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Storage of High Level Nuclear Waste in Geological Disposals: The Mining and the Borehole Approach

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1. Introduction

Nuclear energy is the energy in the nucleus, the core of an atom. Atoms itself are tiny particles of the universe. Nuclear energy can be used to generate electricity in nuclear power plants which currently satisfies about 35% of the European Unions' electrical energy needs. As of January, 2011 there is a total of 195 nuclear power plant units (including the Russian Federation) with an installed electric net capacity of 170 Giga Watt (GW) in operation in Europe and 19 units with approximately 17 GW are under construction in six countries [ENS, 2011]. Nuclear power can be generated from the fission of uranium, plutonium or thorium and by the fusion of hydrogen into helium. In nuclear fission, atoms are split apart to form smaller atoms, releasing energy which is used to produce electricity. Today it is almost all uranium. Uranium is non-renewable. It is a common metal found in rocks all over the world. Natural uranium is almost entirely a mixture of two isotopes, U-235 and U-238. Digging natural uranium U-235 must be extracted and processed to fission in a reactor. Compared with U-235, U-238 cannot fission to a significant extent. Natural uranium is 99.3 per centum U-238 and 0.7 per centum U-235. Therefore, nuclear power plants use enriched uranium in which the concentration of U-235 is increased from 0.7 per centum U-235 about 4 to 5 per centum U-235. This enrichment is expensive and done in a specific separation plant. The U-235 used in today's reactors seems to be available from natural uranium for a number of decades. But the key energy fact is that fission of an atom of uranium liberates about 10 million times as much energy as does the combustion of an atom of carbon from coal [McCarthy, 1995].

Nuclear power plant reactors contain a core with a large number of fuel rods. Each of which is filled with pellets of uranium oxide, an atom of U-235 fissions when it absorbs a neutron. The fission produces two fission fragments and other particles that fly off at high velocity - about 80 per centum of the neutron absorptions in U-235 result in fission; the other 20 per centum are just (n, gamma) reactions, resulting in just another gamma flying about. When they stop the kinetic energy is converted to heat [McCarthy, 1995]. The heat from the fuel rods is absorbed by water which is used to generate steam to drive the turbines that generate the electricity. The steam withdrawn and run through the turbines controls the power level of the nuclear power plant reactor. Hence, nuclear power plants use nuclear fission for producing electrical energy.

Electricity generated in nuclear power plants does not produce polluting combustion gases like traditional coal and/or gas power plants, an important fact that plays a key role helping to reduce global greenhouse gas emissions and tackling global warming especially as electrical energy demand rises in the years ahead. Hence, nuclear power is back in favor, at least in political circles. Worldwide are 436 nuclear power plants in operation, and 47 under construction. 133 nuclear power plants are planned, and 282 are proposed. In total 898 nuclear power plants will run in the near future worldwide. This could be assumed as an ideal win-win situation, but the other site of the coin is that the production of high-level nuclear waste (HLW) outweighs this advantage. Therefore, management and disposal of radioactive waste became a key issue for the continued and future use of nuclear power plants in the EU. Because the safe and sustaining disposal of HLW is not solved yet, of high political and public concern, and part of international research programmes. Thus the objective of this chapter is to highlight the state-of-the-art of possible concepts for safe and sustaining storage of HLW in geological disposals that are exist, are under construction, and/or under discussion.

2. Nuclear waste

Nuclear waste is a specific type of waste that contains radioactive chemical elements that do not have any practical purpose. Nuclear waste is produced as by-product of a nuclear process like nuclear fission in nuclear power plants, the radioactive left over from nuclear research projects, and nuclear bomb production. But the largest source of nuclear waste is naturally occurring radioactive material as isotopes such as carbon-14, potassium-40, uranium 238, and thorium-232. If these radioactive elements are concentrated they may become highly enriched to be treated as nuclear waste. In general nuclear waste is divided into low, medium, and high-level waste by the amount of radioactivity the waste produces. The majority of nuclear waste belongs to the so called low-level nuclear waste (LLW) which has a low level of radioactivity per mass or volume. This type of waste is all-around, and can be estimated to be approximately 80 per centum of the overall nuclear waste. It often consists of items that are only slightly contaminated but still dangerous due to radioactive contamination of a human body through ingestion, inhalation, absorption, or injection. Hence, it should not be handled by anyone without training. LLW usually includes

- material used to handle the highly radioactive parts of nuclear reactors such as cooling water pipes and radiation suits, etc.,
- low level radioactive waste from medical procedures in diagnosis and treatments or x-rays,
- industrial waste which may contain α, β, or χ emissions,
- earth exploration in order to find new sources of petroleum,
- industrial production like producing plastics,
- agricultural products, most notably for the conservation of foodstuffs, etc.

Not only LLW is still dangerous for the human body, also low-level radioactive material. Opposite to LLW nuclear power plants produce high-level nuclear waste (HLW) in their core that averages approximately 20 per centum of the total of nuclear waste. This waste depends on the rods (fuel elements) which includes large quantities of high level radioactive fission products and is generating heat. Also their extremely long half-live-time transuranic fragments (longer than 500,000 years) create extreme long time periods before the nuclear waste will settle to safe levels of radioactivity. Therefore, this nuclear waste at the very first is put in an intermediate and/or temporary storage facility, under strict safety conditions.

This facility normally is a large storage reservoir, a so called wet storage device, located next to the reactor. The wet storage reservoir is not filled with ordinary water but with boric acid, which helps to absorb some of the radiation given off by the radioactive nuclei inside the spent fuel elements. Within this large wet storage reservoir the high-level radioactive isotopes become less radioactive due to their decay and also generate less and less heat. Hence, the final disposal of HLW is delayed to allow its radioactivity to decay. Forty years after removal from the reactor less than one thousandth of its initial radioactivity remains, and it is much easier to handle. Thus canisters of vitrified waste, or spent fuel elements assemblies, are stored in large wet storages in special ponds, or in dry concrete structures or casks for at least this length of time. But this requires specific methods to handle the HLW. Some of the methods being under consideration include short term storage, long term storage, and transmutation. The longer the spent fuel element is stored in the intermediate storage facility, the easier it will be to handle. But many nuclear power plants have been holding spent fuel elements for so long that their reservoirs are getting full. They must either send the spent fuel elements off or enlarge their wet storage reservoirs to make room for more spent fuel elements. As the wet reservoirs are filled up a major problem occur. If the spent fuel elements are placed too close together, the remaining nuclear fuel could go critical, starting a nuclear chain reaction. Therefore, another method of temporary storage is used because of the overcrowding of wet reservoirs, which is the dry storage reservoir. The dry storage reservoir accommodates the HLW and putting it in reinforced casks or entombing it in concrete bunkers. This is after the HLW has already spent about 5 years cooling in a wet storage reservoir. The dry casks reservoirs are also usually located close to the reactor site. But for long-lived and HLW it is usually envisaged that this waste has to be placed in a final disposal facility, whatever this connoted. From the political perspective it seems there is no immediate economic, technical or environmental need to speed up with the construction of final geological disposal facilities for radioactive waste. Because the European Commission has prolonged the time schedule for their member states to develop their sustainable permanent HLW disposal facilities, which first were terminated for 2018. But now the year is 2030. With this in mind and from a sustainable development perspective – and if we do not want to pass the burden finding a permanent repository solution for HLW on the future generations – it has to be noticed that the temporary storage of HLW today is clearly not a satisfactory solution which with we can proceed for longer.

3. Options for disposing nuclear waste

The basic idea in long-term storage of HLW that is currently preferred by international experts consists of placing the waste in a depth of at least 500 metres below the surface in a stable geological setting, that has maintained its integrity, and will maintain its integrity for millions of years. The ambition is to ensure that the HLW will remain undisturbed for the few thousand years needed for their levels of radioactivity to decline to the point where they no longer represent a danger to present and future generations. The concept of deep geological disposal is not new, it is more than 40 years old, and the technology for building and operating such repositories is now mature enough for use.

