NATURAL ANALOGUES, PARADIGM FOR MANMADE REPOSITORIES FOR RADIOACTIVE WASTES

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ABSTRACT
Natural analogues are given by nature. They show the results of natural processes which have lasted thousands or millions of years. They provide an excellent example of what could happen in an underground site, offering in the same time the opportunity to test by observation and measurement, many of the geochemical processes that are expected to influence in a realistic and appropriate way, the predicted reliability of the radioactive waste repository over long periods of geological time. The natural analogue studies attempt to understand the multiprocessing complexity of the natural system, which contrasts with the limitations of the laboratory experiments and bring arguments to overcome the difficult time scale issue. By this the natural analogues are a useful paradigm for manmade repository for radioactive wastes. The paper discusses the implicit link in the public mind between natural analogues and manmade waste repository with an accent of the positive impact on public acceptance. It is also discussed the decisive qualities of the natural analogues concerning providing valid long term data and increasing the confidence of the public for manmade repositories. The debate is conducting in terms of sustainable development, having at base high-level principles in order to protect humans and their environment, both now and in the future, from potential hazards arising from such wastes. Safe radwaste management involves the application of technology and resources in a regulated manner so that the public, workers and the environment are protected in accordance with the accepted national and international standards. There are at least seven high-level principles which are mentioned in the paper. It is presented the general concept of the deep geological repository, very important for an acceptable solution for the management of nuclear waste, what is a prerequisite for a renewal of nuclear power. Further are introduced natural and archaeological (manufactured) analogue projects. In this way is expected to understand better how the results of the natural analogues may be applied to help to solve the geological disposal safety issues and so be able to fill the gap between decision makers, public acceptance and waste management understanding. The main conclusions are that the natural analogues can play an important role in explaining some of the essential components of the “safety case” and can attract very large audience from the large public in the feasibility of deep manmade repository and implicit of the nuclear energy. The challenge is to build and maintain an integrated programme including face-to-face presentations during site visits, publications for technical and non-technical audiences, radio, TV, film and, especially now, the Internet.

1 INTRODUCTION
Every industrial activity produces waste materials, some of which are extremely toxic and may cause illnesses (such as genetic effects or cancer) if inhaled or ingested, or may simply be dangerous (burnable or explosive). Before the environmental awareness movement started in 1960, some normal methods of disposing the wastes involved the discharging them into streams, rivers, lakes or the sea; discharging them directly in the atmosphere; burning them (in which case the wastes in some form or another again entered in the atmosphere); or placing them in the landfills, directly on the surface of the ground or in shallow burial sites. Examples of industrial wastes (other than nuclear) are arsenic, mercury, cadmium and other heavy metals, etc. Unfortunately, industrial nations were not careful in the past about the disposal of wastes. As a result, many sites containing these dangerous substances, most of which remain toxic for ever, exist in many countries.
With respect to the wastes, the nuclear industry is not an exception. The nuclear industry produces radioactive wastes that must be properly treated to protect man and his environment.

According to IAEA [1] the most convenient definition for radioactive waste is the following: “any material that contains or is contaminated by radionuclides at concentrations or radioactivity levels greater than exempted quantities established by the competent authorities and for which no use is foreseen”. However, it is recognized that different countries may have various interpretations concerning the last part of the definition “for which no use is foreseen”. Indeed, some countries as United Kingdom, Japan or France would regard spent fuel (SF) as a resource, as it is recycled, whereas the most countries as US, Finland, Sweden or Romania for example, would regard it as pure and simple waste without value of use. The interpretation, therefore, can depend as much on national policy as well as any scientific or technical description. The most indicated way to treat the problem of the nuclear waste is to insulate it by disposal. By this, according again to IAEA [1] we have to understand the emplacement of nuclear waste in an approved, specified facility without the intention of retrieval. But again the reality of the definition depends as much on government policy and public perception. For instance, some countries require retrievability to be a post disposal option. In this context, even if SF was regarded as a waste in this generation, future ones may regard it as a resource. Moreover, there is often the public perception that the disposal is too final, raising the question: what if something goes wrong and we need to get it back? Radioactive waste problem is, therefore, about addressing both technical and sociopolitical aspects.

