominantly in subvertical fractures, focusing toward the larger faults with increasing depth. At the repository horizon, ~90% of modeled water flux occurs in fractures and 10% occurs in the rock matrix (DOE 2008a, Table 2.3.2.7). Percolation that reaches the water table below the repository horizon joins the generally north-to-south flow in a regional aquifer that carries water from the highlands to the north toward discharge points at lower elevations in the south of the site (DOE 2008a, Section 2.3.9.1).

The Engineered Features of the Repository
The engineered features of the repository include the waste packaging and the other materials emplaced in the underground disposal tunnels, including emplacement rails and pallets, ground support, and shields that would have been placed over the waste packages to divert potential drips and seeps of water (Fig. 3).
Engineered components of the repository considered at Yucca Mountain.

Waste packages would have varied in size to accommodate different waste forms, but most would have been approximately 5 m in length and 2 m in diameter. Maximum loaded weight of the packages would have been 40–73.5 metric tons. The outer shell of the waste packages would have been 2.5 cm of Alloy-22 (UNS N06022), which is a nickel-based alloy with high concentrations of chromium and molybdenum and chosen for its high resistance to general and localized corrosion in oxidizing environments. An inner vessel of 5 cm thick 316 stainless steel (UNS S31600) would provide structural support. In addition, waste packages containing commercial SNF would have included a third, and innermost, 2.5 cm thick stainless steel “transportation, aging, and disposal” canister that would have been loaded and sealed at the reactor sites (DOE 2008a, Section 1.3).

Waste would have been emplaced in approximately 100 cylindrical tunnels, 5.5 m in diameter and 600–800 m in length (FIGS. 2 AND 3). Tunnels would have a floor (“invert”) of crushed tuff overlain with steel supports and rails, the latter being used to transport waste packages and Alloy-22 emplacement pallets into the disposal region. Tunnels would be lined with perforated stainless steel sheets to provide ground support during operations. To provide an additional barrier to delay intermittent seepage from reaching the waste, a continuous 1.5 cm thick titanium (Grades 7 [UNS R52400] and 29 [UNS R56404]) drip shield would have been emplaced over the waste packages prior to closure of the repository (roughly 100 years after disposal commenced). Backfill would have been emplaced in the access tunnels and ramps (but not in the disposal regions), and the remaining surface facilities would have been removed (DOE 2008a, Section 1.3).

Radioactive Waste Considered for the Yucca Mountain Repository

Two primary waste forms were considered for the Yucca Mountain repository: first, spent nuclear fuel (SNF), of which the large majority is uranium oxide fuel from commercial power plants; second, borosilicate glass derived from the vitrification of liquid high level waste (HLW) from the defense-related reprocessing activities of the US government. In addition, the waste stream would have included smaller amounts of other irradiated fuel forms, including naval propulsion fuel, unprocessed plutonium production fuel from defense programs, and research fuel of various types (DOE 2008a, Section 1.5.1). As shown in Figure 3, the smaller-diameter HLW and DOE-managed SNF canisters (not including the naval SNF) would have been grouped in “co-disposal” packages for disposal. Commercial and naval SNF would have been disposed of in canisters containing only a single waste form, and co-disposal and SNF packages would have been placed in the same disposal tunnels. About 70% of the 11,629 waste packages evaluated in the post closure safety assessment would have contained commercial SNF (TABLE 1).

THE CONCEPTUAL BASIS FOR WASTE ISOLATION AT YUCCA MOUNTAIN

In all future scenarios, the arid environment at Yucca Mountain plays a central role in isolating the radioactive waste from the human environment. Not only is present-day mean annual precipitation small, but only a small fraction of the precipitation infiltrates below the soil horizon (Note: Modeled net infiltration over the region ranges from 1.5% to 13% of precipitation, with higher infiltration rates associated with high annual precipitation [DOE 2008a, Table 2.3.1-2]). Even under the wetter conditions that are projected to occur during future climates, the region is anticipated to remain semi-arid, with the wettest and coolest conditions perhaps analogous to those of present-day Spokane, Washington (DOE 2008a, Table 2.3.1-6). At the maximum future precipitation levels considered credible for the site, 380 mm/y, approximately 25% of precipitation is modeled to infiltrate into the rock (DOE 2008a, Table 2.3.1.4). Capillary effects at the surface of the emplacement tunnels would further reduce the amount of water that enters the disposal region. Despite the unsaturated disposal environment, water provides the primary mechanism for corroding the waste packages, degrading the waste form, and transporting.

**TABLE 1** INVENTORY CONSIDERED IN THE YUCCA MOUNTAIN REPOSITORY LICENSE APPLICATION.

<table>
<thead>
<tr>
<th>Waste Form</th>
<th>Mass [metric tons of heavy metal (MTHM) equivalent]</th>
<th>Number of disposal packages</th>
<th>Radioactivity (bequerels in year 2117)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Commercial SNF</td>
<td>63,000</td>
<td>8,213</td>
<td>1.07 × 10^10</td>
</tr>
<tr>
<td>DOE-managed SNF</td>
<td>2,333^b</td>
<td>3,416^d</td>
<td>4.03 × 10^17</td>
</tr>
<tr>
<td>Vitrified HLW</td>
<td>4,667^c</td>
<td></td>
<td>9.40 × 10^17</td>
</tr>
</tbody>
</table>

**Notes:**

a Includes 400 disposal packages that are a surrogate for naval spent nuclear fuel (SNF), which was modeled for the post-closure safety assessment as having characteristics bounded by commercial SNF.

b Includes 65 MTHM of naval SNF, projected as of 2035.

c MTHM equivalency of HLW estimated assuming 0.5 MTHM per HLW canister.

d Canisters of DOE-managed SNF and HLW would be placed together in “co-disposal” packages.

**Sources:** DOE (2008a)

Mass in Yucca Mountain inventory: DOE 2008a table 1.5.1-1

Number of disposal packages: Values used for post-closure safety assessment, DOE 2008a Section 2.3.7.4.1.

Radioactivity: Year 2117 consistent with the assumed start of post closure performance; DOE 2008a Section 2.3.7.4.1. Values derived from DOE 2008a Table 2.3.7-5.
radionuclides to the human environment. Consistent with isotopic data discussed previously, models for groundwater flow in the unsaturated zone at Yucca Mountain allow for rapid water flow in fractures. For example, about 1% of water flow in the non welded tuff above the repository is modeled to penetrate the unit in less than 50 years (DOE 2008a, Section 2.3.2.2.1.2). Although saturated conditions are not expected at any time in the disposal region, seeps and drips could be present over the waste, and relative humidity would rise as the repository cools, allowing for the possibility of condensation and the creation of continuous water films. Corrosion processes are anticipated to occur slowly on both the titanium drip shields and the Alloy-22 waste packages, with the potential for both general and localized corrosion dropping as temperature decreases with radioactive decay. Modeling that was conducted to support the 2008 license application indicated that a mean of approximately 10% of the waste packages will experience general corrosion failure within 1 million years (DOE 2008a, Figure 2.1-10).

Once corrosion exposes the waste form to humid air and seeping water, degradation processes will allow radionuclides to be mobilized in the form of both dissolved and colloidal species that are potentially capable of being transported by diffusion in thin films of water. Once radionuclides reach flowing water in fractures within the host rock, transport may occur relatively rapidly (on a scale of tens to thousands of years) downward to the water table (DOE 2008a, Figure 2.3.8-36), and then southward with regional groundwater flow. Modeled groundwater flow paths suggest that human exposure could occur through hypothetical future water withdrawal wells in the Amargosa Valley, where a shallow water table currently supports agricultural uses approximately 30 km south of the repository site and could potentially support future agricultural activities at the 18 km site boundary (Fig. 4).

Consistent with past geologic activity in the region, evaluations of the future performance of the repository have included possible disruption of the site by seismic and volcanic activity. Because of complexities inherent in predicting future geologic events, the DOE convened expert panels to provide detailed estimates, with uncertainty ranges, of the characteristics and likelihood of future seismic and volcanic activity at the site (CRWMS M&O 1996, 1998; SNL 2008a).

Ground motion events at Yucca Mountain at some point during the next million years due to earthquakes within the region are essentially certain, and the DOE’s 2008 license application included seismically induced rockfall, rubble accumulation in the tunnels (eventually leading to mechanical failure of the drip shields and changes in the capillary processes controlling seepage), damage to waste packages during accelerations, and subsequent stress corrosion cracking of packages (DOE 2008a, Section 2.3.4). Damage to the spent fuel itself was included implicitly by a conservative assumption that cladding on all non naval SNF fails at the time of emplacement (DOE 2008a, Section 2.3.7.6). Direct rupture of packages due to fault displacements within the repository block was also included in the analyses, but was less likely—major displacements being far more likely to occur on already existing faults outside of the disposal region—and of lower consequence because they would affect fewer packages than regional ground motion events, which could impact all packages in the repository.

Disruption of the site by volcanic activity in any given year is unlikely but cannot be ruled out. The most recent expert panel estimate of the mean probability of volcanic activity directly intersecting the waste is $3.1 \times 10^{-5}/y$, with an uncertainty range extending one to two orders of magnitude above and below that value (SNL 2008a). Several small basaltic cones formed ~1 Mya in Crater Flat about 7 km west of Yucca Mountain (Fig. 4), and the most recent eruption in the region occurred approximately 77,000 years ago 18 km south of the repository site (Heizler et al. 1999). Results presented in the DOE’s 2008 safety assessment are based on a mean million-year probability of igneous disruption at the site of $1.7 \times 10^{-2}$ (DOE 2008a, Section 2.4.1.6).

DOE’s 2008 license application for the repository included two volcanic disruption events. In one scenario, a subsurface igneous dike was assumed to intrude into the repository and flood the emplacement tunnels with magma. All waste packages in the repository were assumed to be so damaged that they could provide no further protection for the waste and the entire radionuclide inventory was assumed to be then available for groundwater transport following the event. In the second volcanic disruption scenario, an eruptive conduit was assumed to form within the repository footprint. Waste packages intersected by the conduit were assumed to be disrupted and the waste entrained in the rising magma and brought to the surface in lava flows and ash. Models estimated the transport of radioactive waste to an off-site receptor by both direct deposition of an airborne ash plume and the subsequent redistribution of ash by fluvial processes in intermittent stream channels (DOE 2008a, Section 2.3.11).

**Figure 4** Modeled groundwater flow paths originating in the saturated zone below the repository considered at Yucca Mountain, superimposed on a false-color composite Landsat image of the region. Note circular areas of irrigation at the southern boundary of the image. Note also dark regions southwest of the repository site that correspond to million-year-old basaltic volcanoes. **GROUNDWATER FLOW PATHS FROM FIGURE 2.3.9-15 IN DOE (2008a); BASE IMAGE FROM US GEOLOGICAL SURVEY.**
EVALUATING LONG-TERM PERFORMANCE FOR REGULATORY COMPLIANCE

To evaluate compliance with long-term regulatory requirements (see text box), the DOE constructed a total system performance assessment (TSPA) model capable of generating multiple Monte Carlo realizations of repository evolution. Component-level submodels of the TSPA covered a broad range of processes associated with the interactions of the natural and engineered systems—climate change, infiltration, unsaturated zone flow, thermal hydrology in the disposal region, rock fall, evolving water chemistry, corrosion, waste form degradation, radionuclide transport in unsaturated and saturated rock, atmospheric transport of contaminated ash, and dose conversions in the biosphere—and each provided a quantitative estimate of uncertainty in the component’s future behavior. In total, the TSPA incorporated approximately 25 submodels, which collectively used thousands of input parameters; for the purposes of Monte Carlo uncertainty analyses, 387 parameters were sampled as independent variables in tens of thousands of realizations of various scenarios (SNL 2008b, Appendix K). For a full review of the Yucca Mountain TSPA and its component submodels, see DOE (2008a, Section 2.4), SNL (2008b), Helton et al. (2014) and references therein.

The DOE’s 2008 license application included analyses of scenarios representing (1) the undisturbed evolution of the site, (2) early failure of waste packages and drip shields due to undetected manufacturing defects, (3) disruption by seismic ground motion and fault displacement, and (4) disruption both by intrusion of an igneous dike and by volcanic eruption. Consistent with regulatory requirements, dose estimates for each scenario included consideration of event probabilities and associated uncertainties. Dose estimates for each scenario were summed to generate an overall distribution of dose estimates, and the overall mean dose estimate was displayed for comparison to regulatory limits (Fig. 5). The peak estimated mean annual dose was 0.02 mSv/y (2.0 mrem/y), occurring at the end of the 1 Myr assessment period.

For most of the million-year period, the largest contributions to the total estimated dose come from the seismic ground motion and igneous intrusion scenarios, in part because both are assumed to affect the entire waste disposal region and have the potential to result in the exposure of large amounts of waste to groundwater. Contributions from other disruptive scenarios are significantly smaller and have little impact on the mean, primarily because of the smaller number of waste packages involved. Releases due to nominal corrosion and degradation processes are negligible for much of the assessment period, but they increase after general corrosion causes waste package failures. As modeled, this starts to happen ~600,000 years after closure. By the end of the assessment period, releases resulting from general corrosion processes are the largest contributor to the estimated mean annual dose.

The largest contributions to total dose come from isotopes of plutonium. Other first-order contributors to the total dose at 1 million years include $^{237}$Np and $^{226}$Ra (included for dose estimates with its short-lived decay product, including $^{222}$Rn), and $^{129}$I. The prominent contribution of plutonium and neptunium to the peak dose at 1 million years reflects solubility limits of actinide elements that are higher in oxidizing environments than in chemically reducing conditions, and is in contrast to dose estimates conducted elsewhere in the world for repository concepts located in such settings. Similarly, the contribution of $^{228}$Ra, which with its half-life of 1,600 years exists at 1 million years only due to ingrowth, reflects the mobility of

REGULATORY REQUIREMENTS FOR LONG-TERM SAFETY

The primary US regulatory standard for long-term performance for a nuclear waste repository at Yucca Mountain is a limit on the estimated annual radiation dose received by an individual member of the general public during the 1 million years after repository closure. Dose estimates are to be quantitative and are to be computed using “performance assessment,” which “estimates the dose incurred by the reasonably maximally exposed individual, include the associated uncertainties, as a result of releases caused by all significant features, events, and processes, weighted by their probability of occurrence” (Title 10 Code of Federal Regulations part 63.2). Specifically, “compliance is based upon the arithmetic mean of the projected doses” and “DOE must demonstrate, using performance assessment, that there is a reasonable expectation that the reasonably maximally exposed individual receives no more than [an annual dose of] … 0.15 mSv (15 mrem) for 10,000 years following disposal … and 1.0 mSv (100 mrem) after 10,000 years but within the peroid of geologic stability,” defined to be 1 million years (10 CFR 63.302, 63.303, and 63.311). Additional requirements define criteria for identifying the features, events, and processes that must be included in the performance assessment, and specify the characteristics of the reasonably maximally exposed individual and its location at the site boundary above the highest future groundwater concentration of radionuclides, which, functionally, is a location 18 km south of the repository.