As a general concept, the natural security afforded by the chosen geological formation is enhanced by additional precautionary measures. The wastes deposited are vast immobilised in an insoluble form, in blocks of glass for example [Donald, 2010; Lutze, 1988; Weber et al., 1995], and then placed inside corrosion-resistant containers. Spaces between waste packages are filled with highly pure, impermeable clay, and the repository may be strengthened by means of concrete structures. These successive barriers are mutually reinforcing and ensure that radioactive waste can be contained over the very long term. The main reason for relying on the deep geological disposal concept is based on the assumption that a geological environment is an entirely passive disposal system with no requirement for continuing anthropogenic involvement for its safety. It is assumed that it can be abandoned after closure with no need for continuing surveillance and monitoring. Thus, the safety of the deep geological repository system is based on multiple barriers, both engineered and natural, the main one being the geological barrier itself [OECD-NEA, 2003; Rao, 2001]. One option of disposing HLW which meets the above condition is the concept of a geological repository in the deep ocean floor, which is called seabed disposal [Carney, 2001]. It includes burial beneath a stable abyssal plain and burial in a subduction zone that slowly carry waste downward into the Earth's mantle. These option is currently not being seriously considered because of technical considerations, legal barriers in the Law of the Sea, and because in North America and Europe sea-based burial has become taboo from fear that such a repository could leak and cause widespread contamination [Nadis, 1996].

Another option of disposing HLW based on the above condition is the land-based waste disposal method of a geological repository in the deep rock, which is called the rock bed disposal. This repository concept can be realized as mined [Alexander, 2007; Loon, 2000; Miller, 2000] or borehole disposal [Anderson, 2004; Brady, 2009; Gibb, 1999; Gibb, 2005]. These repositories require as an essential boundary condition the option of recovering nuclear waste from the deep geological disposal during the initial phase of the repository, and during subsequent phases, which results in increased cost. But recovering nuclear waste provides a certain degree of freedom of choice to future generations to change waste management strategies if they wish or if there is a need for.

Based on the state-of-the-art in science and engineering [IAEA, 2001] geological repositories must be designed in such a way that it can be assumed that no radioactivity will reach the Earth's surface. Hence, environmental impact assessments must cover a 10,000 years analysis for worst-case scenarios, including geological and climate changes and inadvertent anthropogenic intrusion. These assessments maintain that even under those conditions the impact on the environment would be less than current regulatory limits, which in general are lower than natural [IAEA, 2006]. In 2007 a symposium on "Safety Cases for Deep Geological Disposal of Radioactive Waste: Where Do We Stand?" [OECD_NEA, 2007] was organized by the Nuclear Energy Agency (NEA) of the Organization for Economic Co-operation and Development (OECD), in co-operation with the European Commission (EC) and the International Atomic Energy Agency (IAEA) to share experiences on

- developing and documenting a safety case both at the technical and managerial levels,
- regulatory requirements and expectations of the safety case,
- progress made in the last decade, the actual state of the art and the observed trends,
- international contributions in this field.

Beside the existing concepts of man-made geological disposal facilities for long-lived waste another optional solution is to reduce the mass of long-lived, high-level waste using a technique known as partitioning and transmutation. Transmutation involves isolating the transuranic elements and long-lived radionuclide's in the radioactive waste and aims at transforming most of them by neutron bombardment into other non-radioactive elements or into elements with shorter half-lives. The governments in some countries are investigating this option but it has not yet been fully developed and it is not clear whether it will become available on a large scale. This is because in addition to being very costly, partitioning and transmutation makes fuel elements handling and reprocessing more difficult, with potential implications for safety. Cost is an important issue in radioactive waste management as related to sustainable development. If the nuclear industry did not set aside adequate funds, a large financial burden associated with plant dismantling and radioactive waste disposal would be passed on to the next generations. Henceforth, in most of the OECD countries, the costs of dismantling nuclear power plants and of managing long-lived wastes are already included in electricity generating costs and billed to end consumers; in other words, they are internalised. Although quite high, in absolute terms, these costs represent a small proportion – less than 5 per centum – of the total cost of nuclear power generation.

Today different waste management and disposal strategies exist which deal with all types of radioactive waste originating in particular from the operation of nuclear power plants and back end nuclear fuel element cycle facilities. Short-lived low and intermediate level radioactive waste, generated comparatively in large volumes, have meanwhile successfully been managed from the disposal perspective world-wide. But high level radioactive waste disposal is an unsolved problem today. Worldwide it is accepted and a consensus view to dispose HLW in deep geological formations for long term and safe radioactive waste management [IAEA, 2006]. On the one hand the depth for geological disposal of nuclear waste is seen several hundred meters' below the surface in a mine, which is deemed as mined disposal concept. On the other hand the depth for a disposal zone is seen in much deeper depth. This depth can become achievable through boreholes in 1 to 6 kilometers' underground, in hard rock, which is deemed as borehole disposal concept in nuclear waste management [Brady, 2009].

4. National management plans disposing nuclear waste

The ultimate disposal of vitrified wastes, or of spent fuel elements without reprocessing, requires their isolation from the environment. The most favoured method is burial in dry, stable geological formations some 500 metres deep. Several countries in Europe, America and Asia are investigating sites that would be technically and publicly acceptable. But no country has yet established a workable, permanent and safe storage site for HLW or even a successful interim storage policy in place. A good overview on national HLW management plans can be found in [Wiki, 2011-1], to which is referred in the following paragraph, partly literally.

The United States has 104 civilian nuclear reactors in operation today, generating approximately 20 per centum of the total electricity. Beside the 104 existing nuclear reactors 1 nuclear reactor is under construction and 11new nuclear reactors are on the immediate horizon. Nuclear fuel and HLW is currently stored in the U.S. federal states at 126 sites around the nation. In 1978 the U.S. Department of Energy (DoE) began studying Yucca Mountain, Eureka County, Nevada, to determine whether or not it would be suitable for the nation's first long-term (final) geologic repository for spent nuclear fuel and HLW. Yucca Mountain is located in a remote desert on federally protected land within the secure boundaries of the Nevada Test Site in Nye County, Nevada. The depth of the nuclear geological waste repository will be between 200 and 425 m under surface. The host rock is volcanic tuff. Signing the Joint Resolution 87 on July 23, 2002, allow the DoE to take the next step in establishing a safe repository in which to store the United States nuclear waste. The DoE is preparing an application to obtain the Nuclear Regulatory Commission license to proceed with construction of the repository. If the DoE receives a license from the U.S. Nuclear Regulatory Commission to build and operate a repository at Yucca Mountain, Nevada, it will begin shipping nuclear waste from commercial and government-owned sites to the repository sometime after 2017. But this opening date of 2017 is a best-achievable schedule because the Yucca Mountain is years behind schedule, and according to a new economic analysis, its construction may cost more than $50 Billion. For Yucca Mountain it is planned to use underground cavities with a connecting gallery to build up the log-term geologic repository storing the casks in horizontal galleries. The effectiveness of different technical barriers is under investigation. But the potential risk of this long-term geological repository can be seen by future trends in the global climate and earth quakes. Because it is not possible for computer models to precisely replicate all conditions of a realistic disposal facility. Thus the staffs of the U.S. Nuclear Regulatory Commission (NRC) use abstraction to simplify the information to be considered in a performance assessment. The degree of abstraction has to reflect the need to improve reliability and reduce uncertainty. Nonetheless, it is important for the model to be sufficiently detailed to ensure that it yields valid results for the performance assessment. Hence, a suitable model is a compromise between mathematical difficulties attached to complicated equations and the accuracy in the final result. In general, there are two different approaches to obtain a model of a realistic disposal facility:

1. Deductive or theoretical approach, based on the derivation of the essential relations of the disposal facility
2. Empirical or experimental approach, based on experiment on the disposal facility

Practical approaches often use a combination of both approaches, which might be the most advantageous way to precisely replicate conditions of a realistic disposal facility.