Taking IAEA[1] wording again, the main objective of radwaste problem is to deal with radioactive waste in a manner that protects human health and the environment now and in the future without imposing undue burdens on future generation. But this does not mean to say that the radwaste disposal solutions have to be found at any cost! We also have a responsibility to the present generation, which has to pay for disposal, in order to provide an environmental solution that is economically viable. This solution has to be consistent, offering both, an adequate safety and, an optimized approach.

Radwaste problem and disposal policies must also be consistent with higher-level policies aimed at enhancing the environment, in particular, policies such as sustainable development, defined as development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs [2]. In essence this comes back to state that the radioactive waste shall be managed in ways that: 1) ensure that criticality and removal of residual heat generated during SF and HLW management are adequately addressed, 2) ensure that the generation of radwaste is kept to the minimum practicable, 3) take into account interdependencies among the different steps in radwaste management, 4) provide the effective protection of individuals, society and the environment by applying at the national level suitable protective methods, 5) take into account the biological, chemical and other hazards that may be associated with the radwaste management, 6) strive to avoid actions that impose reasonably predictable impacts on the future generations greater than those permitted for the current generation and 7) seek to avoid imposing burdens on future generations.

Radioactive wastes differ from other industrial wastes in two respects: 1) the risk that they pose to man decreases with time and 2) the volume of nuclear wastes is much smaller than the of other industries ( per unit of the same product, for example kWh(e)) [3]. Through the years scientists have looked at a number of different options for disposing of waste. The following are among several explored: 1) burial in the ocean floor, 2) sending waste into outer space and 3) burial in polar ice caps. Finally, scientist community decided not to pursue these approaches further because of too many uncertainties and questions about the disposal process itself. In the same time it became clear that these methods were environmentally unsound, politically infeasible and socially unacceptable.

So, today the majority of countries (including also Romania) using the nuclear power as an energy source are pursuing the underground repository option to dispose of high-level radioactive waste. It is a strong belief through the scientific community that a geologic repository is not only technically feasible, but offers an environmentally sound approach to disposing high-level waste.
2 DEEP GEOLOGICAL DISPOSAL CONCEPT

Finding a solution for nuclear waste is a key issue, not only for protection of the environment but also for the future of the nuclear industry. Fifteen years from now, when the first decisions for the replacement of the existing nuclear power plants will have to be made, the general public will require knowing the solution for nuclear waste before accepting new nuclear plants. This comes to say that an acceptable solution for the management of nuclear waste is a prerequisite for a renewal of nuclear power.

There are two primary functions for a geological repository: 1) to physically insulate the waste from the environment (i.e. by burial) and 2) to prevent or minimize processes which could result in the transport of radioactive materials from the repository back to the biosphere.

Deep disposal in geological formations is a means of safe containment of long-lived radioactive materials, such as SF or high level waste (HLW).

A central concept for repository design is the use of multiple barriers against the release of radioactivity to the biosphere [4]. In this way, if one barrier fails to perform as expected, the others should still operate. Because they are fundamentally different, it is common to divide release barriers into engineered and natural barriers. There are four primary mechanisms by which such barriers can act to protect people: 1) by limiting the amount of waste that could be transported, 2) by having the travel time from repository sufficiently long that radionuclides decay before reaching the biosphere, 3) by ensuring that any releases reaching the biosphere would be diluted to concentration levels where they would be harmless; 4) by having any eventual releases occur in locations where there would be minimal opportunities for human exposure to the radiation.

The engineered barriers can be divided into three classes: 1) waste form, 2) container and 3) buffers, backfill and seals. The natural barriers at a site consist of the host geological formation and the overlying geological strata which separate that formation from the biosphere. It is essential that the natural barrier mechanisms are effective for extremely long time periods and that their behavior be well understood and predictable.

