

Storage of High Level Nuclear Waste in Germany

Dietmar P. F. Möller¹

Uloženie nukleárneho odpadu vysokého stupňa v Nemecku

Nuclear energy is very often used to generate electricity. But first the energy must be released from atoms what can be done in two ways: nuclear fusion and nuclear fission. Nuclear power plants use nuclear fission to produce electrical energy. The electrical energy generated in nuclear power plants does not produce polluting combustion gases but a renewable energy, an important fact that could play a key role helping to reduce global greenhouse gas emissions and tackling global warming especially as the electricity energy demand rises in the years ahead. This could be assumed as an ideal win-win situation, but the reverse side of the medal is that the production of high-level nuclear waste outweighs this advantage. Hence the paper attempt to highlight the possible state-of-art concepts for the safe and sustaining storage of high-level nuclear waste in Germany.

Key words: nuclear energy, nuclearwWaste, nuclear waste storage

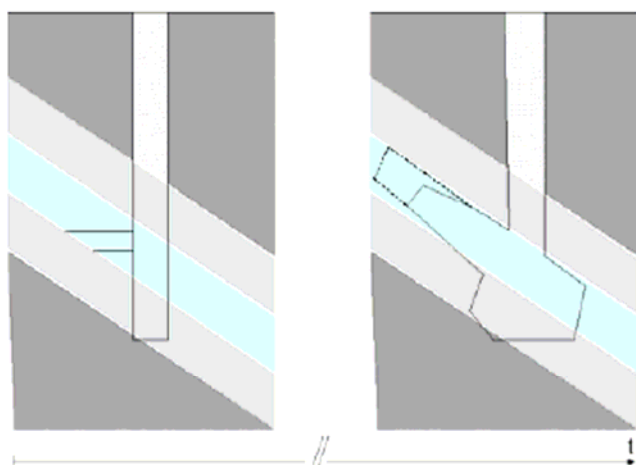
Introduction

The subject of this paper is related to the actual and to-be concepts for the storage of high level nuclear waste that already exist or they are under construction, or discussion. Henceforth this paper, we will focus on the respective situation in North America and Europe, and especially in Germany.

The nuclear waste is a specific type of waste that contains radioactive chemical elements without, a general and practical purpose. It is sometimes a product of the nuclear process, such as nuclear fission. The majority of radioactive waste, belongs to the so called low-level nuclear waste, meaning it has low levels of radioactivity per mass or volume. This type of waste is all-around, and can be estimated to represent be approximately 80 %, It consists of items that are only slightly contaminated but still dangerous due to a radioactive contamination of a human body through ingestion, inhalation, absorption, or injection. But not only low-level nuclear wastes are still dangerous for the human body. It is also a low-level radioactive material. This happened in the recent crime, when the former coworker of the Russian intelligence service, Alexander Litwinenko, was killed by a small dose of ingested polonium.

Opposite to the low-level nuclear waste nuclear power plants also produce the so called high-level nuclear wastes, that partakes with approximately 20 % of the total nuclear waste. All types of nuclear waste require a specific disposal concept such as a repository in deep geological formations, several hundred metres below the surface in a mine. In Germany, it seems to be agreed use old salt mines as a temporary repository for nuclear wastes.

The salt deposits have a layered structure, shown in Fig. 1, for the model of the salt mine of Stassfurt,



Germany, where alternating more or less potassium bearing salt rock layers appear. Salt rocks of different composition show different characteristics. They have to be distinguished in a corresponding geometrical model that can be used for a further usability analysis. In case of the Stassfurt salt mine, the analysis is focussed on salt leaching and the possibility of resulting earth falls.

Fig. 1. Salt leaching effect in the salt mine in Stassfurt, Germany. The left picture shows 3 different salt rock layers and the mining shaft, the right picture show additionally the growing brine body.

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The characteristic of the potassium bearing salt is that a salt is leached resulting in some kind of salty water-the so called brine. In fact, a circulation process occurs, in which certain components become leached but other drop out (Sander 1988) and accumulate at a lower level, masking the leaching process in this area. A composition of the brine is therefore changed over time while interactions constantly operate between salt rock and the solution.

These dynamic interactions can be localized along the reaction interface between the brine (fluid) and the rock (solid), more basically between objects with different geochemical attributes. The direction and velocity of the solution process can be described by vectors, determined by an underlying process model, which integrates relevant parameters of the involved objects (rock, fluid, reaction surface).

None of the classical geometrical modeling methods optimally meet the requirements of modeling salt domes as well as the possible salt leaching process. The implicit geometry and Constructive Solid Geometry (CSG) have never been realcandidates. Subdivision and parametric models come at a high price, that bring the cell decomposition which fits well the hydro-geochemical process in one cell can simply switch attributes from the salt to the brine without bringing the topology into any trouble. One issue which has to be dealt with is that the reaction surface moves very slowly, perhaps 1cm per cycle of the underlying process model, which would then be the required resolution for a voxel, which may result in a model that combines the cell decomposition and the parametric properties by linking the attributes not to the voxel but to a regular grid of control points which we linearly interpolate. This allows a finer transition between the control points / voxel without requiring a more memory. Formally, this is a linear solid B-Spline but since the control points lie on a regular grid, and the geometry is thus implicit, similarities to the voxel are obvious. They first test in 2D seems to confirm our expectations. Figure 2 shows a mimicking (no process model is used) of the salt leaching process, which does not show the hard edges which are typical for the voxel.