However, the Yucca Mountain project [Mascarelli, 2009; YUCCA, 2008] was widely opposed, with some major concerns being long distance transportation of waste from across the United States to this site, as well as the possibility of accidents, and the uncertainty of success in isolating nuclear waste from the human environment in the long term range. Yet, in 2009, the Obama Administration rejected use of the site in the United States Federal Budget proposal, which eliminated all funding except that needed to answer inquiries from the NRC (Nuclear Regulatory Commission), "while the Administration devises a new strategy toward nuclear waste disposal" [OMB, 2010]. On March 5, 2009, the Energy Secretary told in a Senate hearing "the Yucca Mountain site no longer was viewed as an option for storing reactor waste."[Hebert, 2009].

As with many countries with a significant nuclear power program, the 18 operating nuclear power plants in Canada generated about 16 per centum of its electricity in 2006; Canada has focussed its research and development efforts for the long-term management of HLW on the concept of deep geological disposal. In 1975 the Canadian nuclear industry defined its waste-management objective as to "...isolate and contain the radioactive material so that no long term surveillance by future generations will be required and that there will be negligible risk to man and his environment at any time. ... Storage underground, in deep impermeable strata, will be developed to provide ultimate isolation from the environment with the minimum of surveillance and maintenance." [Dyne, 1975]. In 1977 a Task Force commissioned by Energy, Mines and Resources Canada concluded that interim storage was safe, and recommended the permanent disposal of used nuclear fuel in granites', with salt deposits as a second option [Hare, 1977]. This recommendation was echoed shortly afterward by a concurrent Royal Commission on Electric Power Planning [Porter, 1978; Porter, 1980].

Many European countries have studied the deep disposal of HLW concept for a long time. In 1983, the Finnish government decided to select a site for permanent repository by 2010.

With four nuclear reactors providing 29 per centum of its electricity, Finland in 1987 enacted a Nuclear Energy Act making the producers of radioactive waste responsible for its disposal, subject to requirements of its Radiation and Nuclear Safety Authority and an absolute veto given to local governments in which a proposed repository would be located. The Finnish Parliament approved the deep geologic repository Onkalo in igneous bedrock at a depth of about 500 meters in 2010, a huge system of underground tunnels that is being hewn out of solid rock and must last at least 100,000 years [Ford, 2010]. The repository concept is similar to the Swedish model, with containers to be clad in copper and buried below the water table beginning in 2020.

In Sweden there are ten operating nuclear reactors that produce about 40 per centum of Sweden's electricity. The responsibility for nuclear waste management has been transferred in 1977 from the government to the nuclear industry, requiring reactor operators to present an acceptable plan for waste management with a so called absolute safety to obtain an operating license. The conceptual design of a permanent repository was determined by 1983, calling for a placement of copper-clad iron canisters in a granite bedrock about 1,650 feet underground, below the water table known as the KBS-3 method an abbreviation of *kärnbränslesäkerhet*, nuclear fuel safety [Wiki, 2011-2]. Space around the canisters will be filled with betonies clay. On June 3rd 2009 Swedish government choose a location for deep level waste site at Östhammar, near Forsmark nuclear power plant. A legal and institutional framework of the Swedish radioactive waste management is described in [Berkhout, 1991].

France 59 nuclear reactors contributing about 75 per centum of its electricity. France has been reprocessing its spent reactor fuel since the introduction of nuclear power. France also reprocesses spent fuel elements for other countries, but the nuclear waste is returned to the country of origin. Disposal in deep geological formations is being studied by the French agency for radioactive waste management in underground research labs. Government in 1998 approved Meuse/Haute Marne Underground Research Lab for further consideration. Legislation was proposed in 2006 to license a repository by 2015, with operations expected in 2025. Moreover, a good perspective of the French waste management strategy for a sustainable development of nuclear energy is described in [Courtois, 2005].

Nuclear waste policy in Germany is the most controversial. With 17 reactors in operation, accounting for about 30 per centum of its electricity, Germanys planning for a permanent geologic repository began in 1974, focused on the salt dome Gorleben. The site was announced in 1977 with plans for a reprocessing plant, spent fuel element management, and permanent disposal facilities at a single site. Plans for the reprocessing plant were dropped in 1979. In 2000, the federal government agreed to suspend underground investigations for three to ten years, and committed to ending its use of nuclear power, closing one reactor in 2003. Meanwhile spent fuel elements have been transported to interim storage facilities at Gorleben, Lubmin and Ahaus until temporary storage facilities can be built near reactor sites. Previously, spent fuel was sent to France or England for reprocessing, but this practice was ended in July 2005. Meanwhile the exploration of the salt dome Gorleben is carried on. Moreover, the legal and institutional framework of the German radioactive waste politics is described in [Berkhout, 1991; Wellmer, 1999].

Switzerland's four nuclear reactors provide about 43 per centum of its electricity. ZWILAG, an industry-owned organization, built and operates a central interim storage facility for spent nuclear fuel elements and HLW, for conditioning LLW and for incinerating wastes. The Swiss program is currently considering options for the siting of a deep repository for HLW disposal, and for low & intermediate level wastes. Construction of a repository is not foreseen in this century. Research on sedimentary rock is presently carried out at the Swiss Mont Terri rock lab.

Great Britain has 19 operating reactors, producing about 20 per centum of its electricity. It processes much of its spent fuel elements at Sellafield where nuclear waste is vitrified and sealed in stainless steel canisters for dry storage above ground for at least 50 years before eventual relocate in a deep geologic disposal. In 2006 the Committee on Radioactive Waste Management (CoRWM) recommended geologic disposal in 200–1,000 meters underground, based on the Swedish model, but has not yet selected a site. Moreover, the Britain radioactive waste management politics is described in [Berkhout, 1991].

The Ministry of Atomic Energy (Minatom) in Russia is responsible for 31 nuclear reactors which generate about 16 per centum of its electricity. In the long term, Russia is planning for a deep geologic disposal. Most attention has been endowed to locations where waste has accumulated in temporary storage at Mayak, near Chelyabinsk in the Ural Mountains, and in granite at Krasnoyarsk in Siberia.

In the People's Republic of China, ten nuclear reactors provide about 2 per centum of electricity and five more are under construction. Geological disposal has been studied since 1985, and a permanent deep geological repository was required by law in 2003. Sites in Gansu Province near the Gobi desert in northwestern China are under investigation, with a final site expected to be selected by 2020, and actual disposal by about 2050.

The 16 Indian nuclear reactors produce about 3 per centum of electricity, and seven more are under construction. Interim storage for 30 years is expected, with eventual disposal in a deep geological repository in crystalline rock near Kalpakkam.

The 55 Japanese nuclear reactors produce about 29 per centum of its overall electricity. In 2000, a Specified Radioactive Waste Final Disposal Act created a new organization to manage HLW, and later that year the Nuclear Waste Management Organization of Japan (NUMO) was established under the jurisdiction of the Ministry of Economy, Trade and Industry. NUMO is responsible for selecting a permanent deep geologic repository site, construction, operation and closure of the facility for waste emplacement by 2040

5. Mining disposing concept of nuclear waste

Geological disposals in deep geological formations as radioactive waste repositories have been recognized since 1957 [NAS, 1957]. Such deep geological sites provide a natural isolation system that is stable over a long-term to contain long-lived radioactive waste. In practice LLW is generally disposed in near surface facilities or old mines. Compared with LLW HLW is generally disposed in host rocks that are crystalline (granite, gneiss) or argillaceous (clay) or salty or tuff. The depth of these mined repositories is in between 300 and 700 m.