FIGURE 5

Distributions of total expected annual radiation dose after repository closure. (Left) Plot showing the first 10,000 years. (Right) Plot showing the entire million-year time period. After Figure 2.4-10 in DOE (2008a).
its long-lived parent species $^{234}\text{U}$ and $^{230}\text{Th}$ in the oxidizing environment. The fourth largest contributor to the peak dose at 1 million years, accounting for about one-tenth of the total, is $^{129}\text{I}$, which is highly mobile in essentially all chemical environments: its contribution would be unchanged by the presence of reducing conditions.

**SUMMARY OF THE SAFETY CASE FOR THE REPOSITORY AT YUCCA MOUNTAIN**

As is the case for other repository concepts, the Yucca Mountain repository would have relied on both natural and engineered components to achieve robust isolation of the radioactive wastes. Attributes of the natural system that contribute to long-term safety include the aridity of the region, the low rate of water infiltration into the mountain, the capillary diversion of water around openings in the unsaturated rock, the depth to the water table below the repository, and the long lateral flow path in saturated rocks before the water table is close enough to the surface to make future human use likely. Attributes of the engineered system that contribute to robust isolation include the structurally robust stainless steel inner waste packages, the corrosion-resistant Alloy-22 outer shell of the waste packages, and the defense-in-depth provided by the choice of an alternative corrosion-resistant metal (titanium) for the drip shields above the waste packages. The DOE's approach to evaluating the long-term safety of the repository, consistent with regulatory requirements, explicitly includes hypothetical disruption of the site by future geologic events, including seismic and volcanic activity. Dose estimates for all scenarios were below regulatory limits.

In addition, the site provides significant advantages to an overall safety case that considers both operational and post closure risks. Specifically, the choice of a design without backfill allows for an extended period of ventilation prior to repository closure, providing an effective way to remove radioactive decay heat from the repository. The ability to dispose of much larger waste packages than envisioned for other repository concepts has the potential to reduce the time and labor associated with packaging the waste. Site geology and topography facilitate rail access to the disposal region by relatively low-angle inclined ramps and allow for a repository design that accommodates a larger quantity of waste than that considered for any other repository worldwide.

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Every nation that has adopted a strategy for the long-term management of its high-level radioactive waste (HLW) and spent nuclear fuel (SF) has opted for disposal in a deep-mined, geological repository. Identifying a site for such a facility has proven to be a technical and social challenge. Over the last 50 years, both challenges have been met (at least so far) in only three of the ten countries that have tried. This historical experience makes clear how important it is to gain social acceptability for a site’s selection: such acceptability is a prerequisite for policymaking in democratic societies. The inability to gain social acceptability has proven to be the Achilles’ heel for most efforts to choose a repository site.

**INTRODUCTION**

In 1957, a committee convened by the US National Academy of Sciences advanced a blueprint for addressing the long-term management of high-level radioactive waste (HLW) and spent nuclear fuel (SF) (Hess et al. 1957). This committee proposed that the waste could be disposed of hundreds of meters underground in specially constructed mined cavities. If a site were properly chosen, a repository system comprising both natural and engineered barriers would provide a high level of protection from the toxic effects of the waste. This approach has been embraced by all countries that have decided on a long-term management strategy.

As these countries have discovered, however, a proposed repository site must not only be technically suitable but also be socially acceptable. For many years, the implementers of national waste-management programs believed that social acceptability could be secured by relying on the authority of science and the power of government. In pluralistic democracies, however, such shortcuts are rarely workable. Achieving a sustainable level of social acceptability requires, at a minimum, a transparent process that respects the views of interested and affected parties, that appreciates the authenticity of those beliefs, and that incorporates into action the positions held by others. Crafting such a process has been problematic. Indeed, the quest for social acceptability has become the Achilles’ heel of most national site-selection efforts. Those interested in avoiding this pitfall in the future need to understand why the pursuit of social acceptability has so often failed, and why that understanding, in turn, needs to be grounded in prescriptions for what to do next.

**HISTORICAL EXPERIENCE**

The search for technically suitable and socially acceptable repository sites for HLW and SF began in the mid-1960s. Since then, some two dozen discrete site assessments have been launched in ten countries. Seventeen were terminated. Of those, work was halted in 14 because the implementer was unable to secure a sustainable level of social acceptability. In only three countries—Finland, France, and Sweden—has the site-selection process reached what appears to be a stable conclusion (NWTRB 2015). Herein, six case studies will illustrate the wide range of outcomes that can arise once a nation commits to identifying a location where HLW and SF might be isolated and contained for hundreds of thousands of years. NWTRB (2015) provides additional information and examples.

**Canada**

In 1996, the Canadian government established a panel to review the safety case that had been developed by Atomic Energy of Canada Limited (AECL) to dispose of SF in granitic basement rock. The panel concluded (Seaborn Panel 1998, p 2):

“From a technical perspective, safety of the AECL concept has been on balance adequately demonstrated for a conceptual stage of development, but from a social perspective, it has not... The concept in its current form does not have the required level of acceptability to be adopted as Canada’s approach for managing nuclear fuel wastes.”

**NOTE:** Affiliation is for identification purposes only. The views presented here are those of the author and do not represent the views of the US Nuclear Waste Technical Review Board, an independent federal agency charged with evaluating the technical and scientific validity of the actions taken by the Secretary of Energy to implement the Nuclear Waste Policy Act, as amended.

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2 Research conducted under the rubric of “science and technology studies” supports the proposition that assessments of “technical suitability” and judgments about “social acceptability” are not independent of each other. The distinct drawing between “facts” and “values” by logical positivists does not hold for issues where technical uncertainties are high and conflicts over goals are intense. Just how that interdependence manifests itself varies from issue to issue and case to case. Readers interested in this subject should refer to NWTRB (2015) (pp 143–157) to see how that interdependence expressed itself in the search for repository sites.

3 The remaining case is the selection of the Waste Isolation Pilot Plant (WIPP) repository site in New Mexico (USA) to dispose of transuranic waste generated in the US nuclear weapons complex.
To reconstitute its waste management program, Canada brought into force the Nuclear Fuel Waste Act in 2002, which assigned responsibility to a new utility-owned entity, the Nuclear Waste Management Organization (NWMO). Between 2002 and 2005, NWMO held public meetings and consultations throughout the country. Afterwards, the NWMO proposed to implement its Adaptive Phased Management plan, which was rooted in voluntarism. Communities would be invited to learn about the implications of hosting a repository for SF. They could withdraw for any reason up to the point when large investments to develop a facility would have to be made (NWMO 2005). In 2007, the Canadian government accepted NWMO’s proposal.

In 2010, a set of site-suitability criteria was finalized by the NWMO that would be used to determine whether there were locations within any volunteer community that might be suitable for developing a repository. What distinguishes NWMO’s approach was that the criteria not only specified technical characteristics of a suitable site but also included requirements that “go beyond safety” to consider the well-being of a community and its neighbors (NWMO 2010).

Twenty-two communities expressed an interest in learning being of a community and its neighbors (NWMO 2010). Twenty communities participated in the initial screenings (Step 2) and preliminary assessments of potential sites against the requirements. As of June 2016, nine localities had passed through the first round of assessments. Of the 13 communities no longer involved, none withdrew of their own volition.

NWMO’s leaders recognized that repository sitting can be an extremely fragile process. The achievements of the NWMO thus far are due, in part, to the organization’s internal culture, which gives much more than lip-service to respectful listening: it allows localities and First Nation tribes to set the terms of their interactions. By all external indicators, it would appear that NWMO has developed a reservoir of trust and acceptance of those with whom it engages.

**France**

Beginning in 1987, the French implementer known as ANDRA, then part of the larger Atomic Energy Commission, sought to investigate sites for a repository for HLW in four host rocks: granite, schist, argillite/clay, and salt. Without much advance notification, technical teams arrived at four locations, prepared to carry out a series of surface-based geological investigations. This approach prompted the mayors of each town to organize voter initiatives, which overwhelmingly rejected the studies. Opponents took to the streets, causing the French government to threaten to bring in the police to protect the geoscientists.

By late 1989, the protests had become so intense that Prime Minister Michel Rocard declared a moratorium on the studies and set in motion a parliamentary process to revise France’s siting strategy. In 1991, a new law, the Research in Radioactive Waste Management Act, came into force. The legislation reconstituted ANDRA as an independent body and charged it with finding sites for two underground research laboratories, one in clay, the other in granite. If the geology at either of the sites proved to be technically suitable, ANDRA would seek permission to develop a repository.

In 1993, the law’s author, Christian Bataille, was appointed mediator and charged with creating a sustainable consensus and a responsible, democratic, and transparent process. He told the French newspaper *Le Monde*, “I propose to verify the geological feasibility of the projects that will be volunteered by interested regions, and not, as was done before, attempt to convince populations of the sites [that were] pre-selected for their geological qualities” [as quoted in Mays (2004)]. Bataille subsequently met with local leaders in eight of France’s departments (a department being a type of regional subdivision used in France). Following those consultations, Bataille concentrated his efforts on four areas: Vienne, Meuse, Haute-Marne, and Gard. Vienne is underlain by crystalline rock; the others by clay/argillite.

In 1997, the technical overseer of the French waste-management program, the National Committee on Scientific Evaluation, published an influential critique that effectively removed the Vienne site from further consideration. Soon it became clear that the Gard site was socially unacceptable, at least to wine producers in the community who were concerned about risks to the public image of the wine produced nearby. As one industry representative argued, “Wine is 40 percent liquid and 60 percent dreams” (Barthe and Mays 2001). Subsequently, only a merged Meuse/ Haute-Marne candidate site remained. Communities along the border of the two departments welcomed their selection as a site for an underground research laboratory (Fig. 2), knowing that the laboratory might be the precursor for an operating repository.

Under the 1991 legislation, however, underground research laboratories had to be established both in clay/argillite and in granite to support claims about the “feasibility” of constructing a repository in both host-rock types. The disqualification of the Vienne site led the government to appoint what was colloquially termed the “Granite Mission” to determine whether a community sitting atop a suitable crystalline rock formation might be willing to volunteer.

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4 Personal communication with the French Embassy representatives and according to the Third Committee Assessment Report to the National Committee on Scientific Evaluation in Paris, France, September, 1997.
From the outset in 1999, however, the mission inherited conflicting, and perhaps incompatible, mandates. On the one hand, it was limited to considering only 15 areas, preselected by the BRGM (the French national geological survey) on an “indisputable” technical basis. On the other, it was expected to engage in a “collegial consultation” exercise with the chosen communities.

Demonstrations arose once the BRGM’s candidate sites became publicly known. Hundreds of mayors and leaders of general and regional councils signed petitions against the mission’s work and refused to meet with it. The mission’s members sought to engage with the communities from afar. But the hostility facing the mission could not be finessed, and the government abruptly cancelled it in May 2000.

Although pockets of opposition remain, in 2006, the communities around the Meuse/Haute-Marne underground research laboratory strongly supported the passage of legislation designating a “transposition zone” around that site as the location for a repository to dispose of France’s HLW.

**Germany**

In 1973, the West German government proposed the development of a nuclear waste-management center, consisting of a commercial reprocessing plant, a centralized storage facility for vitrified HLW, and a repository. When the process for identifying a site for this nuclear waste-management center broke down three years later, the government of the State of Lower Saxony decided to search for a site on its own. It began a four-phased process that assessed more than 100 settings. Four possible sites—at Wahn, Lichtenhorst, Höfer, and Gorleben—entered the final round of evaluation. Gorleben emerged as the presumptive choice, not the choice of site. However, that several technical considerations would not, in fact, disqualify the site, the document noted five specific generic issues where “doubts” had been raised. Because “further exploration of the Gorleben salt dome cannot contribute to the clarification of these outstanding questions,” a moratorium on site investigations, which was slated to last from three to ten years, was put in place (quoted in Ahlström et al. 2001, p 30). Except for a brief period in late 2010, when the Christian Democratic Party regained sole power in federal elections, the moratorium has not been lifted. The decision in 2011 to phase out nuclear power by the mid-2020s opened the door to the passage of radioactive waste-management legislation in 2013. Under the law, an independent siting commission was authorized and instructed to make recommendations for a new siting process. As of June 2016, the commission had not completed its work.

**Sweden**

The utility-owned Swedish Nuclear Fuel and Waste Management Company (SKB) initiated efforts to identify a repository site for its SF in 1977. The first test drillings were in crystalline bedrock at Finnsjön, close to the Forsmark nuclear complex north of Sweden’s capital, Stockholm, and at Kråkemåla, near the Oskarshamn nuclear power station south of the capital. These early studies evoked little notice. Desiring to obtain representative samples of the granite, SKB expanded its investigations shortly thereafter. Local residents strongly criticized the company for failing to consult prior to launching its investigations. In Kynnefjäll, ~135 km north of Gothenburg, community groups built a guard hut on a hillside overlooking the sole road to the proposed test site. In Almunge, ~75 km north of Stockholm, the confrontations between the demonstrators and SKB were so intense that the Minister of Energy and the Environment rebuked the company for its autocratic behavior.