Figure 2 illustrates that a geological modelling is important in understanding the intrinsic dynamics of the complex processes of the salt mine itself as well as the salt leaching phenomena. From a more general point of view, the geological modelling is an important tool for the usability analysis of salt caverns that may be used as a repository for wastes, especially nuclear wastes, in order to understand their intrinsic dynamics along their long-term usage.

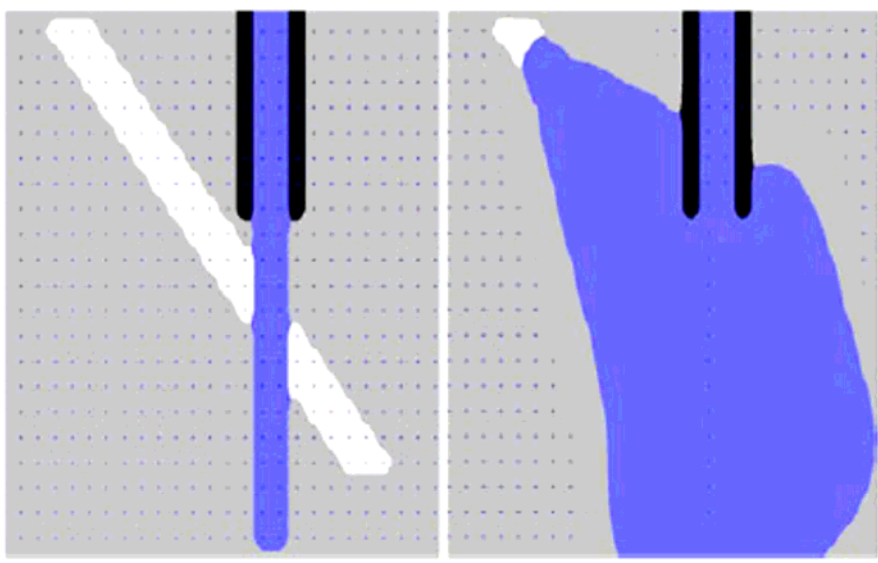


Fig. 2. Bilinear interpolating the 2D cell decomposition of the investigation area.

Nuclear energy

A nuclear energy lies in the nucleus the (so called core) of an atom. Atoms themselves are tiny particles of the universe. The nuclear energy can be used to produce electricity. But at the very first the energy must be released, what can be done in two ways: the nuclear fusion and the nuclear fission. The nuclear power in general can be generated from the fission of uranium, plutonium or thorium as well as by the fusion of hydrogen into helium. In the nuclear fission, atoms are split apart to form smaller atoms, releasing an energy which is used to produce electricity. Today it is almost all uranium. The most important fact is that the fission of an atom of uranium produces 10 million times the energy produced by the combustion of one atom of carbon from coal.

Uranium is non-renewable, though 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. U-235 is relatively rare. Once uranium is mined, the U-235 must be extracted and processed before it can fission in a reactor. Compared with U-235, U-238 can not fission to a significant extent. Natural uranium is 99.3 percent U-238 and 0.7 percent U-235. Henceforth, most nuclear power plants today use enriched uranium in which the concentration of U-235 is increased from 0.7 percents to (nowadays) about 4 to 5 percents. This can be done in an expensive specific separation plant. U-235 in natural uranium which is used in today's reactors seems to be available for a number of decades.

A nuclear power reactor contains a core with a large number of fuel rods. Each rod is full of pellets of uranium oxide, which is an atom of U-235 fissions when it absorbs a neutron. The fission produces two fission fragments and other particles that fly off at a high velocity. When they stop the kinetic energy is converted to heat.

Besides the fission fragments several neutrons are produced. Most of them are absorbed by something other than U-235, and in the steady-state operation one neutron is absorbed by another U-235 atom causing another fission, meaning that these neutrons go on to bombard other uranium atoms, and the process repeats itself over and over again, which is called a chain reaction. The control rods that absorb neutrons can also be moved in and out to control the nuclear reaction. The power level that can be used is limited to avoid letting the fuel rods get too hot. The heat from the fuel rods is absorbed by water which is used to generate steam to drive turbines that generate the electricity. A large plant generates about a million kilowatts of electricity.

Nuclear waste

Nuclear waste in general can be classified in a low level and a high level radioactive waste. The low level nuclear waste in general terms 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 the diagnosis and treatments or x-rays,
- industrial waste which may contain alpha, beta, neutron or gamma emitters,
- 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.