The ideal repository would be located in a stable area and would be deep enough to be protected against surface erosion, large climatic changes such as a new ice age, earthquakes which are much less severe at depth, and human intrusion [5]. It is indicated to have a very flat topography with minimal relief in order to minimize groundwater gradients and flow velocities. It would be located in an impermeable formation, with homogenous rock in the repository host formation, with a thickness of 100 m or more and with very old groundwater that proves that the repository is insulated from the surface. It has to have saline, non-potable groundwater of limited use for drinking or agriculture and no extensive aquifers. It would have vertical salinity stratification of groundwater in order to make impossible for the deeper groundwater to move up from the repository horizon to the surface. It has to be stable, reducing geochemical environment in the host formation because so enhances system performance through lower solubility of many radionuclides and through lower corrosion rates. It would have no apparent mineral resources in order to make it unattractive in the future for exploration of natural resources. The current population density has to be low, with little likelihood of significant increasing. If all these characteristics exist, it would guarantee that there would be no release of highly active and dangerous short lived radionuclides during the first thousand years, the time needed for them to decay completely. After that first period, in the longer timescale (over ten thousand of years) the geological barrier will prevent long lived radionuclides leaking significantly into the biosphere, where the future generation will live.

Prior to construction and operation of a repository, all countries would require the proponent, usually the waste management organization, to go through a licensing process with the operational and post closure safety aspects of the concept to demonstrate that the proposal is based on sound scientific knowledge. Such an exercise is usually referred to as “performance assessment” [5], [10] and the process may involve several iterations as knowledge about the site increases through more detailed site characterization. The main objective of the exercise is to evaluate the radiological safety of a repository after it has been closed and sealed. Different regulators in various countries have their own requirements, but in essence they all require safety performance to be assessed against levels of radiation dose or risk to individuals in the distant future.

All deep repository concepts are based on the understanding that some radioactivity will be released from the facility at some time in the distant future and find its way back to human environment-- Fig. 1
The role of the radioactive waste management organization is to ensure that these very long time scales are taken into account when radioactive waste is conditioned and packaged before being put into interim storage or sent for final disposal. The time-scale factor is the main problem for demonstrating safety of the radioactive waste disposal and has particular resonance in relation to: 1) the longevity of the engineered (manufactured) barriers that are intended to keep the radionuclides within the confines of a repository – mostly copper, titan and clay for a SF repository, 2) the rate of migration of the radionuclides through the rocks surrounding a repository (primary through transport in groundwater, see Fig. 1), the way that one assesses safety for human generations living in the distant future.

A useful and frequently employed tool for addressing the first two of these questions is the use of the analog data. In the case of the engineered barriers, evidence can be obtained from so-called anthropogenic analogs, namely studies of the survival of the metallic manmade objects and the environment conditions that allow this survival for over thousands of years. For the second question, that of migration of radionuclides through the surrounding rocks, natural analogues are extremely useful [2], [6]. This is a complementary and very important approach, already made, but largely ignored. This approach consists of the study of the natural geological systems, the so called natural analogues. These systems provide the opportunity to test, by observation and measurement, many of the geochemical processes that are expected to influence in a realistic and appropriate way, the predicted reliability of a repository over long periods of geological time. The third issue, the way that one judges safety for generations living in the distant future, is usually addressed by examining outcomes for a range of possible climate states. Uncertainties, with respect to human habits, may be addressed by making assumptions that err on the side of safety, that the exposed population only eats products from contaminated soil, for instance.

Mathematical models are utilized to calculate the resultant risk of death or radiation dose [4] that may arise from: 1) the groundwater pathway, in which water will slowly move through the repository and may carry away dissolved radionuclides, 2) the gas pathway, in which there could be the release of gases that find their way back to the biosphere and 3) the human intrusion pathway, in which some future geologic workers may drill into a repository or the groundwater plume and become exposed. A typical output of a mathematical model [4] is shown in Fig. 2.
As it was shown, the repository concepts rely on a combination of natural and engineered barriers to provide the required level of long-term safety.