By 1988, a new generation of leaders at SKB realized that they had to obtain the consent of the municipalities before site investigations could be resumed. It is unclear why they failed to recognize this condition sooner. Long-established law in Sweden gives municipalities a strong voice in the repository approval process.5

Four years later, SKB sent an invitation to all 286 municipalities asking whether they would permit “feasibility” studies to be carried out within their borders. Only two—Malå and Storuman—in the north, far away from Sweden’s twelve operating reactors, were initially open to the possibility. Proponents and opponents, many from outside the

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5 Swedish municipalities can veto the granting of a license to construct a repository, not the choice of site. However, that possibility, in a practical sense, forced SKB to obtain permission to carry out the feasibility studies and the more detailed surface-based site investigations.
two municipalities, stimulated a vigorous debate. Referenda were held in each community. In Malå, 54% voted against the studies; the figure in Storuman was 71%.

SKB subsequently wrote to the five municipalities hosting existing nuclear facilities—Nyköping, Oskarshamn, Östhammar, Varberg, and Hässelby—asking whether, on second thought, they might be interested. The first three agreed; the last two declined. Shortly thereafter, three neighboring municipalities—Älvsåker, Hultsfred, and Tierp—agreed to accept the feasibility studies. Eventually, SKB eliminated Älvsåker because of the complexity of its hydrogeology. Nyköping and Tierp dropped out.

In the final analysis, SKB’s choice boiled down to the Laxemar site in Oskarshamn and the Forsmark site in Östhammar. (The Hultsfred site was too far removed from SKB’s nautical transportation system.) For nearly a decade, SKB personnel embedded themselves in both municipalities. Acting in a transparent and open fashion, they extensively engaged the residents and established strong bonds of trust with them. By the time site investigations ended in 2009, officials in both municipalities raised no objections to the selection of a site within their communities.

United Kingdom

For decades, the United Kingdom focused on the disposal of its intermediate-level and other non-heat generating waste forms. That task ended in 2008 when the British government issued a White Paper (the name given to a governmental proposal) adopting the “Managing Radioactive Waste Safely [MRWS] Program” (DEFFRA 2008) for all wastes. Much like Canada’s Adaptive Phased Management approach, the MRWS process called for volunteers but, in contrast, emphasized the idea of partnership with local governments. In the event, only three local authorities in Cumbria (northwest England and the home of the Sellafield site where most UK waste is stored, but which is also a major tourist destination) were prepared to engage.

A partnership to explore the possibility of hosting a repository was formed that included the three local authorities (Cumbria County Council and the subordinate Allerdale and Copeland Borough Councils in West Cumbria), 12 nongovernmental organizations, and four neighboring local authorities. In 2012, the partnership issued a comprehensive report (West Cumbria MRWS Partnership 2012). This report identified three key issues that were still unsettled: (1) whether a specific suitable site should be identified before moving to the next step in the process; (2) whether the right of withdrawal should be codified in law and not simply be a policy of the current government; (3) what benefits should be offered to a community hosting a repository.

Efforts to obtain a definitive response from the central government to these open issues were only moderately successful. The Department of Energy and Climate Change (DECC) reiterated the findings of the British Geological Survey (now the Institute for Geological Sciences) that, somewhere in West Cumbria’s 1,890 km² of possibly suitable land, a specific site could be found and that DECC’s technical overseer would review the suitability of any proposed site. DECC strengthened its previous commitment and promised to seek legislation that would tighten a community’s right to withdraw. Under the rules, “three green lights” from the borough, county, and central government authorities were necessary to go forward. The county’s negative vote brought the MRWS process to a halt.

The story of what happened on that January day by the Cumbria County Council is still not fully known but whatever the root cause of the county’s veto, DECC hopes to learn from the experience. In 2014, another White Paper announced a new approach that differed in important ways from the MRWS process. DECC would first ask Radioactive Waste Management (RWM, a government-owned company) to assess the geological suitability of all regions of the UK (excluding Scotland), and would itself bring forward initial actions on community representation and community benefits before asking for communities to volunteer. The term “partnership,” which was at the core of the first White Paper, has disappeared. Both the DECC and RWM are scheduled to complete these three “initial actions” by the end of 2016, when volunteer communities will be able to come forward.

United States of America

Efforts to site a repository for defense and commercial HLW and SF in the United States have been numerous and complex. What follows is an abbreviated description of one key siting choice. For more information on this and other siting attempts, see Carter (1986), Lomenick (1996), Vandenbosch and Vandenbosch (2007), Walker (2009), and NWTRB (2015).

The US Congress passed the Nuclear Waste Policy Act (NWPA) in 1982. This law envisioned a detailed and complicated process in which as many as nine sites would be winnowed down through disinterested technical analyses, first to five and then to three. The Department of Energy (DOE) would conduct the analyses and would recommend to the president the three locations where extensive underground site investigations would be carried out. How did that final winnowing step play out?

By the end of 1984, the DOE had identified five potential sites for the first repository. Three were salt formations: Deaf Smith in Texas; Richton dome in Mississippi, and Davis Canyon in Utah. In addition to these three were two sites at nuclear weapons complexes: one in volcanic tuff at the Nevada Test Site (Yucca Mountain), and one in basalt at the Hanford Reservation in Washington. According to the NWPA, the suitability of each site would be evaluated against nearly two dozen individual criteria contained in DOE’s Siting Guidelines (DOE 1984). The evaluation would be based almost entirely on existing surface-based investigations and the available literature.

The Siting Guidelines provided minimal directions on how sites in different host rock would be compared. The DOE proposed three methods for aggregating the scores across the various criteria: averaging, pairwise comparison, and utility estimation. Comments from the five affected states strongly criticized all of DOE’s methodological options. But the most telling critique came from a panel convened by the National Academy of Sciences (NAS). It reviewed the draft evaluations and concluded, “The methodology of comparative assessment is unsatisfactory, inadequate, undocumented, and biased and should be reconsidered” (Parker 1985).

The DOE launched an intensive program to develop a more technically defensible procedure for comparing the five sites. In 1996, it adopted an intricate and sophisticated technique called “multiatribute utility analysis” (MUA). This choice passed muster with the NAS panel but did little to convince the finalists in Nevada, Texas, and Washington.
These states brought lawsuits and lobbied Congress to void their selection. They vowed sustained opposition and actions that would continually thwart DOE’s activities to move forward with site selection. These threats compounded the political turmoil that DOE was already experiencing. In 1987, Congress passed the Nuclear Waste Policy Amendments Act, which instructed DOE to limit its site investigations to Yucca Mountain.

During the next two decades, DOE conducted wide-ranging laboratory studies and underground investigations. In 2002, over the State of Nevada’s opposition, Congress approved President George W. Bush’s determination that the Yucca Mountain site be chosen as the country’s first repository for HLW and SF. In 2008, DOE submitted to the Nuclear Regulatory Commission (NRC) a license application to construct the repository.

Two years later, following sustained opposition from the State of Nevada, the DOE sought (unsuccessfully) to withdraw the license application, claiming that the project was unworkable (Chu 2010). President Barack Obama instructed the DOE to form the Blue Ribbon Commission on America’s Nuclear Future (BRC) to recommend a new path forward for managing the country’s HLW and SF. In 2014, the commission released its report, which endorsed the creation of a new consent-based process for siting a repository. In the meantime, under court order, the NRC staff resumed its evaluation of the license application and published its Safety Evaluation Report (NRC 2010-2015). If Congress provides additional funds, that report and the nearly 300 technical objections submitted by the State of Nevada will become the subjects of an adjudicatory hearing before an independent panel.

As of June 2016, the BRC’s proposals have languished in Congress where strong support still exists for developing a repository at Yucca Mountain. Until that political logjam breaks, the waste-management program in the United States will remain in limbo.

LEARNING FROM HISTORY

A report from the International Atomic Energy Agency observed (IAEA 2007, p 40):

“Members of the general public and representatives of local communities recognize that they have a clear stake in the outcomes of [siting] decisions and almost always seek to have their views taken into account by the policy elites.”

What motivates those voices, both pro and con?

Standard and Special Effects

Social scientists distinguish between “standard” and “special” effects created by the introduction or closure of large institutions, such as universities, factories, or prisons. Among the first type of impacts are changes in employment, taxes, and traffic congestion. The second type arises because of public perceptions of the risk associated with an institution’s activity. These perceptions generate concerns about the stigmatization of communities and their agricultural products, about psychological distress, and about the loss in value of property located “too close” to the institution. Public perceptions of the risk associated with nuclear waste-management facilities are especially powerful in spawning special effects (Slovic 1987).

Social scientists disagree about how extensive and permanent those special effects might be (Jenkins-Smith 2001). But they concur that they have shaped searches for repository sites. In France, opposition from the wine growers around Gard led to the elimination of that site. In the United Kingdom, worries about how a repository in West Cumbria might stigmatize tourism in the Lake District were difficult to diffuse. In the United States, the gaming industry and those connected with it in Nevada were troubled about how a transportation accident involving the shipment of SF to Yucca Mountain might deter tourists from coming to Las Vegas.

A counter to these negative special effects is the promise of positive standard ones. In Canada, community well-being is a principal consideration in the NWMO’s siting philosophy. In France, ANDRA has taken the lead in bringing new employment opportunities to the Meuse/Haute-Marne region. But the promises have to be concrete.

In the United Kingdom, DECC offered benefits but declined to specify precisely what they might be. Proponents of the Yucca Mountain repository believed that Nevada’s opposition would be withdrawn if the state was presented with a deal that was too good to be refused. Yet none was put on the table.

The dynamic between standard and special effects leads naturally to one element of a siting strategy: concentrate efforts on economically underdeveloped and nuclear communities. Following such a strategy, either explicitly or implicitly, brought SKB to Östhammar and ANDRA to Meuse/Haute-Marne. By contrast, Nevada had a bustling economy, and the promise of economic benefits for accepting the Yucca Mountain site was not such a powerful argument. Nevertheless, the sparsely populated host county remains quite supportive because of the economic benefits accompanying the development of a repository. But, as the next section of this article maintains, balancing positive standard effects and negative special effects is not the only challenge facing those responsible for selecting a repository site.

Trust and transparency

The NWMO (Canada), ANDRA (France), and SKB (Sweden) have established authentic interactions with communities as a critically important organizational priority. By all accounts, they have been successful in forming strong bonds of trust with local populations. The process used to select the Gorleben site in Germany and the US DOE’s exercise of discretion when it carried out the MUA analysis both contributed to and reinforced the view that the organizations involved were not trustworthy.

In two respects, trust and transparency play essential roles in the repository-siting process. First, trust and transparency lower the local community temperature that siting controversies inevitably raise. Tough trade-offs have to be made. When disagreements emerge, a full reservoir of trust allows those opposed to a particular choice to view it in the most favorable light, especially if the rationale for the decision is transparent. Conversely, if that reservoir is depleted, a vicious cycle can develop in which increased opposition becomes increasingly likely (Carter 1986).

Second, advancing the case for the projected safety of a repository developed at a specific site requires complex technical arguments, which may be open to differing, even incompatible, interpretations. Uncertainty will attach to those projections. Even if the uncertainty can somehow be bounded, it may be understood differently by interested and affected parties. If trust has been established, however, they will be more likely to accept the assessment of a site’s proponent (Flynn et al 1992).
Allocating Power Between the Center and the Periphery

National political traditions can affect the repository siting process. In Sweden, allocating strong power to municipalities is a long-standing practice. Applying it in the case of selecting a repository site is unexceptional. In France, the communities were given the power to decline an underground research laboratory, but once they accepted it, they lost the formal power to object to a repository.

How power is distributed between the central government and local authorities, including the United States’ tribal nations, is a particularly delicate issue in countries that embrace federalism. In Germany, the states and the federal government were often at odds about whether to develop the Gorleben site, a situation that paralyzed the process for several decades. In the United Kingdom, Cumbria County Council exercised a veto during the MRWS process. It is unclear what power, if any, that level of government will retain under the siting strategy now being fleshed out by the UK. In the United States, a state can object to a presidential decision on selecting a repository site, but its dissent can be overruled by a majority vote in Congress, as it was in the case of Yucca Mountain.

MOVING FORWARD

Waste-management programs in Germany, Japan, the United Kingdom, and the United States are currently deliberating about how to re-create processes that can identify a technically suitable and socially acceptable site for a repository. Each country is attempting to develop “consent-based” siting processes that are compatible with its political culture. Although such an approach has resulted in the selection of sites in Sweden and France, it has not, so far, been successful in the United Kingdom, and a consent-based case failed in Japan (NWTRB 2015). Moreover, many interested and affected parties maintain that such a process cannot—and need not—be pursued in the United States, at least when it comes to a repository for HLW and SF.

My own view is that regardless of what approach is settled upon in those nations, unless their waste-management programs learn history’s lessons, they will continue to struggle to succeed.

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MODELLING THE MINERALOGICAL WORLD: HOW AND WHY

GNM Workshop – Roma, 14–15 June 2016

A workshop on the use of computational methods in mineralogical sciences – Modelling the Mineralogical World: How and Why – which was organized by the National Mineralogical Group (GNM), an informal group within the aegis of the Italian Society of Mineralogy and Petrology (SIMP) was held 14–15 June 2016. Both SIMP and the Italian Society of Geochemistry (SoGeI) sponsored the workshop, and SIMP also provided financial support.

The workshop took place in the Department of Earth Sciences at the Sapienza University of Roma (Italy), in a room named after the recently deceased Sergio Lucchesi, who was professor of mineralogy at Sapienza.

Artem R. Oganov (Stony Brook University, New York, USA) was the keynote speaker and he presented a fascinating lecture addressing how to predict “impossible compounds” just on the basis of chemical composition and how such compounds might become stable under an increase in pressure, the new chemistry of the planet-forming chemical systems Mg–Si–O and N–H–O, and on the modelling of new ultra-hard materials.