The low level nuclear waste is comparatively easy to dispose of. The level of radioactivity as well as the half life of the radioactive isotopes in the low level nuclear waste is relatively small. Storing the waste for a period of 10 to 50 years will allow most of the radioactive isotopes in the low level nuclear waste to decay, at which point the waste can be disposed of as a normal refuse.

In most OECD countries, all short-lived, low- and intermediate-level nuclear wastes (the latter one can be classified into short-lived waste, mainly non-fuel materials from reactors, and long-lived waste from fuel and fuel-reprocessing), whatever their source, are disposed of using surface or underground repositories that are safe for the human beings and the environment during the time that these wastes maintain their radioactivity.

The wastes, mentioned above, representing some 90 % of the total radioactive waste, are conditioned and stored in facilities isolated from the environment by specially engineered barriers.

In comparison to the low level nuclear waste, the high level nuclear waste in general is a radioactive material from the core of the nuclear reactor. This waste, based on the so called fuel rods, includes large quantities of high level radioactive fission products and are generating heat at a high rate. Also their extremely long half-lives (longer than 100,000 years) create extremely long time periods before the nuclear waste will settle to safe levels of radioactivity. Hence this nuclear waste at the very first is put in an intermediate/temporary storage facility, under strict safety conditions, which could be a large tank of water. Within this large water tank the high-level radioactive isotopes become less radioactive due to their decay and also generate less and less heat. Henceforth, the final disposal of high-level nuclear waste is delayed to allow its radioactivity to decay. Forty years after the removal from the reactor, less than one thousandth of its initial radioactivity remains, and it is much easier to handle. Hence, canisters of vitrified waste, or spent fuel assemblies, are stored under water in special ponds, or in dry concrete structures or casks for at least this length of time. But this requires specific methods for dealing with this high level nuclear waste. Some of the methods being under consideration include a short term storage, long term storage, and a transmutation. As it has been stated above, the longer the spent fuel is stored in the intermediate storage

facility, the easier is their handling, but many reactors hold the spent fuel so long that their tanks get full. They must either send the rods off or build more tanks.

But, generally for the long-lived and the high-level nuclear waste it is usually envisaged that they have to be placed in a final disposal facility, whatever this connoted. From a political point of view, it seems that there is no immediate economic, technical or environmental need to speed up the construction of final disposal facilities for the radioactive waste. The European Commission has prolonged the time schedule for their member states to satisfactory show their sustainable permanent high-level nuclear waste disposal facility, which first was terminated for the year 2018. But now it should be shown in 2030. Also the German Minister of Environment has prolonged the time schedule for the final decision of a permanent disposal facility for the high-level nuclear waste. Recently, he said that a research work on the nuclear waste deposits is necessary for next 14 years to establish a broader data base for the final decision making as to where to locate set up the permanent high level nuclear waste disposal facility in Germany.

Bearing this in mind and from a sustainable development perspective – and if we do not want to pass the burden of finding a permanent solution for the high-level nuclear waste on to future generations – we have to state that the temporary storage, as it is in use today, is clearly not a satisfactory solution we can stay with for longer.

One possible long-term solution that is currently preferred by international experts (more details can be found at www.formal-stanford.edu/juc/progress/nuclear-faq.html) consists in placing the waste in a deep of at least 500 metres below the surface in a stable geological setting, such as granite, clay, tuff and salt formations that have remained virtually unchanged for millions of years. The ambition is to ensure that such wastes will remain undisturbed for a few thousand years needed for their levels of radioactivity to decline to the point when they do not represent a danger to present or future generations. The concept of a 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 the deployment. As a general concept, the natural security afforded by the chosen geological formation is enhanced by additional precautionary measures. The wastes deposited are immobilised in an insoluble form, in blocks of glass for example, and then placed inside corrosion-resistant containers; spaces between the 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 together ensure that the radioactive waste can be contained over a very long term. But the nuclear waste can be recovered during the initial phase of the repository, and also during subsequent phases, albeit at an increased cost. This provides a certain degree of freedom of choice to future generations to change waste management strategies if they wish.

Based on the state-of-the-art in engineering and science repositories are designed in such a way that it can be assumed that no radioactivity will reach the Earth's surface. Following the precautionary principle, the environmental impact assessments spanning 10,000 years analyse the worst-case scenarios, including geological and climate changes and inadvertent anthropogenic intrusion. The assessments maintain that even under those conditions, the impact on the environment and man-made would be less than current regulatory limits, which in general are lower than natural.

Beside the existing man-made geological disposal facilities for the long-lived waste, another partial solution is to reduce the mass of this waste using a technique known as partitioning and transmutation, which involves isolating the transuranic elements and long-lived radionuclides in the radioactive waste and aims at transforming most of them by the neutron bombardment into other non-radioactive elements or into elements with shorter half-lives. 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 an industrial scale. This is because in addition to being very costly, partitioning and transmutation makes fuel handling and reprocessing more difficult, with potential implications for the safety.