In Germany, it is planned but not decided yet to dispose radioactive waste in a repository in deep geological formation several hundred metres below the surface in a salt dome. It is assumed that salt will be a natural barrier which is able to protect the environment from radiation. Rock salt possesses particularly good isolating properties for radioactive, heat-generating wastes. Henceforth, the investigation of repository sites in Germany concentrate on rock salt formations as a host rock which actually is the Gorleben project [Wellmer, 1999]. In northern Germany more than 200 salt structures are known with massive rock salt formations about 250 million years old at deep depths. Thus, the selection was quickly narrowed down to the 200 salt domes located in Lower Saxony in northern Germany. There was never a search for alternatives, such as those in granite or clay. Hence, the Gorleben salt dome, with a mined depth of 840 m, was explored for decades. Since 1979, more than1.5 milliards € has been conducted at Gorleben to determine whether the salt dome can be used to securely store the hot radioactive waste for hundreds of thousands of years.

The hazardousness of radioactive waste decreases in time due to the radioactive decay. Nevertheless, in case of long-living nuclides the radiation after 100,000 years requires to isolate waste from the biosphere. Therefore, in long-term analysis periods up to 1 million years and more have to be considered. 1 million years is a very long time scale but from a realistic viewpoint man-kind is unable to forecasting within the same time period in the future. But 1 million years are short compared with geological situations that can be traced back for several 10 or 100 millions of years. Therefore, the question rises whether the actual repository concepts can reliable be forecasted within the next 1 million years.

Long-term safety analyses have been performed to estimate the radiological effects of the considered repository on the biosphere for the next 1 million years. For this purpose, assumed future events and processes such as the thermal expansion of the host rock, subrosion, gas generation or appearance of an ice-age, salt leaching in a salt dome, etc. are combined to scenarios and the consequences of these scenarios can be estimated by numerical simulation.

A simulation study can be performed to test and/or optimize the behavior of engineered systems before construction. This help avoiding costly re-designs necessary due to fatal hypothetical errors, and ensuring cost-effective, high quality, and safe engineered solutions.

The diversity and interdisciplinary nature and the intrinsic complexity of a conceptual approach of a geological disposal necessitate using computational modeling and simulation (CMS) to accomplish advanced and secure solutions. Using CMS in geological repository analysis requires data obtained from measurements at the real world system under test. Thus, building a model of a salt dome for scenario analysis require data sets obtained from (laser) measurements. Such data represent a scatter plot, as shown in Figure 1.

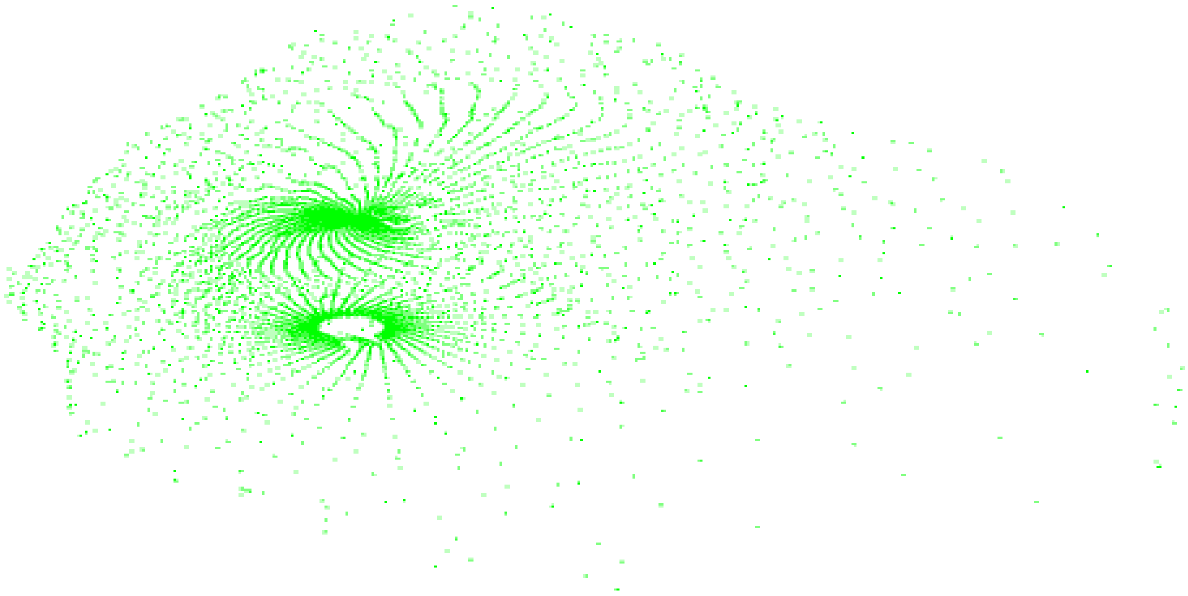


Fig. 1. Laser data obtained from a salt dome scan after (Koerber, 2004; Moeller, 2005)

The scatter plot dot distribution in Figure 1, which represents the measured data, can be applied for surface morphing in conjunction with NURBS (Non Uniform Rational B-Splines). This result in solids that are closed surfaces or more usually poly-surfaces that enclose a volume, as shown in Figure 2.

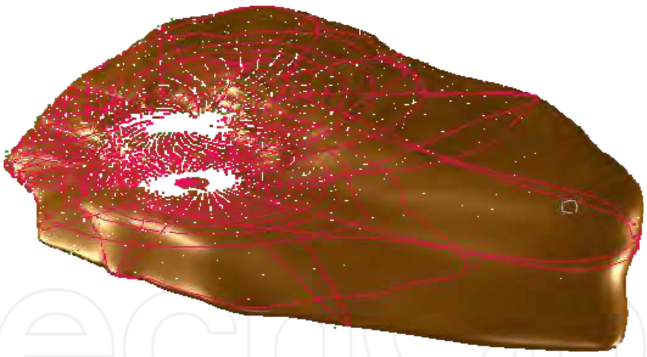


Fig. 2. B-Spline representation of laser measurements obtained from a salt dome scan after (Koerber, 2004; Moeller, 2005)

The special kind of B-Spline representation (NURBS) in Figure 2 is based on a grid of defined points *Pi,j*, which can be approximated through bi-cubic parameterized analytical functions as follows:

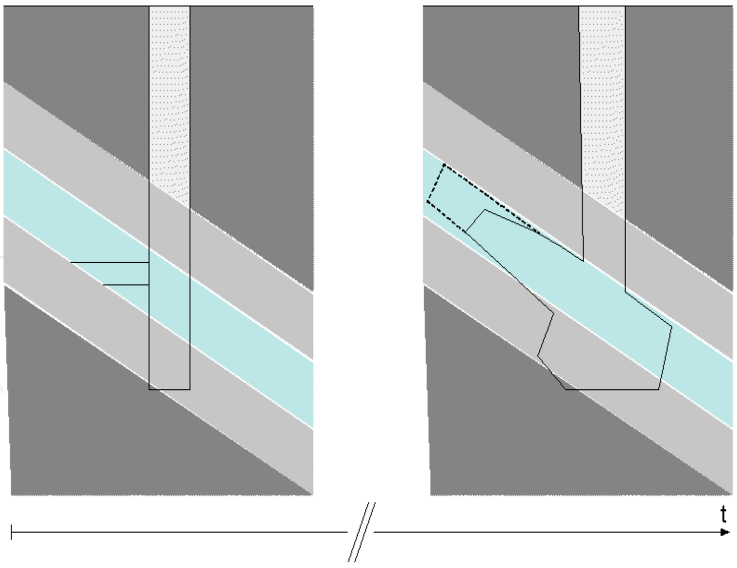
$$P(u,v)=\frac{\sum_{i=0}^{n}\sum_{j=0}^{m}N_{i,p}(u)N_{j,q}(v)w_{i,j}S_{i,j}}{\sum_{i=0}^{n}\sum_{j=0}^{m}N_{i,p}(u)N_{j,q}(v)w_{i,j}}, \qquad 0\le u,v\le 1$$

in which $N_{i,p}$ and $N_{j,q}$ represent the basis of a B-Spline, *Si,j* are the weighted control points with the weights $\omega_{i,j} \in \Re$: As the parameter values *u* and *v* can be chosen continuously, the resulting object is mathematically defined at any point, synonymic showing no irregularities or breaks. But there are several parameters to justify the approximation of the given points which change the look of the described object. Therefore, if needed, interpolation of all points can be achieved:

- First, the polynomial order describes the curvature of the resulting surface or curve, giving the mathematical function a higher level of flexibility.
- Second, the defined points can be weighted according to their dominance in accordance to the other control points. A higher weighted point influences the direction of the surface or curve more than a lower weighted. Furthermore, knot vectors *u* and *v* define the local or global influence of control points, so that every calculated point is defined by smaller or greater arrays of points, resulting in local or global deformations, respectively.