Other talks were given by a variety of speakers from Italian universities. Celestino Angeli (University of Ferrara) spoke on diffusion processes operating through microporous materials and how to model them by applying Maxwell–Stefan equations. Donato Belmonte (University of Genova) spoke on the use of first principle theory and computational thermodynamics in the study of deep mantle processes. Marco Bruno (University of Torino) spoke on how to model crystal surfaces using quantum-mechanical, semi-empirical or empirical simulations. Manuele Faccenda (University of Padova) spoke on how to numerically model the petrology of a convective mantle in Earth. Marcello Merli (University of Palermo) spoke on how to determine electron densities during phase transitions via the use of catastrophe theory. And Claudia Stangarone (University of Parma) spoke on the use of vibrational frequencies of crystal lattices in the interpretation of Raman and infra-red (IR) mineral spectra. During their spare time, participants had the chance to visit the historic mineralogical collections in the museum at Sapienza University.

This workshop was targeted at PhD students and young researchers and, with more than 50 people attending, can be said to have been a great success. Participants and organizers also had the great pleasure of welcoming to the event, as a special guest, the now 94-year-old retired professor of mineralogy, Marcella Federico.
Low electrical resistivity means high thermal conductivity, which has profound implications for the thermal history of the core and the origin of Earth's geodynamo. Recent paleomagnetic field intensity measurements by Tarduno et al. (2015) indicate that the geodynamo has been functional since the early history of the Earth, possibly from the Hadean Era. Scientists have assumed that thermal convection was responsible for the geodynamo, at least before the onset of inner core crystallization. If this were the case, however, the thermal evolution model for the core, as reported by Labrosse (2015) and using our high conductivity value, suggests that the temperature at the top of the core should have exceeded 6,000 K during the Hadean. This problem is called the “new core paradox” (Olson 2013). More than one alternative mechanism has already been already proposed, which will be a matter of debate in the near future (see http://www.nature.com/news/magnetic-mystery-of-earth’s-early-core-explained-1.19058).

Kei Hirose
The Earth-Life Science Institute (ELSI)
Tokyo Institute of Technology

REFERENCE


Dear Members of the DMG,

The Second European Mineralogical Conference, also known as the emc2016 meeting, will be held 11–15 September 2016 in Rimini (Italy). And activity is starting to heat up. Almost 700 abstracts have been submitted, and these will be organized into parallel sessions that will cover the whole range of mineralogical disciplines (emc2016. socminpet.it). The meeting is organized by the Italian Society of Mineralogy and Petrology (SIMP). Several European mineralogical societies, including the DMG, will take advantage of the Rimini conference to hold their annual member meetings at it. The European Mineralogical Union (EMU) and the International Mineralogical Association (IMA) will also have several business meetings during emc2016.

As the second conference of its type (the first one took place in Frankfurt, Germany; in 2012), it will offer the opportunity to have exchanges on the role of mineralogy in the geosciences in different European countries. From the list of submitted abstracts, it seems that the research fields covered by the different national societies are not identical. I was surprised to see that, in a country with several active volcanoes, very few Italian colleagues are participating in sessions focusing on the geochemistry and mineralogy of volcanic and related magmatic systems. Evidently, there are different national conceptions of mineralogy and its associated research fields. I think that Rimini will offer a good platform for the representatives of European national societies, the EMU, and the IMA to discuss diversity across the discipline of mineralogy, something that has, perhaps, not yet been fully appreciated either by mineralogists themselves or by the wider scientific community.

I invite all DMG members to participate in our society's annual business meeting, which will be held 13 September 2016 at 12:30 h during emc2016. There will be a minor revision of our bylaws, and the DMG board plans to put forward names for honorary membership. This has to be approved by at least 4/5 of the present members. I myself will report on the activities of the DVGeo (our new umbrella organization which represents geologists, geophysicists, mineralogists, and paleontologists).

The emc2016 meeting will offer all of us the opportunity to attend the talk by Eva Stücken (Woods Hole, USA), who received the Victor Moritz Goldschmidt Prize in 2015. We can also congratulate the new medalists: Gerhard Brey (petrologist and geochemist; professor at Frankfurt University until 2015), who received the Abraham Gottlob Werner Medal in silver, and Ulrich Förstner (applied and environmental mineralogy; professor at TU Hamburg-Harburg until 2005) who received the Georg Agricola Medal. Both Aurelia Zirner (University of Bonn, Germany) and Maria Staff (GFZ Potsdam, Germany) received the 2015 Paul Ramdohr Award. The name of the young scientist who may get the 2016 Victor Moritz Goldschmidt Prize is not yet known, but I am confident that a person will be selected among the excellent candidates who have been nominated (deadline was May 31).

I will be at Rimini during the whole meeting, as will other members of the DMG board. Don't hesitate to contact us for any question relevant to the DMG. We are open to any suggestions or problems that the DMG board can help to solve. As usual, the society will be continuously present at the DMG booth under the kind and efficient supervision of Heidi Höfer and Klaus-Dieter Grevel.

And remember ... new student members benefit from reduced meeting fees. See you in Rimini!

François Holtz  
(DMG President)

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**SHORT COURSE REPORT**

**Applications of Solid State NMR Spectroscopy in Geosciences**

After 16 years, one can justifiably start to speak about a tradition. So it was that, once again, Dr. Michael Fehrtelkord (Ruhr University, Bochum, Germany) enthusiastically introduced the quantum mechanical principles of solid state nuclear magnetic resonance (NMR) spectroscopy and its possible applications in mineralogy and material sciences to interested students from the German cities of Regensburg, Freiberg, Karlsruhe, Weimar, Jena, and, of course, Bochum, plus Salzburg (Austria).

The 16th DMG short course on solid-state NMR, held 17–20 May 2016 at the Institute of Geology, Mineralogy and Geophysics of the Ruhr University Bochum, covered a wide range of topics that was suitable both for NMR beginners and for more advanced practitioners. Starting with a solid theoretical foundation on NMR spectroscopy, Dr. Fehrtelkord introduced the students to 1H spin-lattice relaxation, magnetic dipolar interactions, the magic angle spinning (MAS) method, 2-D multi-pulse techniques, cross-polarization MAS (CPMAS), double rotation (DOR), multiple quantum MAS (MQMAS) and satellite transition spectroscopy (SATTRAS). Each day was split between a theoretical and a practical session, where the participants could actively implement their theoretical knowledge on the institute's Bruker ASX 400. Optionally, students had the opportunity to earn 3 credit points (ECTS) for a passed exam.

I would like to thank Dr. Fehrtelkord for this terrific and perfectly organized short course, in which he gave a comprehensive (and comprehensible) introduction to this complex and versatile method and also proved spectroscopic NMR investigations can be a vital tool in mineralogy and material sciences.

Ralph Michael Bolanz (Jena)

**SIMS SHORT COURSE 2016**

**Helmholtz-Zentrum Potsdam, Deutsches GeoForschungsZentrum – GFZ**

7–11 November 2016

This short course will provide students (including post-docs or other researchers) with a solid grounding in secondary ion mass spectrometry (SIMS) and they will get the opportunity to use the Potsdam Cameca 1280-80 user-facility. Other analytical geochemists with a general interest in SIMS technology are also welcome to sign-up. Participants will learn the fundamentals of vacuum technology, the theory of secondary ion generation and matrix effects, data assessment and be given a realistic assessment of this technique's strengths and limitations.

The course will be guided by Dr. Michael Wiedenbeck at the Helmholtz Zentrum Potsdam–Deutsches GeoForschungsZentrum in the lecture rooms of Haus H. In addition, there will be an optional trip to Dresden and Leipzig from Sunday, 13th November through Tuesday, 15th November 2016 in order to visit the other facilities within the Helmholtz SIMS network. For further information and registration: michael.wiedenbeck@gfz-potsdam.de, gfz-potsdam.de/SIMS/short-course/.
2017 EAG AWARDS: CALL FOR NOMINATIONS – NEW CRITERIA

To ensure the recognition of deserving scientists from all generations, your nomination can make a difference. Below is a short description of EAG Awards and the criteria for candidates.

The Urey Award recognizes outstanding contributions that have advanced geochemistry over a career.

The Science Innovation Award subject area differs every year according to a five-year cycle. This award recognizes important and innovative breakthroughs by scientists within 30 years from the start of PhD (which must be completed). Hence, candidates for the 2017 award should have started their PhD in 1986 at the earliest. In 2017, the award will honour Heinz Lowenstam for his work in biogeochemistry.

The Houtermans Award recognizes a single exceptional contribution to geochemistry, published as a single paper, or a series of paper on a single topic, and is bestowed to scientists within 12 years from the start of PhD (which must be completed). Hence, candidates for the 2017 award should have started their PhD in 2004 at the earliest.

The GS/EAG Geochemical Fellows Award is bestowed upon outstanding scientists who have made major contributions to the field of geochemistry.

Please submit your nominations before 31 October 2016 for the GS/EAG Geochemical Fellows and before 15 November 2016 for all other awards. All details are available at www.eag.eu.com/awards/nomination.

WRITING NOMINATION AND SUPPORT LETTERS

Recognizing the achievements of researchers at various career stages by presenting awards and honors is one of the most important roles of any scientific society. In order to strive towards excellence, we need to be able to recognize it. Furthermore, there needs to be some consensus as to how excellence is defined. One of the best ways to exercise our right to define excellence is to nominate a colleague who we think exemplifies it and to justify this by writing a persuasive nomination letter.

There is no prescribed structure as to how to write a nomination or support letter but committees look most favorably on letters that are detailed and specific about the contributions the nominee has made. Letters which just state that the candidate is a good scientist and has written some interesting papers are rarely successful.

An award committee may, in ideal circumstances, have many nominations to examine. Each package will include a nomination and up to 3 letters, so it is imperative to make the information as concise as possible. Many successful nomination and support letters are no longer than 2 pages (excluding headings).

The letter must explain why the candidate deserves this award, what contributions they have made and the impact of their contributions. How has their work changed the field and what new work or insights have been stimulated as a result? Because the award committee may be confronted with many such impressive records, it is essential to make the candidates achievements stand out by being quite specific as to why they are special.

Many successful letters are able to express to non-specialists the broad significance of one or two specific accomplishments. An effective way to do this is by detailing each of the achievements in a separate paragraph, each of which explains, for example, the nature of a long-standing problem, grounds as to why the field may have been at an impasse, the way in which the candidate advanced that problem and how the field has responded to this work.

Supporting letters, while similarly recognizing a candidate’s major achievements, should also try to focus on other aspects of their work not mentioned in the nomination. Although most scientific awards focus on scientific excellence, some colleagues have made important impacts on the field by organizing or facilitating large-scale scientific objectives, such as expeditions or infrastructure development. Many scientists have also dedicated time to advance meetings, societies, journals, outreach or teaching, and this service can also tip the balance once a short list is assembled.

A final point. Even for some of the most prestigious awards there are sometimes only a handful of nominations. This means that, if you know of a colleague who merits an award, it is well worth taking the time to make a nomination. It may be much easier than you think to make a successful nomination.

See how to make a nomination at www.eag.eu.com/awards/nomination.

GOOD TO KNOW…

Early career scientists. There is a new section on the EAG website entitled ‘Early Career’ which lists the various programs EAG has put in place to support junior researchers. We also recently added a database of available geochemistry programs, short courses and bursaries. Check www.eag.eu.com/early-career

Posting job ads on the EAG website is free. All job ads will be advertised in social media and in the EAG newsletter, which is sent monthly to over 12,000 scientists from the geochemical community. Check www.eag.eu.com/jobs

Looking for bloggers. If you’re interested in blogging about Earth sciences, or science communication in general, you could post on the EAG Blog (blog.eag.eu.com). Posts are shared on social media and in the newsletters. If interested, contact office@eag.eu.com.

2016 DISTINGUISHED LECTURE PROGRAM

We are thrilled to announce the selection of Prof. Alexandre Anesio (University of Bristol, UK) as this year’s Distinguished Lecturer. Alexandre Anesio’s research interests are broad and combine concepts from geography, biology and chemistry to understand the carbon cycle in the cryosphere. He will be visiting several institutions in Poland, Romania, Slovenia and Ukraine in October 2016. Find out more at www.eag.eu.com/outreach/dlp.
The main Geochemical Society awards are as follows:

- **The V. M. Goldschmidt Award** is the society’s highest honor. This award is presented for major achievements in geochemistry or cosmochemistry, consisting of either a single outstanding contribution or a series of publications that have had great influence on the field. It is named after Victor M. Goldschmidt (1888–1947) whose classification of the elements in the Earth and meteorites and pioneering work on crystal chemistry laid the basis of modern geochemistry. The importance of this award has been recently reinforced by a generous gift from former Goldschmidt award winner Prof. Gerald Wasserburg: the recipient will now be able to travel to the Goldschmidt conference to receive his or her award as a guest of the conference.

- **The C. C. Patterson Award** recognizes an innovative breakthrough of fundamental significance in environmental geochemistry, particularly in the service of society, consisting of either a single outstanding contribution or a short series of papers published within the last decade. Clair C. Patterson (1922–1995) developed the uranium–lead dating method. Using lead and uranium isotopic data from the Canyon Diablo meteorite, he calculated the first accurate and precise age for the Earth.

- **The F. W. Clarke Award** recognizes an early-career scientist for a single outstanding contribution to geochemistry or cosmochemistry, published either as a single paper or as a series of papers on a single topic. Frank Wigglesworth Clarke (1847–1931) was a chemist who determined the composition of the Earth’s crust.

- **Joint GS–EAG Geochemical Fellows.** In 1996, the Geochemical Society and the European Association of Geochemistry established the honorary title of Geochemical Fellow, to be bestowed upon outstanding scientists who have, over some years, made a major contribution to the field of geochemistry.

- **The Alfred Treibs Award**, presented by the Geochemical Society’s Organic Geochemistry Division, is given for major achievements, over a period of years, in organic geochemistry. The legacy of Alfred Treibs (1899–1983) consists of his classic papers on porphyrins, which provided the starting point of organic geochemistry.

GS President Barbara Sherwood Lollar (left) presented the 2015 Clair C. Patterson Medal to Karen Johannesson (right) during the 2015 Goldschmidt Conference in Prague, Czech Republic.

2016 F. W. Clarke Award recipient Anat Shahar (right) joined GS President Barbara Sherwood Lollar (left) during the award ceremony in Prague, Czech Republic.