In general, the cost is an important issue in the radioactive waste management as related to the sustainable development. If the nuclear industry did not set aside adequate funds, a large financial burden associated with the plant dismantling and radioactive waste disposal would be passed on to the next generations. In most of the OECD countries, the costs of the dismantling nuclear power plants and of managing long-lived wastes are already included in the electricity generation 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 % – of the total cost of the nuclear power generation.

As a very first but important conclusion, it could be put on record that addressing the public's concerns and negotiating acceptable solutions is an important challenge. A decision-making process should be set up in a step by step manner, and all the affected groups should be allowed to participate. The role of governments will be crucial in defining this process, and they should act as a confident source of objective information. They also need to dedicate adequate resources for this purpose, so that the public confidence may be a won in the proposed scientific solutions.

Nuclear waste storage in the North America and in Europe

The ultimate disposal of vitrified wastes, or of spent fuel assemblies without reprocessing, requires their isolation from the environment for long periods, as outlined in the Chapter 2. The most favoured method is a 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 nation has yet established a workable, permanent storage site for the high-level nuclear waste; indeed, no nation has even a successful interim storage policy in place. The concept of the deep geological storage of the high-level waste, considered worldwide as the most promising disposal option, is increasingly falling into disfavour. The U.S. Department of Energy (DOE) began studying Yucca Mountain, Eureka County, Nevada, in 1978 to determine whether it would be suitable for the nation's first long-term geologic repository for the spent nuclear fuel and high-level radioactive waste. The Yucca Mountain is located in a remote desert on the federally protected land within the secure boundaries of the Nevada Test Site in Nye County, Nevada. It is approximately 100 miles northwest of Las Vegas, Nevada. The depth of the nuclear waste repository will



Fig. 3. Yucca Mountain area in Nevada, U.S.A. Downloaded from, http://en.wikipedia.org/wiki/Yucca_Mountain

be between 200 and 425 m under the surface. The host rock is volcanic tuff. It is planned to make use of underground cavities with a connecting gallery to build up the long-term geologic repository storing the casks in horizontal galleries. The effectiveness of different technical barriers are still under investigation. But future trends in the global climate and earth quakes in this area represent a potential risk of this long-term geological repository. But all U.S. federal states, except Nevada, are in favour for the Yucca Mountain long-term repository. This will take the burden from the shoulder of the east coast U.S. federal states, that run the most of the nuclear power plants in the U.S.



The nuclear fuel and high-level radioactive waste is currently stored in the U.S.A. at 126 sites around the nation, these materials are a result of nuclear power generation and national defence programs. On July 23, 2002, President George W. Bush signed the House Joint Resolution 87, allowing the DoE to take the next step in establishing a safe repository storing the nation's nuclear waste. The DoE is currently in the process of preparing an application to obtain the Nuclear Regulatory Commission license to proceed with the construction of the repository.

Fig. 4. Yucca Mountain (left), the inside (middle) and north portal (right) of the Nuclear Waste Repository. Downloaded from YuccaMountain.org

If the DoE receives a license from the U.S. Nuclear Regulatory Commission to build and operate the repository at Yucca Mountain, Nevada, it will begin shipping the nuclear waste from commercial and government - owned sites to the repository sometime after 2017. This opening date is a bestachievable schedule and is predicated upon enactment of a new legislation.

But the Yucca Mountain project in Nevada is years behind the schedule, and according to a new economic analysis, its construction may cost more than \$50 Billion.

As with many countries with a significant nuclear power program, Canada has focussed its research and development efforts for the long-term management of high-level nuclear waste on the concept of the so called 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 a 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 (known as the "Hare Report") concluded that the 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 (known as the "Porter Commission") [Porter 1978, 1980].

But recently, a scientific advisory body to the country's nuclear agency recommend against the geological storage as scientifically suspect and politically impossible.

England recently rejected the deep geological storage at the only site under study at Sellafield too. Although the geological storage at a different site, as yet unfound, has not been ruled out. Four Members of the House of Lords made an official visit to the U.S. in May to look for new waste storage ideas. In France, in summer 1997, revelations of contamination problems at the nuclear reprocessing facility at La Hague, and the subsequent temporary closure of some beaches along the Normandy coast, shattered the notions that the French nuclear program is environmentally sound and popularly-supported. The government's subsequent announcement that it will begin a search for a geological repository has prompted an anti-nuclear organization and activity unprecedented in that nation.

But it is in Germany where the radioactive waste issue is the most controversial and the lessons are directly relevant to the U.S. experience. This the reason why the German Minister of Environment Sigmar Gabriel has prolonged the time schedule for the final decision of a permanent disposal facility for high-level nuclear waste.

Anyway, the U.S.A. is pushing ahead with a repository site in Nevada for all the nation's spent fuel. The first man-made geological disposal facility for the long-lived nuclear waste started its operation in New Mexico, U.S.A. in March 1999 and will provide an industrial experience. But it only takes defence wastes.