NURBS [Cottrell, 2001] are easy to use while modeling and especially modifying is achieved by moving control points, which allows adjusting the objects by simply pulling or pushing the control points. Based on this concept a methodology to interpolate given sets of points is available. Using multiple levels of surface morphing, the multi-level B-Spline approximation (MBA) adjusts a predefined surface. Constraints like the curvature or direction at special points can be given and are evaluated within the algorithm.

Mined repositories in salt often show salt deposits which have a layered structure as shown in the model of a salt mine in Figure 3, where alternating more or less potassium bearing salt rock layers appear. It is assumed that a leaching process occur in the salt mine under test which result in major structural changes in terms of instability of the cavern, erosion, and so on [Koerber, 2004; Moeller, 2005].



(a) (b)

Fig. 3. Salt leaching effect in a salt mine. Figure 3.a show three different salt rock layer and the mining shaft, figure 3.b additionally show the growth of a brine body after (Koerber, 2004; Moeller, 2005)

Characteristically for potassium bearing salt is that not just salt is leached resulting in some kind of salty water the so called brine. In fact a circulation process occurs, while certain components become leached, others drop out [Sander, 1988] and accumulate at lower level, masking the leaching process in that area. The composition of the brine constantly changes over time while interactions constantly take place between salt rock and solution. These dynamic interactions can be localized along the reaction surface between brine (fluid) and rock (solid), more basically between objects with different geochemical attributes. The direction and velocity of the solution can be described by vectors, determined by an underlying process model, which integrates the relevant parameters of all involved objects (rock, fluid, reaction surface, and so on). The leaching problem in the salt mine can be approximated based on data obtained from laser measurements and modeling based on NURBS. But this approach don´t optimally meet the requirements necessary to model the salt leaching process. Implicit geometry and CSG were no candidates, as well as subdivision and parametric models. It appears questionable whether the easily differentiable structure of parametric models or the arbitrary grid structure of subdivision models, justify the hassle expected from maintaining legal topology due to dynamic topology, which brings cell decomposition into the focus which fit well with the hydro-geochemical process as one cell can simply switch attributes from salt to brine without bringing topology into any trouble. One major concern in this investigation is that the reaction surface moves very slow, perhaps 1cm per cycle of the underlying process model, which would then be the required resolution for e.g. voxel. Hence, currently a model which combines cell decomposition and parametric properties by linking attributes not to voxel but to a regular grid of control points between which linearly interpolation is possible is in favor. This allows finer transition between control points/voxel without requiring more memory executing the model. Formally this is a linear solid B-Spline but since the control points lie on a regular grid, and the geometry thus is implicit, the similarities to voxel are obvious. First tests in 2D show very good fits. Hence, Figure 4 shows the mimicked (no process model is used) leaching process in a salt mine, which does not highlight the hard edges which are typical for voxel.

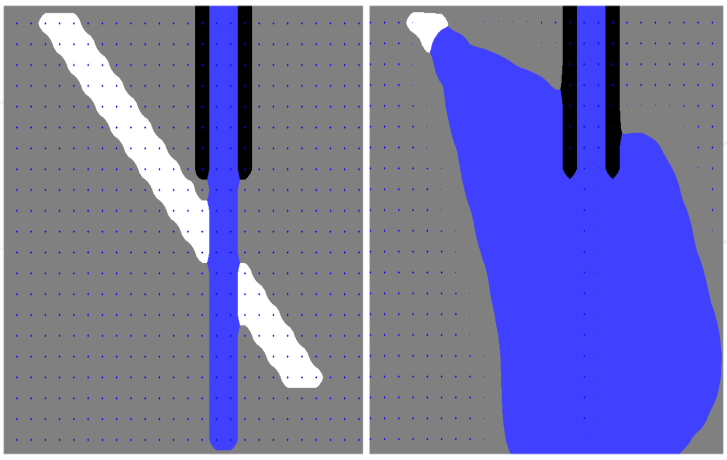


Fig. 4. Bilinear interpolating 2D cell decomposition of the investigation area in a salt mine with superposed leaching process after (Koerber, 2004; Moeller, 2005)

Some issues, like embedding different objects in one geometrical model, identifying the reaction surface and deriving its differential properties still have to be too considered while analyzing what may happen in a salt dome if water became an important fact and leaching will be became a potential risk for stability of the salt dome under test.

6. Borehole disposing concept of nuclear waste

Boreholes occur when using drilling technique, which has been economically developed on the basis of long-year experiences of the rotary drilling method in the petroleum industry. Moreover, petroleum drilling costs have decreased to the point where boreholes are now routinely drilled to multi-kilometer depths. Research boreholes in Russia and Germany have been drilled to 8 – 12 km which are super or ultra deep. Boreholes with a depth of 3 – 5 km are called deep and with a depth of 5 – 7 km are the very deep ones. The risk when drilling rock at medium deep up to the deep depth in between 2- 4 km is stress which may result in a hole breakout through stress. Thus, stress breakout is a feature of deep wells particularly in strong rock. Hence casing throughout the full depth of the borehole is essential. Drilling at deeper depth up to 7 km has to bear in mind temperature as a risk factor. Another important issue when drilling deep boreholes are the resulting enormous costs. In a case study it was shown for 950 deep boreholes to dispose the entire 109,300 metric tons of heavy material inventory will end up in calculated costs of around $ 20 million per borehole, which sum up to approximately $ 19 billion [Brady, 2009].

When drilling deep boreholes the achievable borehole diameter is depending on the drilled depth. This only allows a limited tailoring to suit the waste packaging. Because the deeper the depth the less the size of the diameter. At 8 km depth the size of the borehole will be approximately less than 0.5 m and in 1 km depth the borehole size can be more than 5 m. The foregoing mentioned drilling diameters suit with that which come up in the petroleum industry which raise the question are they adequate with the boreholes necessary for a HLW geological disposal. A deep borehole disposal of HLW which use off-the-shelf oilfield and geothermal drilling techniques into the lower 1 – 2 km portion of a vertical borehole with a conic width of approximately 0.4 – 1.2 m diameter and 3 – 5 km deep, followed by borehole sealing, is described in [Brady, 2009]. This disposal at a depth of 3 – 5 km allows a 1 – 2 km long HLW disposal zone, as shown in Figure 5.