In order to increase student participation, the GS grants free 2-year memberships to students in countries that are under-represented in the society. Introductory Student Memberships offer benefits including print and online subscriptions to Elements, the weekly Geochemical News email, and discounted registration rates for the Goldschmidt Conference and other scientific meetings. More information is available at www.geochemsoc.org/programs/ism/. For students from countries not included in this program, membership is just US$15. If you know students studying geochemistry, encourage them to join!
**IAGC AWARDS**

**Harmon Distinguished Service Award**

Brian Hitchon has had a very long-standing affiliation with the IAGC and has served our organization in many capacities through the years. Brian was born in St. John, New Brunswick (Canada) in 1930 but was educated in England, where he received his doctorate from Manchester University in 1955. After two years as a geologist with the Northern Rhodesia Geological Survey, he returned to Canada in 1957 and joined the Alberta Research Council in Edmonton, Alberta. He has held many positions there, including Research Fellow, Vice-President for Facilities, and Acting Director: he is currently emeritus. He retired in 1989 and started Hitchon Geochemical Services Ltd., branching out into publishing with Geoscience Publishing Ltd. in 1995. He was Secretary of the IAGC from 1984–1992, as well as Executive Editor of *Applied Geochemistry* (1986–1993). He has also been the longest-standing chair of the Water–Rock Interaction (WRI) Working Group, leading it from 1974 to 1983, and he hosted the 3rd WRI meeting in Edmonton, Alberta, in 1980. His service to the IAGC also includes a review of the early history of the association, which appeared in the first issue of *Applied Geochemistry* in 1986, as well as an introductory piece in the June 2009 *AG* Special Issue that reflected on the 40th anniversary of the IAGC. For his long record of service to the IAGC and for his contributions to the geochemical community, Brian Hitchon receives the Harmon Distinguished Service Award for 2016.

**Kharaka Award**

Kingsley Odigie is from Nigeria and is currently a postdoctoral researcher at the US Geological Survey in Santa Cruz, California (USA). He completed an undergraduate degree in microbiology and forensic science with a minor in chemistry at San Jose State University (USA) while working at two jobs to support himself. He continued on to a PhD program at University of California Santa Cruz where he was awarded a US Department of Energy Office of Science Graduate Fellowship. His 2014 dissertation, "Pyrogenic Remobilization of Toxic Metals," used isotopic lead compositions to investigate the sources and mobility of toxic metals released from wildfires in southern California, central Africa, and South America. His work illustrates an important application of geochemistry to the solution of global problem of toxic metals in the environment. This environmental-based research is in tune with what distinguished isotopic geochemist Gunter Faure called “our obligation to humankind … to monitor the quality of the environment both locally and on a global scale.” This work produced publications in *Environmental Science and Technology* and *Applied Geochemistry*. Dr. Odigie is a young geochemist from a developing country with a great career ahead of him. The IAGC is happy to bestow the Kharaka Award to Kingsley Odigie in recognition of his past and present accomplishments, and we wish him well in all his future endeavors in geochemistry.

**Elsevier PhD Student Research Grant Winners**

The IAGC is pleased to announce the recipients of the 2016 Student Research Grants, sponsored by Elsevier and the IAGC. Every year, we have many strong research proposals from students from around the world, and every year the awards become even more competitive. We set another record with 37 submissions this year. The success of these grantees demonstrates the high caliber of their research. Congratulations to our grantees!

**Andrea Rielli**

Andrea Rielli earned his BSc in Earth Sciences and MSc in Geoscience and Geotechnologies at the University of Pisa (Italy). He is currently conducting his PhD research at the School of Earth, Atmosphere and Environment, at Monash University (Australia). His work is focused on understanding the role of subduction in the oxidation of the Earth’s mantle, with particular attention on the cycling of redox-sensitive elements, such as sulfur, at subduction zones. Andrea is studying the metasomatic alteration of ultrahigh-pressure peridotites from the Western Gneiss Region of Norway with the aid of synchrotron X-ray absorption near-edge structure (XANES) spectroscopy, in situ sulfur–carbon isotope measurements, and laser ablation inductively coupled plasma mass spectrometry (LA-ICPMS) analyses. He believes that a better understanding of redox processes at subduction zones will help build more accurate models for the genesis of arc-related ore deposits, the temporal evolution of the atmosphere, and constrain the chemical exchanges between the surface and the interior of our planet.
Mineral of the Year 2015

The International Mineralogical Association (IMA) is pleased to announce that the Mineral of the Year award for 2015 goes to **chanabayaite**. This mineral was discovered and studied by Nikita V. Chukanov of the Russian Academy of Sciences (Chernogolovka, Moscow Region) in collaboration with Natalia V. Zubkova (Moscow State University, MSU), Gerhard Möhn (Niedernhausen, Germany), Igor V. Pekov (MSU), Dmitry Yu. Pushcharovsky (MSU), and Aleksandr E. Zadov (NPP Teplokhim, Moscow). Chanabayaite, Cu₆(N₂C₃H₃)Cl(NH₃)₂Cl₂H₂O·4H₂O, is a new mineral species from Mt. Pabellón de Pica near the village of Chanabaya in the Tarapacá region of Chile (Chukanov et al. 2015). This unusual organometallic mineral does not only have a unique crystal structure that features the 1,2,4-triazolate anion (N₂C₃H₃)⁺ (see at left), but also acts as a “bridge” between the geosphere and the biosphere because its deep-blue crystals formed when guano deposits (the source of the C and N) came into contact with a chalcopyrite-bearing gabbro (which supplied the Cu). Chanabayaite formed by Na and Cl leaching from, and by the dehydration of, another triazolate-bearing natural compound – and potentially another new mineral (below) – NaCu₂Cl₃[N₂C₃H₃]₂[NH₃]₂·4H₂O (Zubkova et al. 2016). Prof. Chukanov is known internationally both for his fascinating mineral discoveries (chanabayaite is but one of the 190 new species under Chukanov’s belt) and his prominent contributions to mineral spectroscopy [most recently, Chukanov (2014) and Chukanov and Chervonnyi (2016)]. A close runner-up to the winner was decagonite (Al₁₇Ni₂₂Fe₃), the second naturally occurring quasicrystal from the Khatyryk CV3 carbonaceous chondrite (Bindi et al. 2015).

Society News

**Tracey Crossingham** graduated with a BSc in Geological Sciences from the University of Queensland (UQ) (Australia) in 2011, and began researching Cenozoic volcanism in Eastern Australia as an honors student in 2012. Following graduation, she continued to pursue a keen interest in eastern Australian volcanism as a PhD student within the School of Earth Sciences at UQ. Her work focuses on understanding the depth of origin of two seismically shallow hotspot tracks in eastern Australia: the central volcanoes and the Tasmanid Seamounts. Volcanic samples were collected through terrestrial fieldwork and participation in a research cruise aboard the Marine National Facility Research Vessel, RV Southern Surveyor. Tracey will use helium isotopes to identify the depth of origin of these two hotspot tracks. Helium isotopes will be complemented by ⁴⁰Ar/³⁹Ar geochronology, major and trace element geochemistry, and radiogenic isotopes to further evaluate the timing of magma emplacement, any different mantle source components, and the interaction between the upwelling magma and the lithosphere.

**Ana Martínez Fernández** earned a BSc in Environmental Sciences from the Universidad Autónoma de Madrid (Spain) in 2009. She spent a year at Umeå Universitet and at the Climate Impact Research Centre of Abisko, both in Sweden, where she became involved in several research projects related to plankton, pollution and climate change. She is currently a PhD student in the Department of Earth and Planetary Science at the University of California, Santa Cruz (California, USA). Ana is using a multidisciplinary approach to investigate the effects of ocean acidification on Caribbean corals and benthic foraminifera. She is using δ⁰¹⁵N and δ³¹C as paleoceanographic proxies to study the impacts of nutrients input through submarine groundwater discharge on calcification of corals living in a natural, low-aragonite saturation environment. She is also studying coral gene expression to assess the potential for adaptation and acclimation to ocean acidification.

**Ibiyemi Ogungbuyi** obtained her BSc (Hons) in Geology from the University of Ilorin (Nigeria) in 2005 and her MSc in Geochemistry/Mineral Exploration at the University of Ibadan (Nigeria) in 2010. Her research focuses on carbonatites from the Eocene Dicker Willem Complex (SW Namibia) and their associated silicate rocks. Her work focuses on unravelling the timing and sources of REE enrichment using Lu/Hf, Rb/Sr, Nd/Sm, and U/Pb radiogenic isotopes, and also determining rare earth minerals of economic importance by X-ray diffraction and by electron microprobe analysis. Her work will also generate high-quality inductively coupled plasma mass spectrometry trace element data that will further improve our understanding of the petrogenesis of carbonatites in the study area.
IAG’S SPRING COUNCIL MEETING

The governing council of the International Association of Geoanalysts (IAG) meets roughly every six months in order to discuss pending business of the association and to plan new initiatives in support of the society goals. Our most recent meeting was held 25–26 April 2016 at the Adlershof office of the Bundesanstalt für Materialforschung und -prüfung (BAM; the German Federal Institute for Material Research and Testing) in southwestern Berlin (Germany). The IAG is grateful to BAM for providing an excellent venue for this meeting and, even more importantly, for providing the opportunity for new networking connections to be developed between BAM, who are world leaders in the production of reference materials, and the IAG.

In order to make the most of having the IAG Council in town, BAM’s division of Inorganic Trace Analyses and Inorganic Reference Materials organized a special colloquium entitled “BAM meets International Association of Geoanalysts”. This gave members of both institutions the opportunity to present their current research related to metrology and analytical methodologies. Four presentations by IAG Council members during the colloquium covered a wide spectrum of topics, including recent developments in microanalytical technology, IAG proficiency testing programs, and isotopic analyses as a tool for food product authentication. The colloquium was followed by an evening dinner in one of Berlin’s many smaller restaurants, which provided an informal atmosphere for members of the IAG Council to further discuss future needs with about a dozen members of BAM’s inorganic metrology group.

The next day (Tuesday, 26 April 2016), was devoted to discussing IAG projects that support our association’s membership. The trend in recent years of an ever-lengthening meeting agenda was continued: members this year needed to work through much of the scheduled lunch break. Noteworthy points from the meeting included a report on the high level of member satisfaction, as documented by the recent IAG membership survey, and a discussion related to the evolving needs of the geoanalytical community for new proficiency testing initiatives. A much-needed, and very pleasant, break in the early afternoon gave council members the chance to tour BAM’s sample preparation facility, a key component in the production of high quality reference materials. Finally, after a long day’s work, including more than eight hours of discussion needed to complete all the agenda items, the IAG Council adjourned its spring 2016 meeting to enjoy an evening walking tour of central Berlin and a dinner at one of the city’s wonderful restaurants.

Michel Wiedenbeck
(michael.wiedenbeck@gfz-potsdam.de)

ANNOUNCING THE VENUE FOR GEOANALYSIS 2018

It is with the greatest pleasure that the IAG announces the venue for the next in its series of triennial Geoanalysis conferences: Geoanalysis 2018 will be held 8–13 July 2018 to be hosted by the Department of Earth and Planetary Sciences of Macquarie University. Since the selection of Sydney (Australia) as the next venue for the IAG’s flagship conference, much progress has been made towards identifying the optimal conference facilities on Macquarie University’s campus, as well as defining the overall structure of the event. After discussions with numerous senior members of the IAG, many of whom themselves have organized previous Geoanalysis conferences, Geoanalysis 2018 will focus on topics of particular relevance to the host nation, Australia. These topics will include new techniques for investigating ore materials, new strategies for better estimating recoverable reserves, and the geoanalytical aspects of post-extraction remediation. Thus, resource-related topics will feature alongside the traditional core theme of geochemical metrology. Being held at a university venue, the July dates for the next gathering will coincide with Macquarie University’s semester break, allowing delegates to avail of university housing while also enjoying a less hectic campus setting.

This will be the first time in its 25-year history that a Geoanalysis conference will be held in Australia. We would like to invite all members of the International Association of Geoanalysts, as well as all scientists pursuing the best means of characterizing the composition of natural materials, to come to Sydney in July 2018!

For the most current information about Geoanalysis 2018 please check 2018.geoanalysis.info for the latest updates.
Congratulations! A detailed report on the Atlanta conference will be of QMINERAL & KU Leuven / ONDRAF-NIRAS Heverlee (Belgium). Reynolds Cup this year was won by Gilles Mertens and Rieko Adriaens to students in the form of research awards and travel grants. The Dr. Donald L. Sparks (University of Delaware, USA), the Pioneer in Marilyn and Sturges W. Bailey Distinguished Member Award; and Marion L. and Chrystie M. Jackson Mid-Career Clay Scientist Award; Dr. Janice Bishop (SETI Institute, California, USA) who received the E. (Chuck) Weaver, emeritus professor at the Georgia Institute of journal (The CMS is an American scientific organization, but 60% of its members are from outside the US, and the same applies to the authors of CMS's journal (Clays and Clay Minerals) and to participants in the Reynolds Cup, which is an international contest in quantitative mineral analysis of rocks that is organized every two years by the society. Another international service provided by the CMS is the Source Clays project: this supplies clay materials used worldwide in clay-related research. Furthermore, annual meetings of the CMS are important international events – the most recent one being hosted in Atlanta (Georgia, USA) and described briefly below.

The CMS is unique as an integration platform because of its multidisciplinary character: it unifies geologists, soil scientists, mineralogists, chemists, and material scientists. The basis for this unification is not the approach but the object of interest: clay, which accounts for over one third of the mass of sedimentary rocks. For some of us, clay is a mineral; for others, it is an important component of rocks or soils; and, for most of us these days, it is a material that can be modified and used in endless applications. Mankind's interest in clay as a versatile utilitarian material dates back many thousands of years: some ceramic pots and sculptures (terracotta) date from ~13,000 BC; the sorption properties of clays (fuller's earth) have been used since 5000 BC; and medical applications of clays were first reported on clay (!) tablets from Mesopotamia from about 2500 BC.

Today, there is a resurgent interest in clays as materials: this resurgence has dominated the entire clay-science field over the last decade and has had repercussions across many related disciplines. The very name given to the scientific theme at the 53rd Annual Meeting of the Clay Minerals Society (held early June in Atlanta) was “Resurgent Clays.” And this theme had additional resonance because Atlanta’s official city motto is “Resurgens,” which is Latin for “rising again”.