After being buried for about 1,000 years most of the radioactivity will have decayed. The amount of radioactivity then remaining would be similar to that of the naturally-occurring uranium ore from which the fuel originated, though it would be more concentrated.

Layers of protection

Thus, to ensure that no significant environmental releases occur over periods of tens of thousands of years after disposal, the so called multiple barrier disposal concept has to be used to immobilise the radioactive elements in high-level nuclear wastes and to isolate them from the biosphere. The possible and known principal barriers are:

- to immobilize the nuclear waste in an insoluble form e.g. borosilicate glass, Synroc, or leave them as uranium oxide fuel pellets
- to seal the nuclear waste inside a corrosion-resistant container, e. g. stainless steel
- to seal the nuclear waste in a wet rock: to surround the containers with bentonite clay to inhibit the groundwater movement
- to locate the nuclear waste in a deep underground in a stable rock structure
- to site the nuclear waste repository in a remote location.

For any of the radioactivity to reach human populations or the environment, all of these possible barriers would need to be breached before the radioactivity decays.

Simulation in North America and Europe

In U.S.A. high-level civil wastes all remain a spent fuel stored at the reactor sites. It is planned to encapsulate these fuel assemblies and dispose them in an underground engineered repository about 2017, at Yucca Mountain, Nevada. (for more details, see www.uic.com.au/news.htm). This program has been

funded by electricity consumers to US\$ 18 billion (i.e. 0.1 cent per kWh), of which about US\$ 6 billion has been spent.

In Europe some spent fuel is stored at reactor sites, similarly awaiting disposal. However, much of the European spent fuel is sent for reprocessing to either Sellafield in UK or La Hague in France. The recovered U and Pu is then returned to the owners and the separated wastes (3 % of the spent fuel) are vitrified, sealed into stainless steel canisters, and either stored or returned. Eventually, they also will later geologically disposed. In general, the European funding for the geological disposal of nuclear waste is at a similar level as in the U.S.A. per kWh.

Nuclear waste storage in Germany

The German and U.S. nuclear programs are quite similar. Each of them has a mixture of Pressurized and Boiling Water Reactors that provide about 20 % of the nation's need for electricity.

Moreover, both nations have chosen a geological storage as their preferred high-level nuclear waste storage approach but neither nation has been able to implement this option yet in a successive manner.

In Germany, the chosen site is a salt dome near the small farming community of Gorleben. As everywhere, a high-level waste dump has been proposed. This caused a large-scale public opposition in the region, known as Wendland. In addition, the owner of much of the land above the dome is a leader of the opposition, and refused to sell his land to the government. For these reasons, and due to scientific concerns about the adequacy of the site, the Gorleben project is about as far behind the schedule, as the Yucca Mountain project is in the U.S., and faces the same type of uncertain future.

Gorleben from a historic point of view

Close to the Gorleben Project nuclear storage site an over ground temporary storage facility with a capacity for 420 large, so called CASTOR casks of high-level waste, was built. When the government announced it would ship its first cask to the site, early in 1995, local residents and anti-nuclear activists formed a coalition to protest the shipment. Around 100 citizen's groups were formed. Not knowing the exact day of the shipment, they called for demonstrations on a day X, and the X quickly became a symbol of the new anti-nuclear power movement. They adopted the slogan "We Stand in the Way"

The shipment arrived on April 25, 1995, and 3,000 people came, on short notice, to the small town of Dannenberg, where the cask was removed from the train (traveling on from the southern Germany) and placed on a truck for the final 8 miles to Gorleben. The shipment, including the police presence necessary to remove the 3,000 people, costed more than \$15 million.

May 8, 1996, the government tried again to ship its cask to this site. This time, they were more prepared, and 19,000 policeman accompanied the cask the entire length of its shipment. The protestors were more prepared too, and 9,000 attempted to block the shipment when it reached Dannenberg. The resulting confrontations resulted in numerous arrests, injuries and finally the bill showed some \$40 million.

The third shipment to Gorleben was planned for early March 1997. Six casks of high-level nuclear waste were accompanied by a largest mobilization of force in the post-war history, 30,000 policeman. Tens of thousands of protestors attempted to block the shipment throughout the nation, 20,000 in the Dannenberg/Gorleben area alone, where more than 500 were arrested and 175 injured. Roads in the region were barricaded and dug up by local farmers. Rail lines were sabotaged. The cost to the government finally showed an amount of \$100 million.

In March 1998, the German government again moved six casks to a different storage facility holding the remains of a decommissioned experimental thorium reactor at Ahaus, close to the Dutch border. This time, the German government changed tactics while announcing a shipment date, but started the shipment six days earlier in an effort to throw off protestors. In the resulting chaos, the 30,000 policeman guarding the shipment were also thrown off by the early start. 7,000 protestors reached Ahaus anyway, but with no time to plan, which finally ended up in a less disciplined protest. Scores were hurt, more than 1,000 were arrested. Thousands more protested across the transport route, which traverses major cities, including a violent outbreak in the college town of Göttingen. The final bill for the government ends up at \$100 million. But the political cost can be stated to be terminal.