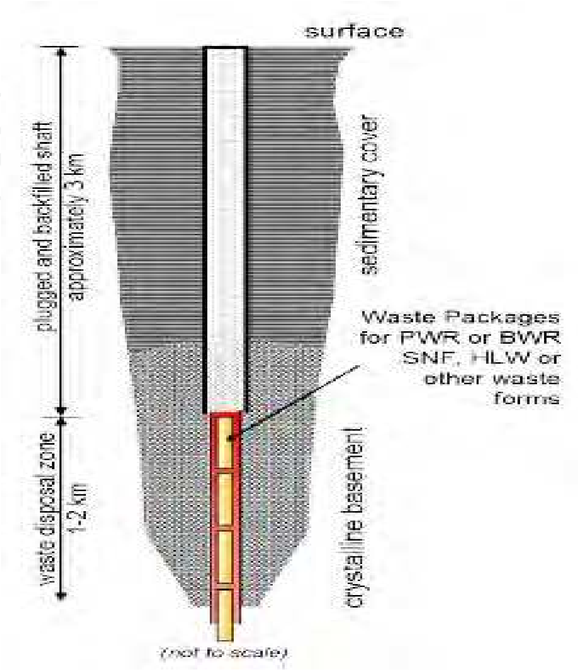


Fig. 5. Deep borehole disposal schematic after (Brady, 2009)

This 1 – 2 km long waste disposal zone can hold 200 – 400 HLW canisters. The canisters could be emplaced one at a time or as part of a canister string which represent a grouping of 10 or 20 canisters. The design concept of this borehole concept is such that the borehole allows accommodating 34 outer diameter canisters. The borehole seal system will use a combination of bentonite, asphalt and concrete, at which a top seal will consist of asphalt from 500 m to 250 m, with a concrete plug extending from 250 m to surface.

But the diameters for the borehole shown in Figure 5 are not comparable with the ones necessary to obtain a technology enhanced HLW geological disposal concept as described in the following paragraph of section 5 in this chapter. The background for the technology enhanced HLW geological disposal approach bear in mind that geological deep disposal involves sinking large diameter borehole 3 to 5 km down into the granitic basement of the continental crust, with containers of HLW in the bottom 1km or so, and scaling the hole above the deployment zone. This very deep in engineering terms is described as very deep borehole disposal [Gibb, 2005]. Thus, it is anticipated that deep borehole disposal will be on the under of 3 km deep, and necessitate at least a diameter of more than 10 m. This diameter is necessary for dumping the containers and retrieves the containers if needed. Both can be done if an elevator is embedded as part of the technology enhanced HLW geological disposal approach, because the elevator fit into the drilled diameter. The big advantages of such a deep borehole disposal, the same reason has been discussed by Brady [Brady, 2009], are that it avoid groundwater problems almost together and provides a far-field geological barrier of enormous strength. The geological barrier is the only barrier to any escape of radionuclides that can demonstrably survive on the timescale of millions of years [Gibb, 2005]. In order to evaluate the system performance of a deep technology enhanced HLW geological disposal concept, it is necessary to adopt or develop a standard by which the performance can be measured. But the political decision in Germany to postpone the final judgment for implementation of a final HLW geological disposal only allows estimating the performance differences between the mined and the borehole geological disposal concepts.

As assumed in the preceding paragraph of the borehole geological disposal concept HLW is embedded in mineral and ceramic crystalline lattices, such as zircon, cubic zirconium and monazite, encapsulated in deep boreholes deeper than 3 kilometer and up to five kilometers' underground, in hard rock in order to overcome the uncertainties of the mined disposal concept of a few hundred meters' depth (300 – 800 m). Thus, the deep borehole disposal concept put HLW back inside the rocks from which it came as uranium. The depth of clearance of more than one to five kilometers' is the most critical as one want to get to an area where the geology is stable and there is almost no water flowing. After filling the disposal in the foregoing mentioned depth of the clearance with high radioactive waste, boreholes would be backfilled and secured by rock welding or other techniques of at least 1 – 2 kilometers height, as described by Brady [Brady, 2009]. But the drilling technique of deep boreholes as described by Brady [Brady, 2009], which use off-the-shelf oilfield and geothermal drilling techniques, is not the technical approach introduced in this section of the chapter as technology enhanced HLW geological disposal approach. It is rather a flame melts technique which melts hard rock and it is assumed that this will allow borehole diameters of approximately 10 meters and more which will limit entry of water and migration of contaminants through the borehole after it is decommissioned. It is assumed that this concept is being safe to isolate HLW from the biosphere for a very long time, protecting both mankind and environment from radiation to its best possible extent, compared with the mining approach, described in section 4 of this chapter.

Rock welding is the basic principle of a technology to sink vertical constructions or to drift horizontal driving, which has been developed at the Los Alamos Laboratories in New Mexico, U.S.A., in recent years, performing underground construction of non-specified extent. The achieved results showed that rock welding technology reached a three times higher performance than traditional drilling techniques by only causing 40% less costs [CGER, 1994]. But the staff of this research project report that this technique could not be employed near inhabited areas, since the energy source used to melt the rock was a nuclear reactor which would have contaminated the ground water in case of a disaster. To overcome this energy dependent problem, a research group with scientists from the Universities Hamburg, Germany, Košice, Slovak Republic, Brno, Czech Republic, in co-operation with the German-Czech Science Foundation (WSDTI), Germany, searched and studied an option on a rock welding technique which does not need a nuclear reactor as energy source for rock melting. The resulting technical principle is deemed as flame melting technique beneath extreme high pressure, temperature, and frequency. This approach replaces the nuclear energy source used in the borehole project using a rock welding technique in Los Alamos. This new technique is based on a cost effective high energy oxygen-hydrogen-mixture energy source. Based on this research work a first mock up assessment was carried out in support of implementation of geological disposal based on the flame melting technique concept to melt rock indicate amendatory against present mining geological disposal concepts. The necessary exploration to test the flame melting technique to melt rock material at the laboratory scale was accomplished at the Technical University Košice, and the Slovakian Academy of Science, Slovak Republic. This test site is led by the two Slovakian

Professores Felix Sekula and Tobias Lazar. For this purpose a flame jet pump system, buildup of cobalt, was developed. The crown of the flame jet pump system is covered by a 200 µm thick ceramic coat of hafnium nitride. The head base of the jet pump system has an outflow nozzle by which the oxygen-hydrogen gas mixture flow through and melts the rock by means of the burning flame. Rock boulders with the dimension of 0.5 m^3 were used to melt rock by means of the burning flame. At this laboratory scale holes of approximately 70 mm diameter could be realized. The flame jet pump system melt holes in the rock boulder in such a way, that the burned waste package could disappear through the melted chambers, as shown in Figure 6. In this laboratory investigation the average penetration rate achieved was 7 mm/sec. Investigating the flame melted holes show that no disjoining pressure have occurred under the head of the jet pump system. However, radial cracks of such dimension occur that the rock boulders collapse in the final stage. Thus, the melted rock could pass through the melted chambers into the radial cracks, which has been kept in several records. Moreover, inspecting the flame melting rock boreholes show at several areas a special crust within the ambiance of the melted chambers as well as at the collapsed probes. At this laboratory scale holes of approximately 70 mm diameter the radial cracks are not developed through a disjoining pressure which happened in the Los Alamos test bed in the real rock massive, rather than thermal force. Thermal force generates radial cracks in the direction of the free areas of the rock boulder.