The 53rd Annual Clay Minerals Society Meeting honored Prof. Charles E. (Chuck) Weaver, emeritus professor at the Georgia Institute of Technology (USA), and recipients of the three of our highest awards: Dr. Janice Bishop (SETI Institute, California, USA) who received the Marion L. and Chrystie M. Jackson Mid-Career Clay Scientist Award; Dr. Lisa Heller-Kallai (The Hebrew University, Israel) who received the Marilyn and Sturges W. Bailey Distinguished Member Award; and Dr. Donald L. Sparks (University of Delaware, USA), the Pioneer in Clay Science Award recipient. The CMS also conferred several awards to students in the form of research awards and travel grants. The Reynolds Cup this year was won by Gilles Mertens and Rieko Adriaens of QMINERAL & KU Leuven / ONDRAF-NIRAS Heverlee (Belgium). Congratulations! A detailed report on the Atlanta conference will be given in the October 2016 issue of Elements. The 54th Annual Clay Minerals Society Meeting will be held next summer in Edmonton (Alberta, Canada).

Christopher Jorgensen's research is focused on understanding rift lake hydrology by examining the lacustrine lower Portland Formation in the Mesozoic Hartford Basin of Connecticut (USA). He uses primary sedimentological and petrographic data from wireline rock cores (>700 m of section) to better understand how Portland Formation facies, and the sub-environments they represent, are distributed within a rift valley. Biomarker analysis and powdered X-ray diffraction of the clay-sized fraction of lacustrine mudrocks and paleo-vertisol will be used to identify major changes in basin hydrology in an effort to decouple the roles of climate and active tectonics on lake formation and lake character during the final stages of rift abandonment.

Sabrina Sharmeen Alam is evaluating the efficiency of certain smectites to bind aflatoxin during biofuel production. The specific goal of Sabrina's research is to reduce aflatoxin toxicity in dried distiller's grain (a co-product of ethanol production that is used as animal feed) by using smectites in the corn fermentation solution. Although smectites have a very high aflatoxin adsorption capacity in water and ethanol, as revealed by XRD and FTIR, proteins that exist in the fermentation solution tend to significantly interfere with aflatoxin adsorption onto normal smectites. However, smectites that have been modified by small organic compounds, such as choline and carnitine, remarkably reduce the interlayer fixation of the troublesome proteins yet still allow aflatoxin adsorption.

Sebastian Cardona is investigating the sealing properties of mass transport deposits (MTDs) in deep water settings. Sebastian is integrating different data sets and methodologies (such as seismic, well log, outcrops and microscopic data) from offshore sites in the Eastern Gulf of Mexico and the deep water outcrops of the Taranaki Basin, New Zealand. With the support of the CMS 2015 Research Grant, Sebastian will analyze samples collected during his last field-season in New Zealand by X-ray diffraction, scanning electron microscopy, and X-ray texture goniometry to better understand strain facies within MTDs at the microscopic scale.

Cherie Achilles is analyzing XRD data from the Mars Science Laboratory (MSL) rover's CheMin instrument. During MSL's exploration of a proposed paleo-lacustrine environment in Gale Crater (Mars), two mudstones investigated by the CheMin instrument revealed the presence of clay minerals along with other crystalline and amorphous phases. Determining what type of clay mineral is present – whether it is dioctahedral or trioctahedral – should help to accurately distinguish between d= and trioctahedral clay minerals.
At its meeting in May 2016, the MSA Council voted no increase in dues for 2017 for regular and student members (i.e. remaining at $80 and $20, respectively), and that all members will have access to the electronic versions of both the American Mineralogist and Elements. Sustaining memberships will remain at $150 + regular dues.

Member subscription rates to the print version of the 2017 American Mineralogist will increase. Print subscription price for US members will be $120 (currently $115), and print subscription price for foreign members will be set at $130 (currently $125). The subscription price (paper and electronic) for US institutions will increase to $1,075 (from $1,025), and for foreign institutions will be raised to $1,100 (from $1,050). Institutional electronic-only subscription will increase to $975 (from $950). These prices represent increases of 3% to 5%. Included in the institutional subscription are all the current-year (2017) print issues of American Mineralogist, Reviews in Mineralogy and Geochemistry (RiMG), Elements, as well as access to the electronic versions of these publications on the MSA website, starting with volume 1, number 1. GeoScienceWorld (GSW) institutional subscriber prices for archival print copies of American Mineralogist and the RiMG are $190 and $135, respectively. The year 2017 will be the first that MSA will offer institutional subscriptions to print-electronic or electronic versions of RiMG.

MSA 2017 membership renewals will start by September with membership renewal notices sent electronically, followed by several electronic reminders before a paper copy is sent to those who do not renew online by the end of October.

Members and Fellows who are in the senior, honorary, and life categories are sent renewal notices. Although they need not pay dues, they are sent notices as the best way to prompt an update of membership information, particularly mail and e-mail addresses.

If you subscribe to other journals through MSA—Gems & Gemology, Journal of Petrology, Mineral News, Physics and Chemistry of Minerals, Mineralogy and Petrology, or Rocks & Minerals—please renew early: MSA needs to forward your renewal to those publishers before your subscription expires.

The next GSA meeting will be held 25–28 September 2016 in Denver, Colorado (USA). At this meeting, significant society events will take place: the MSA Awards Lunch; MSA Presidential Address; MSA Joint Reception among MSA, the Geochemical Society, and GSA’s Mineralogy, Geochemistry, Petrology, and Volcanology Division; the MSA Annual Business Meeting; the Council Meeting; and breakfasts for the Past Presidents and Associate Editors. The MSA booth in the GSA Exhibit Hall will be open Sunday (2–7 pm), Monday to Tuesday (10 am–6:30 pm), and Wednesday (10 am–2 pm).

The MSA Awards Lunch is Tuesday, 27 September 2016 at which the Roebeling Medal will be presented to Robert M. Hazen of the Carnegie Institute of Science in Washington DC (USA), and the MSA Award will be presented to Anat Shahar of the Carnegie Institute of Science in Washington DC. The 2015–2016 MSA Distinguished Lecturers will also be recognized: Richard W. Carlson, Rebecca M. Flowers, and Olivier Bachmann. The MSA Awards Lectures, Annual Business Meeting, and Presidential Address session is Tuesday, 27 September 2016, at the Colorado Convention Center: Robert M. Hazen gives the Roebling Lecture at 3:00 pm with a talk entitled “MSA Roebling Medal Lecture: The co-evolution of minerals and life: Insights from Big Data mineralogy”; Anat Shahar gives the MSA Award Lecture at 3:30 pm with a talk entitled “MSA Award Lecture: Mineralogical Effects on Isotopes at Extreme Conditions,” and Rebecca Lange
follows with her MSA Presidential Address at 4:00 pm. The MSA/GS/MGPV Joint Reception will then take place between 5:45 pm and 7:30 pm. Topical sessions have been proposed for the two awardees: [T40], “Non-Traditional Stable Isotope Fractionation at Extreme Conditions: A Session in Honor of Anat Shahar, 2016 MSA Awardee”; and [T129], “Mineralogical Evidence for the Co-Evolution of the Geosphere and Biosphere: A Session in Honor of Robert M. Hazen, 2016 Roebling Medalist.”

- The 2016 Dana Medal to Sumit Chakraborty (Ruhr Universitaet Bochum, Germany) will be presented at the Fall 2016 American Geophysical Union (AGU) Meeting to be held 12–16 December 2016 in San Francisco (California, USA). Three sessions at this meeting specifically coincide with Prof. Chakraborty’s interests: (1) “Experimental Measurements and Theoretical Constraints on Transport Properties of Geomaterials”; (2) “Timescales of Magmatic Processes, from Volcanics to Plutonics: Diffusion Clocks in Crystals Reveal the Tempo of Plutonic, Hydrothermal and Volcanic Processes”; and (3) “Timescales and Rates of Orogenic Processes and Metamorphism”. The Dana Medal presentation will be made during the VGP–MSA–GS Joint Reception. For the second year, MSA will have a booth in the AGU Exhibit Hall.

J. Alex Speer
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2016–2017 MSA DISTINGUISHED LECTURERS

The Mineralogical Society of America is pleased to announce its Distinguished Lecturers and their lecture titles for 2016–2017:


- Cin-Ty A. Lee (1) “Whole Earth Oxygen and Carbon Cycling: Climate and Atmospheric Composition Through the Eons”; (2) “ Continent Formation: From Magmas to Unconformities to the Cambrian Explosion.”

- Daniela Rubatto (1) “The Tale of the Tiny: Petrology, Geochemistry and Geochronology of Accessory Minerals”; (2) “Fast and Furious or Slow and Steady: Rates of Geological Processes.”

The schedule of the lecturers’ tours will be posted on the MSA website (www.minsocam.org). Check to see if they may be at a location near you so that you could attend. MSA expresses its appreciation to these individuals for undertaking such a service to our science.

CONTRIBUTORS AND BENEFACTORS

Many members contribute to MSA by including a contribution with their annual dues and/or by responding to special appeals. Depending on the wishes of the member, the money is deposited with the principal of the MSA Endowment, MSA Outreach, MSA Mineralogy/Petrology, the publication of American Mineralogist; the MSA Undergraduate Prizes; the Mineralogical Society of America Award; the Distinguished Public Service Award; the Dana Medal; the Roebling Medal; the MSA website; and the lectureship program. If you have not done so previously, you may wish to consider contributing at the next opportunity. Here, we want to extend our gratitude to the individuals and organizations that have made contributions to MSA between 1 July 2015 and 30 June 2016. These contributors are listed on the MSA website and can be found by selecting “Contributions to MSA” on the MSA home page (www.minsocam.org), under “About MSA.”

SHORT COURSE ANNOUNCEMENT

Non-Traditional Stable Isotopes

Organizers: Fang-Zhen Teng, Nicolas Dauphas, James Watkins, and Donald J. DePaolo
10–11 December 2016, Lawrence Berkeley National Laboratory (LBNL), Berkeley, CA.

The public have shown considerable interest and concern over the impact of atmospheric greenhouse gases since the 2004 publication of Reviews in Mineralogy and Geochemistry (RiMG) 55. Analytical techniques have significantly improved over the last 10 years, and new research directions have emerged in non-traditional stable isotope geochemistry. The goal for the short course Non-traditional Stable Isotopes and its companion RiMG volume is to review the current status of non-traditional isotope geochemistry from analytical methods, theoretical perspectives, experimental studies, and the analysis of natural samples. In particular, important applications to cosmochemistry, high-temperature geochemistry, and low-temperature geo-biogeochemistry will be discussed. The volume will provide the most comprehensive review on nontraditional isotope geochemistry for high-level undergraduates, graduates, and junior researchers who are interested in both the theory and the application of non-traditional stable isotope geochemistry.

Description and registration online at www.minsocam.org or contact Mineralogical Society of America, 3635 Concorde Pkwy Ste 500, Chantilly, VA 20151-1110 USA phone: +1 (703) 9950 fax: +1 (703) 652-9951.
Greetings fellow mineralogists:

As you are reading this, the 2016 joint Geological Association of Canada–Mineralogical Association of Canada (GAC–MAC) meeting in Whitehorse, Yukon (the first time ever!), is now a distant memory. In the same vein, changes in the MAC are also upon us: the baton has been passed from Ron Peterson to me as president, and we have a new female president: a positive sign of how our association is changing. Many will not think heavily of new faces at the top of the MAC, but new faces hopefully translate into new ideas, new ventures and ways in which the association plans to move ahead. In these days of blogs and so many new methods of communication, it can be a challenge to not only stay on top of how the MAC provides information on what we do for our membership, but also to think far enough ahead so that there is a plan for the future. As president, I have no illusions as to the limitations we are facing and, while I transition into the position with significant trepidation, I also take a great deal of solace in knowing that we have a vibrant association that has been around for more than 50 years – there is something we are doing right! While we certainly stand on the shoulders of the great ones before us, I can only hope that, over the next 50 years, there will be others that will be saying something similar.

Anytime one embarks on a new path, it is reasonable to set tangible goals that one hopes will be achievable. In this respect, I am hoping that by the end of my tenure the MAC will be moving in a direction that offers more Berry Summer Schools, facilitates more advancement in public awareness and media-based perspectives and initiates new directives in regards to outreach. I have ideas, sure; but I will be depending to a great extent on members of the MAC Council to provide their energy, experience and ideas. We have two outstanding new members in Profs. Sytle Antao (University of Calgary, Canada) and Antonio Simonetti (University of Notre Dame, Indiana, USA), and I look forward to working with them and the council as a whole. It certainly is a Brave New World around us, but knowing that the MAC has excellent volunteers that make up its executive and council, combined with a drive to propel the association forward, well, that’s good enough to take the fears out of me.

Andrew M. McDonald
Laurentian University

The generous support from the Mineralogical Association of Canada (MAC) has been invaluable during the past year of my graduate studies. Due to the MAC’s support I was able to conduct fieldwork on both Baffin Island (Canada) and in South Australia. These field campaigns allowed me to gather samples of evaporites in order to track changes in both atmospheric and ocean chemistry across the Proterozoic. Not only were these experiences highlights of my PhD, but the results from the various isotope analyses are very exciting and will form a major portion of my thesis. The MAC’s support also allowed me to attend conferences and to conduct laboratory work: through these avenues, I am hoping that lifelong collaborations have been fostered. In the upcoming year, I will be doing an internship at the Tokyo Institute of Technology (Japan), finishing my PhD, and looking forward to seeking out a post-doc. In sum, it has been a great year. I can’t thank the Mineralogical Association of Canada enough for making it all possible.

I am very grateful to have received the MAC Foundation scholarship in 2015. I have been conducting field work and research in my spare time for a number of years, in addition to my studies. My extracurricular work has led to several articles in Rocks & Minerals magazine, several papers in progress (to be submitted to the Canadian Mineralogist), and, more recently, to the discovery of a new mineral species (in the advanced stages of research). The MAC Scholarship is enabling me to continue my mineralogical research, both in the lab and in the field, and is allowing me to pursue exciting new leads in gem deposit geology, to take on new collaborative projects and to accrue additional field experience with different types of gem deposits.