The worth of this situation accumulated while in April 1998 the French government announced that the fuel in German Castor canisters which have been moved to La Hague for reprocessing were emitting a radiation five times above the accepted limit. On May 12, French officials said that a contamination from the Castors' had exceeded the radiation limits by up to 3,000 times. On May 21, the German Minister of Environment, Angela Merkel, who was in favour with the shipments to both La Hague and Gorleben, suspended all shipments anywhere. On May 25, Angela Merkel issued a tenpoint plan to improve the safety and public accountability of the shipments. But it seems to be probably too late. While the Social Democrats later take over the governmental power together with the Green Party, the shipments to the interim storage

facilities end. It seems that the interim storage program in Germany, is, in all likelihood, politically not practicable. (For details see www.nirs.org).

But the never ending story of moving high level nuclear wastes across Germany popped up again in 2006. The former German Minister of Environment Angela Merkel has been elected as the German chancellor. Under the chancellorship of Angela Merkel, again in 2006, Germany shipped casks across Germany to Gorleben. 16.500 policeman accompanied the cask shipment, and thousands of protestors attempted to block the shipment. Although the protest were predominant untroubled, but the vibe was much more aggressive than earlier protests, as it was acquainted by Friedrich Niehörster, the police officer-in-charge.

The gorleben salt dome

In Germany, it is planned to dispose radioactive wastes in a repository in deep geological formations several hundred metres below the surface in a salt dome, assuming that this will be a natural barrier which is able to protect the environment from a radiation. Rock salt possesses particularly good isolating properties for radioactive, heat-generating wastes. Henceforth the investigations of repository sites in Germany concentrate on rock salt formations as a host rock, for example in the Morsleben repository or the Gorleben project, as well as the iron ore/clay formations, such as in the Konrad mine.

In the northern Germany, more than 200 salt structures are known with massive rock salt formations about 250 million years old at great depths. Worldwide, the German Federal Institute for Geosciences and Natural Resources (BGR) is a top ranked institute with respect to the research on salt formations as potential host rocks for the radioactive waste.

In line with the 1998 coalition, the agreement of the new elected German Federal Government (Social Democrats together with the Green Party) said that beside salt rocks other potential host rocks such as granite and clay formations should also be investigated as regards their suitability to a host repository. The German Federal Institute for Geosciences and Natural Resources (BGR) is therefore involved in an international collaboration with the underground laboratories in Sweden, Belgium, Switzerland and France. The knowledge gained from this will be applied to other geological formations at various locations throughout Germany (For more information contact Volkmar.Braeuer@bgr.de.)

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 will still require the waste to be isolated 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, the mankind is unable to forecast the development within such a 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. Hence the question rises whether our developments can reliably be forecasted within the next 1 million years too?

Long-term safety analyses have been performed to determine the radiological effects of the considered repository onto the biosphere for the next 1 million years. For this purpose, possible future features, events and processes such as the thermal expansion of the host rock, subsosion, gas generation or appearance of an ice-age, etc. are combined scenarios and the consequences of these scenarios are determined by numerical simulation. (For more information contact Jan.Weber@bgr.de.)

A model of a salt dome will be developed based on data obtained from laser measurements which can be used in conjunction with NURBS (Non Uniform Rational B-Splines), as shown in Figure 5.

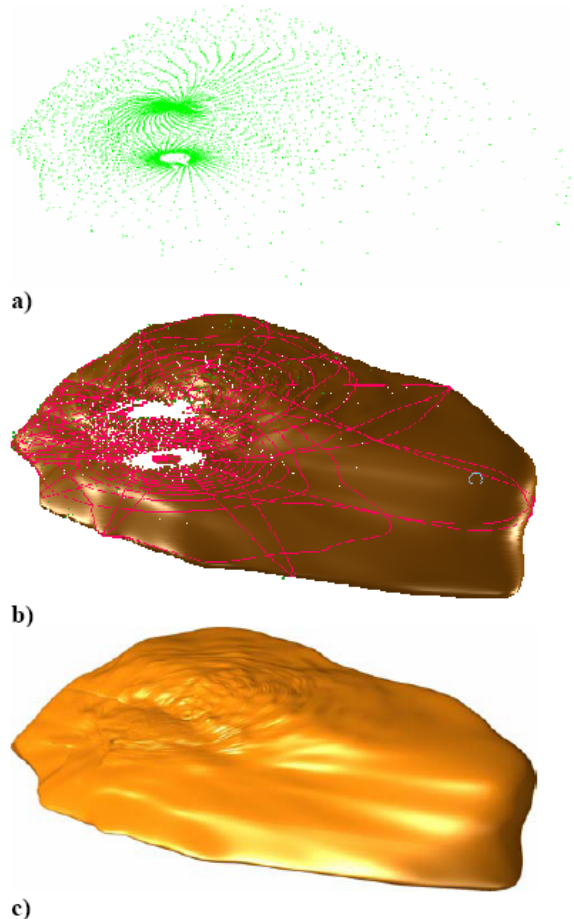


Fig. 5. Laser data obtained from a salt dome a) and the resulting NURBS based model that shows the distribution of measured data b) and the final model c)