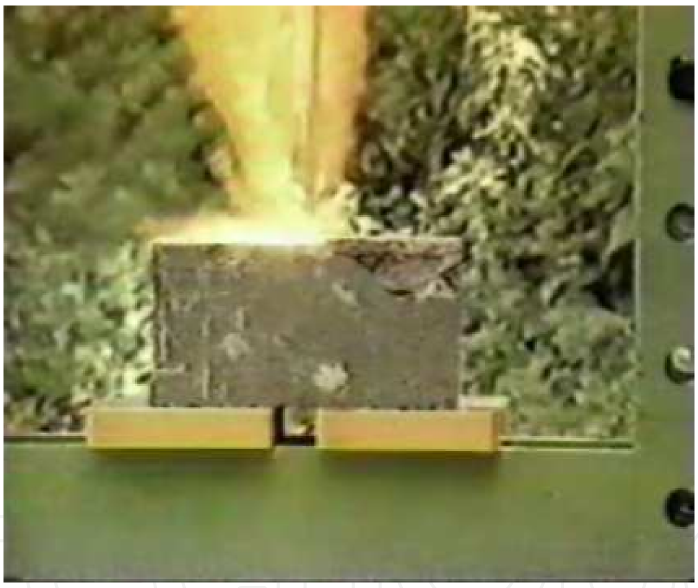


Fig. 6. Laboratory test bed of the flame melting technique (with permission of Professors Lazar and Sekula, Technical University of Košice, Slovak Republic)

The flame jet pump system injection head is shown in Figure 7.
In general, for both concepts, the mined one in salt rock and the borehole one in hard rock, it is assumed that one can thus safely isolate the higher radioactive waste from the biosphere for a very long time, protecting both man and environment from radiation to the best possible extent. Before it can be determined whether a potential location really is suitable to be a site for a long term disposal, all aspects of the overall situation regarding the geological disposal has to be investigated. Thus, one has to investigate in particular the effectiveness of the geological and geotechnical barriers and design a coherent long term management of a higher activity radioactive waste concept.

Fig. 7. Laboratory version of the flame jet pump system injection head (with permission of Professors Lazar and Sekula, Technical University of Košice, Slovak Republic)

For this reason a principle concept as basis for a repository that permit embedding elevators in the large diameter borehole and, provided that the security barriers are arranged in a suitable way, allowing retrieval from the final repository of the containers installed in the smaller boreholes, is shown Figure 8. This assumption is due to the consensus view that at first repositories will be designed for retrievable storage; but there is often a clear implication that if, after a suitable period, there are no technical difficulties and the political climate permits, the system of tunnels and access shafts will be scaled up and the repository will become a disposal. As it can be seen in Figure 8 big borehole diameters in rock massive only will melt the borehole border while the kernel will be mechanical removed.

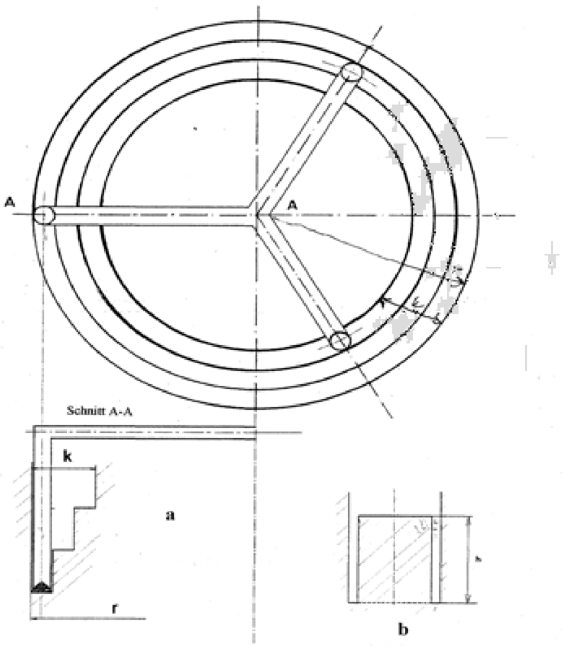


Fig. 8. Deep borehole disposal concept with borehole-border-melting dimensions

The great advantage of this type of disposal is that it prohibits groundwater problems and almost a far-field geological barrier of enormous strength. The geological barrier is the only barrier to any escape of radionuclide's that can demonstrably survive on the timescale of millions of years. In contrast to the very active groundwater flows at conventional repository depth R in Figure 9, the migration of intra-rock aqueous fluids becomes increasingly sluggish with depth.

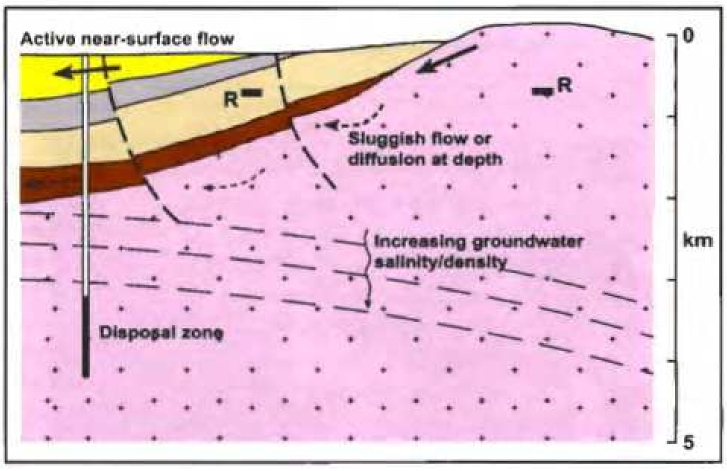


Fig. 9. Conceptual model for a very deep borehole disposal of high level radioactive waste, after Chapman and Gibb, 2005)

At depth of 4 to 5 km in the granite basement, hydraulic conductivities tend to be less, and often much less than 10^{-11} meters per second, i.e. fluids migrate at most a few hundreds of meters in a million years. Due to this ultra-less risk in groundwater contamination by radionuclides one has to achieve water tightness of the storage caverns as most important ancillary condition. Assuming that a drilling techniques exist with a sufficient melting of granite than the solid rock will become individually melted in the cavers as well as in the shaft to preserve the integrity of the container and that the melt will recrystallize completely to holocrystalline granite on a time scale appropriate to the thermal decay of the high level radioactive waste. Henceforth, from the consensus point of view a proof is needed to show that the cracks already present in the host rock and the cracks created there by melting are completely closed against high pressure by the rock melt, down to sufficient depth.

Nevertheless, several main problems are unsolved to date melting solid rock like granite, based on the flame melting technique beneath extreme high pressure, temperature, and frequency, which conduct a bunch of questions. These questions refer to the knowledge gained in our previous research work and are focused on the very details to achieve such a deep borehole with the flame melt technique due to expected constraints, which we are aware. Hence, the questions are answered based on the knowledge to date.

Whichever reactions occur if large quantities of water appear during the melting process?

For a consensus answer at the very first it is necessary being aware that:

- before go for flame melting of solid rock like granite, precise geological and hydro-geological investigations are necessary to select the appropriate location of the geological repository.

Assuming that this has been done as part of the consensus view, the question thereafter can be answered referring to state of the art knowledge based on facts like:

- temperature of the melted rock is in between 1400 and 1800°C,
- temperature of the melting flame is approximately 2530°C,
- water has a temperature gradient of 1°C per 33 m depth; which result for a depth of 2000 m in a water temperature of 66°C; with the precondition that are no aquifers at this location,
- flame melting can be used if and when water inflow from cracks exist, which can be the case in solid rock, as well as additionally generated through the melting temperature,
- evaporating the melted product the water detract energy, but as an additive impact the water vapour pressure acts in a reinforcing manner on the melted product,
- water evaporates incremental,
- water vapour – dissociated due to the temperature of H_2 and O –, press the melted product into the existing fissures and cracks, while the melting flame is continuously burning (temperature approx. 2530°C) – can also burn below water surface level –,
- no chemical reaction between the water and the melting flame itself has to be considered,
- in case of substantial water inflow from cracks, additional special waterproofing procedures are needed. Thus, potential geological repository locations without cracks should be chosen as far as possible,
- high temperatures in the rock, e.g. due to aquifers, have a reinforcing impact on the melting process, because less energy is needed to melt solid rock.

Is the vitrified rock seam around the melted hole hydraulically tight?

A consensus answer depends on the decision on the location selected for the flame jet pump system drilled deep borehole and its depth:

- apart from the cracks, the rock seam must be hydraulically tight without the melted products, which can be determined by sample drillings on the location selected for the the flame jet pump system drilled deep borehole,
- melted products closes the cracks in the rock, and closes the pores of the rock seam,
- quantity of melted products can be regulated by the melting flame,
- thermo-shock tests are needed to determine the depth of crack closure.

How melted holes in solid rock must to be filled for hydraulic tightness?