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The Pinch Medal has been awarded every other year since 2001 to recognize major and sustained contributions to the advancement of mineralogy by members of the collector–dealer community. This medal is named after William Wallace Pinch of Rochester (New York, USA) in recognition of his enormous and selfless contributions to mineralogy through the identification of ideal specimens for study and through his generosity in making them available to the academic community. Nominations for the 2017 medal should be submitted to Ron C. Peterson (Department of Geological Sciences and Geological Engineering, Queen’s University, 99 University Avenue, Kingston ON K7L 3N6, Canada; e-mail: peterson@queensu.ca).

Please submit your nominations by 30 November 2016. Check our website, www.mineralogicalassociation.ca, for additional details.
Submit your session proposal to: RFG2018.org

**UPCOMING GAC–MAC MEETINGS**

**GAC–MAC 2017**

**Back Where it Began**

**Kingston, Ontario, Canada**

**14–18 May 2017**

The 2017 joint annual meeting of the Geological Association of Canada (GAC) and the Mineralogical Association of Canada (MAC) will be held in Kingston (Ontario, Canada). This meeting coincides with the 175th anniversary of the founding of the Geological Society of Canada in Kingston, which is Canada’s oldest scientific agency and was established in 1842. There are 19 technical sessions, 5 short courses, and 6 field trips scheduled.

For more information visit www.kingstongacmac.ca

**CIM–GAC–MAC Joint Meeting**

**Resources for Future Generations**

**Vancouver, British Columbia, Canada**

**16–21 June 2018**

The International Union of Geological Sciences (IUGS), which represents over 1 million Earth scientists from 120 countries around the world, is endorsing its first intercongress international conference in Canada in June 2018. Vancouver will play host to this inaugural event, entitled "Resources for Future Generations". Representing some 25,000 Earth scientists in Canada, this conference is being organized and delivered by four key Canadian partners: the Canadian Institute of Mining, Metallurgy and Petroleum (CIM); the Geological Association of Canada (GAC); the Mineralogical Association of Canada (MAC); and the Canadian Federation of Earth Scientists (CFES). The aim of this event is to address and discuss issues surrounding the importance, availability and access to energy, minerals and water, from the perspective of the Earth because these resources relate to the good of people around the world.

Grounded in geoscience, the conference will serve as a forum for industry stakeholders to discuss their research initiatives and their activities. There will also be discussion on the key issues and trends that might shape the future of energy, minerals and water resources, including the science of the whole Earth and how that underpins sustainable discovery and extraction.

Get Resourceful – Empower A Generation

Submit your session proposal under the technical and non-technical themes and sub-themes. Proposals will be accepted until late fall 2016.

Submit your session proposal to: RFG2018.org

**SOCIETY NEWS**

**Obituary: Zdeněk Johan (1935–2016)**

Zdeněk Johan, emeritus Director of Scientific Affairs of the French Geological Survey (Bureau de recherches géologiques et minières – BRGM), passed away in Orléans (France) on 13 February 2016. He was born on 18 November 1935 in Lomnice nad Popelkou in the north of the Czech Republic (formerly Czechoslovakia) and studied mineralogy at Charles University in Prague, graduating with honours in 1958. In 1961 he defended his PhD thesis on the mineralogy of the Cu–As system. Johan was persecuted by the communist regime, so he decided to emigrate in France in 1969, where he became a research officer in the BRGM. Between 1977 and 1989 he was a Director of the Centre de recherches sur la synthèse et la chimie des minéraux of the Centre national de la recherche scientifique (CNRS) in Orléans. He then returned to BRGM, where he served as a Scientific Director and a Scientific Advisor until his retirement in 2000. Over the years, he collaborated closely with a number of researchers around the world, but particularly with the geoscience community in the Czech Republic, always grateful for his tireless support. In his research activities he underlined the utility of mineralogy and crystal chemistry for understanding geological processes, especially those related to the formation of mineral deposits. Over the years, he significantly contributed to the understanding of ophiolite-type deposits, layered mafic and ultramafic intrusions. He particularly enjoyed working on the mineralization of Cr and the platinum-group elements, as well as the metallogenesis of granitoid-related W and Sn deposits (together with his wife Věra). More recently, he had worked on the mineralogy of high-temperatuure industrial materials of anthropogenic origins (slags, fly ash). He described a number of new minerals, often in tandem with Paul Picot, who was his co-author on the excellent Atlas des minéraux métalliques (1977; published in English in 1982). A special moment came when the arsenate mineral NaPbCu₅(AsO₄)₄Cl·5H₂O (IMA 1992-037), which had been found in 1992 in the Cap Garonne Mine in Var (France), was named zdenekite in his honour.

Zdeněk Johan was a fellow of the Mineralogical Society of America. He was also a member of the Mineralogical Association of Canada, the Société française de Minéralogie et de Cristallographie (SFMC), and several other professional societies. He served as a president of the SFMC in 1993, was a treasurer of the International Union of Geological Sciences (IUGS, 1996–2000), a vice-president of the International Mineralogical Association (IMA, 1994–1998), and a president of the Society of Geology Applied to Mineral Deposits (SGA, 1997–1998). During his life he received many honours, including medals and doctorates honoris causa. In 1990, he was elected a corresponding member of the French Academy of Science, and was decorated by two French national orders: Chevalier de l’Ordre national du mérite (1986) and Officier des Palmes académiques (1993). To cap it all, Zdeněk Johan was elected mayor of Isdes in Loiret (France) from 2001 to 2008: this was the town where he lived.

Zdeněk Johan was not only an excellent mineralogist, but also a man of culture, an excellent pianist, very generous, and always ready to help others. His death will be a great loss to the mineralogical and geological communities in general, and to all of his friends and colleagues around the world. He is survived by his wife, Véra, and his son, Zdeněk, along with his family.

Vojtěch Ettler, Charles University in Prague, Czech Republic
2016 METEORITICAL SOCIETY TREASURER’S REPORT

The society’s finances continue to be on a sound footing, and both the operating fund and our investment fund are currently very healthy. A large portion of the operating budget goes towards publishing Meteoritics and Planetary Science (MAPS), our international monthly journal of planetary science, which covers topics including the origin and history of the Solar System, planets and natural satellites, interplanetary dust and the interstellar medium, lunar samples, meteors, meteorites, asteroids, comets, craters, and tektites. The MAPS journal has been published by Wiley since 2010, and our income from Wiley closely matches the expenses of the editorial office at the University of Arizona (USA), which is managed by Editor Tim Jull.

Society memberships include subscriptions to MAPS and Elements. Membership with subscription to only the electronic version of MAPS has become a popular option, although more than half of our membership still purchases the printed version. Collection of membership dues for 2017 will begin in October 2016. I would like to encourage members to pay their dues in a timely manner because this really helps with our financial planning. Healthy finances depend on a stable membership.

Our investment fund, which includes four separate endowed funds, continues to do as well as we can expect with the current market situation. Many society members contribute generously to support all of these funds, and your donations are always greatly appreciated. The Nier Fund supports the annual Nier Prize, which recognizes outstanding research by young scientists in meteoritics and closely allied fields. The 2016 recipient is Dr. Gregory Bennecka (University of Munster, Germany). The Gordon A. McKay Fund supports an award to the student who gives the best oral presentation at the annual meeting of the society: the award for 2015 was given to Carolyn Crow (University of California, Los Angeles, USA). The Travel for International Members (TIM) Fund to support travel to Meteoritical Society meetings for professional members of the society from low-income countries continues to grow, and, in 2016, the money will be used to fund travel to our 2016 meeting in Berlin (Germany).

The General Endowment Fund supports a variety of outreach projects. During 2015/16, this fund has been used to provide travel support for students to attend the Highly Siderophile Elements Workshop in the UK and the Paneth Colloquium in Germany. Support was also given to attend the Seminar for the Classification of Meteorites, which was held in Chile. Endowment funds were also used to support travel for students to attend the Meteoritical Society meeting in Berkeley (California, USA). This year, endowment funds will be used to help students and post-doctoral scholars attend the Meteoritical Society’s meeting in Berlin. Some of the money used has been contributed directly as part of the annual membership renewal. We always welcome suggestions and ideas for ways in which the General Endowment Fund can be used to promote the goals of the society and enrich its activities.

A total of over $15,000 was donated to the various funds from our generous members. Your contributions provide direct support that helps to strengthen our international community.

2016 MEMBERSHIP REPORT

As of May 2016, the Meteoritical Society is made up of 663 regular members, 90 students, 151 retired members, 27 life members and 9 members from developing countries. This brings us to a grand total of 940 members. Many thanks to Erin Walton for providing these statistics. This year we have added Azerbaijan and Ghana to the growing list of countries in which we have membership. We can be proud that we have members in 47 countries, but the statistic show that we still have a lot to do to gain members in many more countries. The society does have a mechanism to subsidize annual dues for members in low-income countries. Prior approval is required from the Membership Committee for this rate. Please refer to our website for more information.
For those wishing to avoid the hassle of paying dues every year, consider becoming a life member! For more information and details on how to become a member of the Meteoritical Society, please see our society web page at www.meteoriticalsociety.org.

THE PAUL PELLAS–GRAHAM RYDER AWARD WINNERS

The Paul Pellas–Graham Ryder Award is jointly sponsored by the Meteoritical Society and the Planetary Geology Division of the Geological Society of America. It is awarded to an undergraduate or graduate student who is first author of the best planetary science paper published in a peer-reviewed scientific journal during the year prior to the award. The award has been given since 2001 and honors the memories of meteoriticist Paul Pellas and lunar scientist Graham Ryder.

For 2015, the committee for the Paul Pellas–Graham Ryder Award found that two of the nominated papers were of equal excellence. Thus, the Award for the Best Student Paper in Planetary Sciences for 2015 has been given to two students:

Romy D. Hanna
(a graduate student in the Jackson School of Geosciences at the University of Texas, Austin, USA)

Tanya Harrison
(a student at the Centre for Planetary Science and Exploration, Department of Earth Sciences, University of Western Ontario, Canada).

The award to Romy Hanna is in recognition of the paper “Impact-induced brittle deformation, porosity loss, and aqueous alteration in the Murchison CM chondrite,” which was published in Geochimica et Cosmochimica Acta, volume 171, pages 256–282. The award to Tanya Harrison is for her paper, “Global documentation of gullies with the Mars Reconnaissance Orbiter Context Camera and implications for their Formation”, which was published in Icarus, volume 252, pages 236–324.

MEETING INFO

- 2016, August 7–12, Berlin (Germany)
- 2017, July 24–28, Santa Fe, New Mexico (USA)
- 2018, Dates TBD, Moscow (Russia)
- 2019, Dates TBD, Sapporo (Japan)

IN MEMORIAM: ROY S. CLARKE, JR. (1925–2016)

Roy S. Clarke, Jr., Emeritus Curator in the Department of Mineral Sciences at the Smithsonian Institution (Washington, D.C., USA), passed away on 1 April 2016, at the age of 91. Born 23 January 1925, Roy had a distinguished service in the US army during WWII, after which he studied at Cornell University (New York, USA), earning his BA in 1949. Early in his career, he was employed by the US Geological Survey as an analytical chemist, during which time he also earned an MSc at George Washington University (Washington, D.C.) in 1957. He transferred to the Smithsonian in October 1957 where he would spend the rest of his career up until December 1993 and also after he retired as an emeritus curator. Roy began his career as an analytical chemist within weeks of the launch of Russia’s Sputnik satellite and, before long, began analyzing the chemical composition of meteorites. Roy’s research interests centered on understanding the origin of iron meteorites, particularly coarse-structured irons rich in phosphorus. Upon the retirement of Edward P. Henderson from the Smithsonian in 1965, Roy assumed the role of Curator-in-Charge of the US National Meteorite Collection. He became an active member of the Meteoritical Society, serving as Secretary of the Society from 1967 to 1970. He played a pivotal role in the acquisition of the Allende meteorite in 1969, traveling to Mexico to acquire thousands of individual stones. He returned to complete his PhD later in life by studying at George Washington University, where he graduated in 1976. At almost the same time as earning his PhD, Roy would be involved in the contentious legal acquisition of the Old Woman meteorite, which would become the largest single meteorite in the Smithsonian’s collection and, coincidentally, was a coarse-structured iron meteorite rich in phosphorus. Roy played a pivotal role in the formation and management of the US Antarctic Meteorite Program, a cooperation between the Smithsonian, NASA and the USA’s National Science Foundation. Upon retirement, Roy’s interests turned to the history of meteoritics and the history of the Meteoritical Society. This led to a series of papers about meteoritics at the Smithsonian, among other topics. Roy did an outstanding job of growing the National Collection of meteorites and provided countless outside investigators with material for their study. In 2014, he was awarded the Meteoritical Society’s Service Award. Roy was preceded in death by his wife Grace and is survived by three daughters and numerous grandchildren.
MUSINGS FROM LONDON

Time to Reflect
Once upon a time, the summer was when geologists disappeared into the field for weeks on end. As a result, the offices of learned societies were quieter during this period. This is less true nowadays, partly because the work of many Earth scientists, and especially mineralogists, is no longer field based. Nevertheless, summer still does allow one a little more time to reflect and to plan. The Mineralogical Society of Great Britain and Ireland (MinSoc) is busy building a meetings programme for 2017 and 2018 [including support for the forthcoming Melbourne (Australia) meeting of the International Mineralogical Association, which we encourage all mineralogists to attend]. We are also restocking many of the Special Interest Groups with new committees to carry on the good work of those who have served their terms of office. Our financial year is complete at the end of June and our annual accounts is a time to … “Ask what you can do for your Society”!

bursaries/grants, awards, distinguished lecturers, etc. So, the summer teaches the community in the way that we do: meetings, publications, groups, workshops. It is largely for this reason that we are able to continue to serve various ways, including on the council and on other standing committees. This is largely for this reason that we are able to continue to serve the community in the way that we do: meetings, publications, groups, etc. So, the summer is a time to … “Ask what you can do for your Society”!