This special kind of B-Spline representation is based on a grid of defining points $P_{i,j}$, which can be approximated through bi-cubic parameterized analytical functions as follows:

$$S(u,v) = \frac{\sum_{i=0}^n \sum_{j=0}^m N_{i,p}(u) N_{j,q}(v) w_{ij} P_{ij}}{\sum_{i=0}^n \sum_{j=0}^m N_{i,p}(u) N_{j,q}(v) w_{ij}} \quad \left| \begin{array}{l} 0 \leq u \leq 1 \\ 0 \leq v \leq 1 \end{array} \right.$$

$$P_{ij} = \begin{Bmatrix} P_{11} & P_{12} & \cdots & P_{1n} \\ P_{21} & P_{22} & \cdots & P_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ P_{m1} & P_{m2} & \cdots & P_{mn} \end{Bmatrix}, P_{ij} = (x, y, z)$$

$$N_{i,0}(u) = \begin{cases} 1 & \text{if } u \leq u_i \leq u_{i+1} \\ 0 & \text{otherwise} \end{cases}, N_{i,p}(u) = \frac{u - u_i}{u_{i,p} - u_i} N_{i,p-1}(u) + \frac{u_{i,p+1} - u}{u_{i,p+1} - u_{i+1}} N_{i+1,p-1}(u)$$

$$U = \{u_0, \dots, u_m\}, u_i \leq u_{i+1}$$

As the parameter values u and v can be chosen continuously, the resulting object is mathematically defined at any point, meaning showing no irregularities or breaks. But there are several parameters to adjust the approximation of the given points changing the look of the described geological object so that, if needed, an 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 defining points can be weighted according to their dominance with respect to 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 are easy to use, while modeling and especially modifying is achieved by means of control point movement, allowing the user to adjust the objects by simply pulling or pushing the control points.

Based on these concepts a methodology to interpolate given sets of points, for example the results of borehole drillings or surface measurements, has been developed.

Using multiple levels of surface morphing, this multi level B-Spline approximation (MBA) adjusts a predefined surface, i.e. a flat square, or a cylinder. Constraints like the curvature or direction at special points can be given and are evaluated within the algorithm.

The evaluation of the geotechnical safety of subsurface constructions such as caverns or mines as well as the prediction of underground movements on above-ground installations requires special techniques and methods. As part of its tasks in the field of the final disposal of radioactive wastes, the Federal Institute for Geosciences and Natural Resources (BGR) has developed methods and work techniques, for example, a geological 3D construction, as it can be seen for the schematic in Figure 6, which shows the Gorleben exploration salt dome.

For a comprehensive evaluation, it is often necessary, to apply various, partially overlapping, methods. The evaluation of the barrier integrity of an underground depot, for example, requires methods for the determination of the thermal, hydraulic and mechanical properties of the barrier rock in the laboratory and in situ; methods for the numerical simulation of the thermal, hydraulic and mechanical processes over very long periods, methods for the safety assessment and, last but not least, methods for the quality assurance. (For a more information contact Stefan.Heusermann@bgr.de.)

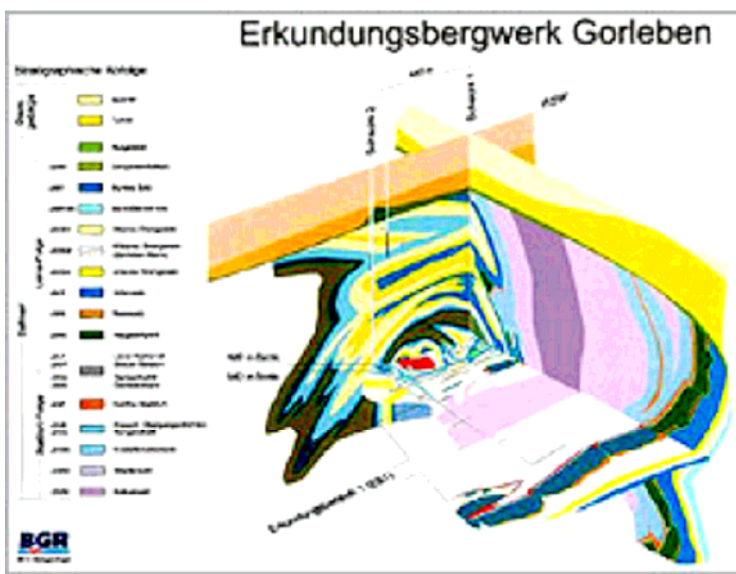


Fig. 6. Geological 3D-Modell of the exploration area I (840 m depth) in the salt dome of Gorleben. Source: BGR (download from www.bgr.de; for more information contact G.Mingerzahn@bgr.de)

Salt leaching phenomena in salt mines

Figure 7 shows the heading face of a drilling in a salt mine Artema in the city of Artomovsk, in the Ukraine.