A consensus answer relates on both, the cracks and the bed of the flame melted hole in solid rock:

- depth of crack to be filled with melted products can be determined by non-destructive measurement devices such as sound measurements, with can additionally be supported by drillings,
- tightness of the bed of large flame melted bore holes is determined by test drillings,
- tightness of completed cavities can be determined by means of water pressure tests.

What is the long-term behavior (ageing) of the solidified melt?

In general, solid rock has a crystalline structure, and the melted products will recrystallize completely to holocrystalline granite on a time scale appropriate to the thermal decay of the HLW. Henceforth, from a consensus view it can be assumed that on the long scale the same long-term behaviour of the real rock massive will happen, because both of which are based on the same primary elements, what has been investigated in a previous research study [Rybar, 2004].

What influence has the chemical milieu i.e. the chemical composition of the rock and the fissure water on the solidified melted products?

From a consensus view it can be assumed:

- influences on the solidified melted products are the same as the influences on the real rock massive,
- aggressive substances do not influence the chemical milieu in the granite rock, since they only occur in small quantities,
- no bacteriological influences can be found at the intended depth.

How will long-tern bonding of filling material influence the vitrified rock?

From a consensus view it can be assumed:

- bonding of the filling material of the vitrified rock seam will not occur,
- retrieving stored containers from the geological repository may have a huge impact on filling the cavities of the repository which can make this process difficulty. Thus, at the very early beginning, one has to investigate the interactions that cohere with this option very carefully.

What is the cooling behavior of the solidified rock melted products (contraction cracks)?

From a consensus view it can be assumed:

- cool down process of the melted products is very slow because of the low thermal conductivity e (e = 0.25 to 0.73 W(m°C)),
- thermo-shock tests will provide detailed knowledge,
- possible appearance of contraction cracks due to thermal tensions are to be closed by subsequent injections.

How far does the melted rock penetrate into the open fracture system of the rock, and what are the factors determining the penetration depth?

From a consensus view it can be assumed, referring to:

- published results from flame melting tests of the Los Alamos geological disposal project in the United States, show in near to the surface cavities that thermally induced cracks may have a length of up to 600 times of the drilling hole diameter (< 100 mm), using the traditional rotary drilling method,
- to date knowledge that the penetration depth of melting material depends on its viscosity and the quantity which can be regulated by the flame melting process.

Demonstrations' or estimates of radiation damages at vitrified rock?

From a consensus view it can be assumed:

- tests at nuclear power stations reactors currently in operation show satisfactory results in their concrete structures with different rock aggregation materials (a precondition for their construction approval),
- in nuclear power stations, the kinetic energy of the neutrons is also slowed down by water – which is also possible with the cavities assembled by melted rock,
- apart from this, the radiation detection methods used in radiation measurement can also be used.

In view of the foregoing preliminary answered questions the operational improvements for supporting final radionuclide's disposal research and technological development can be estimated and valuated. Furthermore, an economic assessment can be carried out to support implementation of a geological repository for HLW based on the flame melting technique concept, as well as a mathematical risk calculation. A risk is mathematically defined by the number of potential hazards. The number of potential hazards can be described through the arithmetical average over an expectation, which represent the conjunction of products of a quantitative indication of possible consequences such as the extent of a claim and the claims amount as well as the quantitative indication of the probability, considering the de facto incidence of the consequence of a claim. The risk analysis formula is:

$$R = H * S$$

with R: risk of the expectation, H: probability of the eventuate of the incidence, S: normative dimension of claim.

This formula allows calculating possible impacts of claims quantitatively, expressed through the probability, which allow comparing potential risks.

Referring to borehole geological disposals the risk analysis allows calculating possible impacts of borehole geological disposals on the civilization quantitatively, expressed through the probability, which allow comparing potential risks, which is essential for planning safety related arrangements. The goal is to keep the potential risk as minor as possible (minimization). By means of physical simulation possible variations of initial and boundary conditions can be embedded to analyze varying safety related arrangements with their specific risk to calculate the pros and cons of technical arrangements and their costs. But the essential risk analysis for borehole geological disposals require quite more than the quantitative approach described before, it also need a qualitative approach.

The quantitative risk analysis for borehole geological disposals requires a scenario planning and analysis with adequate initial and boundary conditions, to run simulation case studies. Thus, a scenario analysis can be performed to predict possible future events of a given entity considering alternative possible outcomes, assuming changing scenarios but inherently consistent constraints, for improved decision-making, that require as prerequisite a scenario planning, a method based on simulation runs for decision making. This runs combine known facts about the future, with plausible alternative trends that are key driving forces. Hence, the quantitative risk analysis leads to the definition of scenarios with adequate constraints, which run as respective physical model of the borehole geological disposal, to predict the needs and expectations of safety related arrangements. With ongoing progress of the borehole geological repository project the physically defined scenarios can be adapted to the major information density available and being used for the whole project duration up to bringing the borehole geological disposal into service.

7. Conclusion

This research work demonstrate the fundamentals of the mined and borehole geological repository approaches for high level radioactive waste with reference on the actual situation of national management plans disposing nuclear waste. These plans are of interest for deciding about the structural approach developing a geological disposal and the possible disposing sites which have been taken into account. For a mining disposal concept the problem of salt leaching is described in detail, referring to NURBS as an option to model the dynamic process of salt leaching mathematically. Beside the mining concept the borehole approach is demonstrated. One borehole approach is based on deep depth but a small borehole diameter of about 1 m. The drilling technique applied is based on the long-year experiences of the rotary drilling method in the petroleum industry. The second demonstrated borehole approach is focused on deep depth too but with a bigger diameter of about 10 m. The drilling approach used in this study is a rock welding principle to sink vertical constructions which has been developed at the Los Alamos Laboratories in New Mexico, U.S.A. But the energy source used to melt the rock in the Los Alamos project was a nuclear reactor which would have contaminated the ground water in case of a disaster. To overcome this energy dependent problem a flame melting technique beneath extreme high pressure, temperature, and frequency has been developed and is demonstrated. Based on the research work described in this chapter a first mock up assessment was carried out in support of implementation of geological disposal based on the flame melting technique concept to melt rock. The main advantages of the research work are:

- demonstration of to date existing approaches to support implementation of geological repositories,
- complementary approach to support the implementation of geological repositories in Europe,
- demonstration of a technology enhanced approach to support implementation of geological repositories,
- collaborative research work at the European level.

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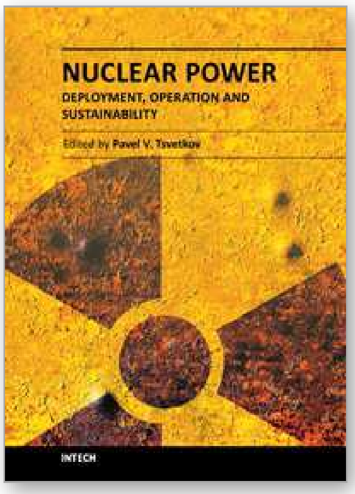

Nuclear Power - Deployment, Operation and Sustainability
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We are fortunate to live in incredibly exciting and incredibly challenging time. Energy demands due to economic growth and increasing population must be satisfied in a sustainable manner assuring inherent safety, efficiency and no or minimized environmental impact. These considerations are among the reasons that lead to serious interest in deploying nuclear power as a sustainable energy source. At the same time, catastrophic earthquake and tsunami events in Japan resulted in the nuclear accident that forced us to rethink our approach to nuclear safety, design requirements and facilitated growing interests in advanced nuclear energy systems. This book is one in a series of books on nuclear power published by InTech. It consists of six major sections housing twenty chapters on topics from the key subject areas pertinent to successful development, deployment and operation of nuclear power systems worldwide. The book targets everyone as its potential readership groups - students, researchers and practitioners - who are interested to learn about nuclear power.

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