Kevin Murphy
Executive Director

NOMINATIONS SOUGHT FOR MINERALOGICAL SOCIETY AWARD FOR BEST PAPER

In honour of R.A. Howie

An award will be made annually to “the lead author of the ‘best paper’ published in English in a mineralogical journal (sensu lato) within three years of award of his/her PhD thesis”. The nomination process is outlined below.

The nominated paper must have been published in the calendar year before the nomination and within three years of award of the candidate’s PhD and will remain on the slate for up to two years.

Nominations should consist of a letter of nomination together with at least one letter of support along with a copy of the paper being nominated and a copy of the nominee’s CV. The letter(s) should address the criteria outlined below and how any or all of them are met by the paper in question. Each nomination package should be submitted in electronic form (as a single pdf file) and sent to the society’s Executive Director, Kevin Murphy (kevin@minersoc.org).

Award criteria
The Awards Committee will take into consideration the following points:

1. Novelty
2. Inter-disciplinarity
3. Applicability
4. How the science is advanced by the new work

Timing
The nominated paper must have been published in the calendar year before the nomination and within three years of award of the candidate’s PhD and will remain on the slate for up to two years.

CONTENTS OF THE MARCH 2016 ISSUE OF CLAY MINERALS

- CEC determination with Cu-triethylenetetramine: recommendations for improving reproducibility and accuracy. Helge Stanjek and Dennis Künkel
- XRD investigation of the intercalation of nacrite with cesium chloride. S. Naamen, N. Jaafar, H. Ben Rhaiem, A. Ben Haj Amara, A. Plançon & F. Muller
- Organophilization of a Brazilian Mg-Montmorillonite without prior sodium activation. Manoella Silva Cavalcante, Simone Patricia Aranha Paz, Rômulo Simões Angélica, Edson Noryuki Ito & Roberto Freitas Neves
- MAS NMR and EPR study of structural changes in talc and montmorillonite induced by grinding. Roger Borges, Livia Macedo Dutra, Andersson Barison & Fernando Wypych
- Diffuse reflectance spectra of methylene blue adsorbed on different types of clay samples. M. Milošević, M. Logar, B. Dojčinović, A. Rosić & S. Erić
CONTENTS OF MINERALOGICAL MAGAZINE – OPEN ACCESS MAY 2016 ISSUE


CONTENTS OF MINERALOGICAL MAGAZINE – JUNE 2016 ISSUE

- Reaction aureoles around uraninites within biotite and plagioclase: evidence of low temperature sequential fluid alteration and LREE-mobilization from monazite. Manoj K. Ozha, Biswajit Mishra and Aiveligaram V. Jeyagopal
- Tavagnascoite, Bi₂O₂(SO₄)(OH)₂, a new oxy-hydroxy bismuth sulfate related to klebselitebergite. Luca Bindi, Cristian Biagioni, Bruno Martini, Adriio Salvetti, Giovanni Dalla Fontana, Massimo Taronna and Marco E. Ciriotti
- The Stillwater Complex, Montana - Overview and the Significance of Volatiles. Alan E. Boudreau
- Observation of Sb₂S₃-type post-post-perovskite in NaFeF₃. Implications for A₂X₃ and A₂X₃ systems at ultrahigh pressure. W. A. Crichton, F. L. Bernal, J. Guignard, M. Hanfl and and S. Margadonna
- Lead-antimony sulfoalts from Tuscany (Italy). XVII. Meerschautite, (Ag,Cu)₅Pb₄₂.₄(Sb₂As₄)₁₅.5Mo₁₂O₇₃, a new expanded derivative of owyheeite from the Pollone mine, Valcaticasto Carducci: occurrence and crystal structure. Cristian Biagioni, Yves Moëlo, Paolo Orlandi and Chris J. Stanley
- BOOK REVIEW – Pore-Scale Geochemical Processes. Reviews in Mineralogy & Geochemistry, Volume 80
- CNMNC newsletter 31

THE 2016 HIGH SCHOOL CRYSTALLIZATION CONTEST

During 2016, more than 200 high schools (secondary schools) throughout Spain participated in a crystallization contest; in total, more than 6,000 students took part. The students worked in their school laboratories to grow the best crystals they could for one or several of the four contest categories: crystallization of ammonium dihydrogen phosphate (ADP), crystallization in a geode, crystallization of sodium chloride, and making scientific videos about the crystallization processes that they had developed in their labs.

During the contest, after months of work, one could easily see how much knowledge the students had acquired when they showed and explained their experiments in the poster session. The contest, however, goes beyond this goal. Students also experience the importance of being systematic and careful when it comes to laboratory work and analysis, and teachers get to teach new ways to learn about crystals and crystallography. Arguably of most importance is that students, teachers, and parents all see that doing science can be very attractive and great fun.

The idea for the contest was born at the Factory of Crystallization, a Spanish research project headed by Juan Manuel García-Ruiz in the Laboratory of Crystallography (CSIC) in Granada. The first contest took place in Andalusia (Spain) and Puerto Rico during the 2010–2011 academic year. The idea proved successful and quickly spread to other Spanish regions in subsequent years. The Spanish Mineralogical Society is happy to participate as sponsor.

For more details: http://www.lec.csic.es/concurso/
The following is an abstract for an article that appeared in issue 171 of the EXPLORE newsletter.

Matthew I. Leybourne*, Lynda Bloom, and Brenda Caughlin

“A common perception in the analysis of rocks and soils in exploration geochemical surveys and ore deposit studies is that Hg is highly volatile and so handling and drying of samples must ensure that temperatures are maintained below ~ 60°C. In order to determine the validity of this assumption, we have reviewed the literature in terms of Hg speciation in geological media. We also performed experiments on pulverizing equipment to determine the range of temperatures attained during sample preparation. During pulverization of rocks, temperatures in excess of 100°C were found for large sample sizes (250 g). Only in cases where there is significant anthropogenic contamination or proximal active hydrothermal or geothermal systems are Hg0 or HgCl2 likely to be major species in samples of interest to geochemical exploration. Both Hg0 and HgCl2 start to volatilize at temperatures < 100°C. However, despite its volatility, relatively aggressive partial leaches are required to fully extract Hg0, such as 12 M HNO3. A consistent result from most studies of Hg in soils is that in soils with abundant organic matter, most Hg appears to be strongly bound, especially to fulvic and humic acids. By contrast, studies using micro X-ray adsorption spectroscopy (XAS) and sedimentation field-flow size fractionation have shown that in some soils, Hg is not associated with organic matter, oxides or clay minerals, but is dominantly present as colloidal cinnabar and metacinnabar. In most soils, stream sediments, and near surface glacial sediments, which exist under generally oxidizing conditions, the predominant form of Hg is bound to organic matter, adsorbed to oxide and clay surfaces, and as insoluble sulfide phases i.e., as Hg2++. Thus, our analysis of the literature indicates that for most samples of geological interest, samples can be dried at temperatures around 100°C with no loss of Hg.” To view the complete article please visit the AAG web site: www.appliedgeochemists.org/index.php/publications/explore-newsletter

AAG’S STUDENT SUPPORT PROGRAM

Helping the next generation of applied geochemists

Geochemical analysis can be a significant cost of thesis work carried out by applied geochemistry students. To support the next crop of applied geochemists, AAG has partnered with four commercial analytical laboratories to provide in-kind support by way of geochemical analysis to bona fide applied geochemistry students identified through AAG’s Student Support Program.

The first version of this program commenced in 2011 and resulted in support for students from Australia and Africa. Their thesis work covered a wide range of topics, including analysis of particle size fractions in laterite, evaluation of diffusion gradients in thin films for the detection of element anomalies in soils, the petrogenesis of Ni, Cu and platinum-group mineralization in gabbro, and an investigation into the potential for granite-hosted mineral deposits.

In 2015, the program was restructured to account for the impact of falling commodity prices on the capability of participating laboratories to support the program. The revised program allows participating laboratories to decide on a case-by-case basis about their level of support. This has attracted commitment from Intertek-Genalysis, Bureau Veritas Minerals, ALS, and Actlabs, all of whom offer a range of analytical services, and many of which are operational world-wide.

The scope of the AAG Student Support Program, conditions, and an application form can be found on the Student page of the AAG website (www.appliedgeochemists.org). Each application is assessed on its merits by the AAG and is passed on to participating laboratories for their consideration. Laboratories can decide on their level of support, and successful applicants are put in touch with the chosen laboratory.

A condition of the program is that the results are published either in AAG’s journal Geochemistry: Exploration, Environment, Analysis, or in its newsletter, EXPLORE, and will include acknowledgement of the supporting laboratory.

Paul Morris
AAG Education Committee

IAG SYMPOSIUM 2018

A proposal to hold the next International Applied Geochemistry Symposium (IAGS) in conjunction with the “Resources for Future Generations” (RFG) meeting, which will be held 16–21 June 2018 in Vancouver (British Columbia, Canada), has been approved by the AAG Council. The AAG will join with the Canadian Institute of Mining and Metallurgy (CIM), the Geological Association of Canada (GAC) and the Mineralogical Association of Canada (MAC) to host the conference at the Vancouver Convention Centre. Supporters include the Canadian Federation of Earth Sciences (CFES), the International Union of Geological Sciences (IUGS), the Canadian Geological Foundation (CGF) and the Canadian National Research Council (NRC). As many as 4,000 to 5,000 scientists, policy-makers and industry representatives are expected to attend. The AAG will organize applied geochemistry technical sessions, workshops, field trips and social events within the broader context of RFG2018. An organizing committee has been formed and work has commenced on planning for IAGS2018.

Peter Winterburn
Chair, IAGS 2018 Organizing Committee

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RFG 2018

RESOURCES FOR FUTURE GENERATIONS

THE CONFERENCE ON

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June 16–21, 2018

Vancouver Convention Centre, BC, Canada
2016

August 7–12 Annual Meeting of the Meteoritical Society, Berlin, Germany. Web page: www.meteoriticalsociety.org


August 18–20 Seventh International Dyke Conference (IDC7), Beijing, China. Web page: idc7.csp.escience.cn/dct/page/1


September 5–9 13th International Nickel-Copper-PGE Symposium, Perth-Fremantle, Western Australia. Web page: www.iagod.org/node/58


September 29–October 1 Subduction Zone Observatory Workshop, Boise, ID USA. Web page: www.iris.edu/hq/workshops/2016/09/szo_16


October 20–23 XXIII Session of the Petrology Group of the Mineralogical Society of Poland. “Subduction systems in the Sudetes and related areas”, Stara Morawa, Poland. Web page: www.ptmin2016.ptmin.pl

October 23–27 MS&T’16: Materials Science & Technology Conference and Exhibition, combined with ACRS 118th Annual Meeting, Salt Lake City, UT, USA. Web page: www.matscitech.org


November 27–December 2 2016 MRS Fall Meeting & Exhibit, Boston, MA, USA. Web page: www.mrs.org/fall2016

December 10–11 Short Course: Measurements, Theories and Applications of Non-Traditional Stable Isotopes. Lawrence Berkeley National Laboratory, CA, USA. Web page: www.minsocam.org/msa/sc

December 12–16 American Geophysical Union Fall Meeting, San Francisco, CA, USA. Web page: fallmeeting.agu.org/2016/

2017


January 22–24 41st International Conference and Expo on Advanced Ceramics and Composites, Daytona Beach, FL, USA. Web page: ceramics.org/icacc2017

February 26–March 2 TMS Annual Meeting & Exhibition, San Diego, CA, USA. Web page: www.tms.org/meetings/annual-17/AM17home.aspx


The meetings convened by the societies participating in Elements are highlighted in yellow. This meetings calendar was compiled by Andrea Koziol (more meetings are listed on the calendar she maintains at homepages.udayton.edu/~akoziol1/meetings.html). To get meeting information listed, please contact her at akoziol1@udayton.edu

Join geologists, mining industry professionals, mineralogists, educators, and interested mineral collectors and laymen in historic Butte, Montana to learn about advances in research and development of metallic mineral deposits in the Northern Rockies. This year’s Symposium features:

Meet and Greet at the Montana Tech Mineral Museum

Two days of technical presentations

Map Chat with MBMG field geologists at the Butte Brewing Company

Field trips to historic Montana mining properties

Early registrants will receive a fee discount.

For more information or to register, please visit our webpage at www.mbmg.mtech.edu/2016symposium.asp

MBMG
Mineral Bureau of Mines and Geology

GEOLGY OF METALLIC MINERAL DEPOSITS
NORTHERN ROCKIES, USA

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JOB POSTING

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TENURE-TRACK FACULTY POSITION IN CRUSTAL DYNAMICS

The Department of Geological Sciences seeks an outstanding scientist to lead a vibrant research and educational program in the broadly defined area of Crustal Dynamics. Specific areas of interest include (but are not limited to) the mechanisms of initiation, growth, linkage, and evolution of fractures and faults; reconciliation of contemporary and geologically observed deformation; the coupling of fluid flow and rock deformation within the crust; the relations between deep and shallow deformation in the crust; the role of rock deformation in development of the near-surface critical zone; and dynamics caused by changes in surface loading (whether by accumulation of ice or sediment, or removal of rock by erosion). We are particularly interested in those who use state-of-the-art laboratory tests, microstructural measurements, developments in material science and applied mechanics, field-based geologic measurements, and computational advances to understand rock deformation.

Research approaches should encompass an integrated combination of field, laboratory, and modeling approaches. The appointment will be at the junior level (Assistant or untenured Associate Professor). The successful candidate will be expected to develop an independent, world-class program of research, interface as appropriate with existing programs in the Geological Sciences and in the School of Earth, Energy & Environmental Sciences, and teach at the undergraduate and graduate levels.

Applicants will need to submit a cover letter, curriculum vitae, statement of research and teaching interests, list of three references with contact information, and three recently-published journal articles that are representative of the applicant’s research. Review of applications will commence October 5th, 2016. Please apply at https://academicjobsonline.org/ajo/jobs/7440

Stanford University is an equal opportunity employer and is committed to increasing the diversity of its faculty. It welcomes nominations of and applications from women, members of minority groups, protected veterans and individuals with disabilities, as well as from others who would bring additional dimensions to the university’s research, teaching, and clinical missions.

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