Fig. 7. Heading face of the salt mine Artema in the city of Artomovsk in Ukraine.

Applied to the leaching problem which often occurs in salt mines one can declare that geometrical models, based on data obtained from laser measurements and modeling based on NURBS, don't optimally meet the requirements necessary to model the salt leaching process. While implicit geometry and CSG were no candidates, subdivision and parametric models are also not into consideration. 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 a legal topology due to the dynamic topology, which brings the cell decomposition into the focus, which was originally declined because this approach doesn't fit into the implemented data model BAGIS [Kesper, Möller 1999], meaning it has to be extended.

Nevertheless, the cell decomposition fits well to the hydro-geochemical process as one cell can simply switch attributes from salt to brine without bringing the topology into any trouble. One issue which had to be dealt with is that the reaction surface moves very slow, perhaps 1cm per cycle of the underlying process model, which would be the required resolution for e.g. the voxel. Henceforth, we currently favor a model which combines the cell decomposition and the parametric properties by linking attributes not to the voxel but to a regular grid of control points linearly interpolated. This allows a finer transition between the control points/voxel without requiring a more memory. Formally this is a linear solid B-Spline but since the control points lie on a regular grid, and the geometry is thus implicit, the similarities to the voxel are obvious. First tests in 2D show a pretty well fit with our expectations. Hence, Figure 8 shows a mimicking (no process model is used) of the leaching process in a salt mine, which does not show the hard edges which are typical for the voxel.

Some issues like embedding several objects in one geometrical model, identifying the reaction surface and deriving its differential properties still have to be handled, but they are considered easier than the mentioned topological and process related disadvantageous properties of other models imply, in order to analyze what may happen in a salt dome if water became an important fact and leaching will become a potential risk for the stability of the salt dome under test.

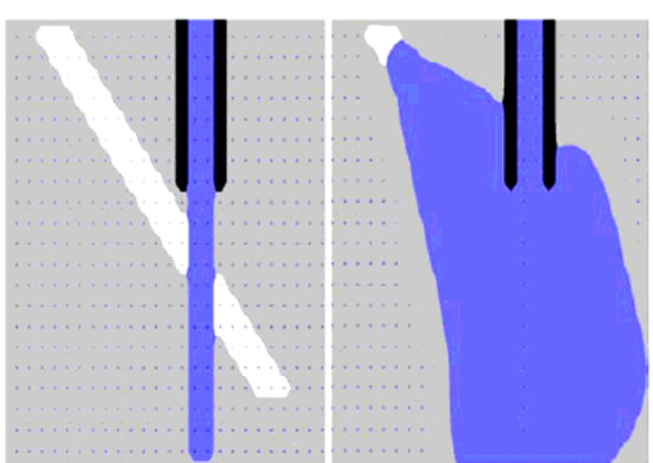


Fig. 8. Bilinear interpolating 2D cell decomposition of the investigation area in the salt mine under test

Outlook

From a sustainable development perspective – and if we do not want to pass the burden of finding a permanent solution for the high-level nuclear waste storage on to future generations – we have to declare that atemporary storage as it is in use today is clearly not a satisfactory solution we can stay with for longer. Henceforth we have to focus our efforts on the research finding acceptable solutions for a long term disposal of the high-level nuclear waste.

Taking into account that during the next 50 years the Earth's population is assumed to expand from 6 billion toward 9 billion, will result in a more energy consumption than before. Keeping the stability of the biosphere and the security of our world in a good order, requires a massive transformation to a clean energy, especially in China, India, Asia and Latin America. Beside renewables like the solar, wind and biomass, only the nuclear power offers a clean, environmentally friendly energy on a massive scale. But this presuppose a soon sustainable solution of the unsolved problem of how to deal with the high level nuclear waste on a long-term scale.

Addressing the public's concerns and negotiating acceptable solutions we have to deal with an important and new challenge. A decision-making process has to be established step by step, and all the affected groups of our generation must be allowed to participate. A long term storage of the high-level nuclear waste is not only a topic for the political profiling. It is an essential topic of responsible human beings. The role of governments have to change; it will be crucial in defining this process, and should act as a source of objective information. They also need to dedicate adequate resources for this purpose so that the public confidence may be a won in the scientific solutions being proposed, a real need when bearing in mind: Today Decides Tomorrow. Tomorrow the next generation has to take over an unsolved burden or will find a solution which seems to be the first one trusted between the public, government, electricity companies, scientists and engineers which all work together for a better and safer world.

Moreover we have to make use of concepts which are not accepted yet as state-of-the-art ones like the Litho-Jet Method or the method of transmutation in fast nuclear reactors or hybrid reactors. Because dealing with the nuclear power on a massive scale requires to open the human mind.

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