Natural analogues are given by nature. These are occurrences of high concentrations of natural radioactivity or geological environments similar to those expected in the repositories and can make an important input into understanding of repository performance. They show the results of the natural processes which have lasted thousand and sometimes millions of years. Some of these natural processes provide a good example of what can happen in underground repository and as such can bring arguments to overcome the difficult timescale issue mentioned already above.

There are plenty of examples of mobile elements trapped for millions of years and just more, by sedimentary salt or clay formations. These include oil and gas fields all over the world, also in Romania, demonstrating the basic feasibility of geological containment and proving that in many cases nature has been able to sustain impermeable conditions for a very long period of time.

In this context, both natural and archaeological (manufactured) analogues are used today to study the long-term performance of the natural and engineered barriers from a repository [5].

For example, the Maqarin site in Jordan contains hyperalkaline material waste- typical of the situation expected in a deep repository. A project there started in 1990 consisting from a consortium of more organizations from various countries, namely: NAGRA (Switzerland), Ontario Hydro (Canada), Nirex (United Kingdom), SKB (Sweden) and UK Environment Agency. El Berrocal, an uranium mine in Spain, was studied as a natural analogue of uranium migration processes in fractured crystalline rock. The CEC/ENRESA/Nirex co-funded project ran from 1991 to 1995. The Alligator River natural analogue project was an investigation of uranium deposits in the Northern Territory of Australia, located primarily at the Koongara deposit. Conditions there are ideal for radionuclide migration studies.

However, the most interesting natural analogues are collectively known as the Oklo Fossil Nuclear Reactors from Gabon, Africa and the Associate Fossil Repositories discovered by Francis Perrin in 1972 [6]. He announced that the uranium isotopes found at Oklo strongly resemble to those in the spent nuclear fuel generated by today’s nuclear power plants. At the beginning the scientific community was very sceptical concerning the existing of such fossil reactors. But slowly it became clear the reaction mechanism due to a common effort of the scientists from around the world. Now it is obvious that water filtering down through crevices in the rock played a key role. Without water, it would have been nearly impossible for natural nuclear reactors to sustain chain reactions. The water slowed the neutrons that were cast out from the uranium so that they could hit-and split-other atoms. Without the water, the neutrons would move so fast that they would just bounce off, like skipping a rock across the water and not produce nuclear chain reactions. When the heat from the reactions became too great, the water turned to steam and stopped slowing the neutrons. The reactions then slowed until the water cooled. Then the process could begin again [7], [8] – Fig.
So we might say that the Fossil Nuclear Reactors are of pulsate type. It is believed that these natural reactors have functioned intermittently for a million of years or more.

Once the natural reactors burned themselves out, the highly radioactive waste they generated was held in place deep under Oklo by granite, sandstone and clays surrounding the reactors areas. Plutonium has moved less than 10 feet from where it was formed almost two billion years ago [7]. As it is very well known today, manmade reactors also create radioactive elements and by-products. So the radwaste scientists involved in the disposal of nuclear waste are very interested in Oklo because long-lived wastes created there remain close to their place of origin in what could be considered Associate Fossil Repositories.

The Oklo phenomenon gives scientists an exceptional opportunity to examine the results of a nearly natural two billion years experiment, one that cannot be duplicated in the lab. By analyzing the remnants of these ancient nuclear reactors and understanding how underground rock formations contained the waste, scientists studying Oklo can apply their findings to containing nuclear waste today.

Scientist community believes that similar spontaneous nuclear reactions could not happen today because too high the proportion of the U-235 has decayed. But nearly two billion years ago, nature not only appears to have created her first nuclear reactors, but it also found a way to successfully make retention of the waste they produced deep underground, in what we could call the First Fossil Repositories. The major lesson is that the radioactive remains of natural nuclear fission chain reactions that happened 1.7 billion years ago in Gabon, West Africa, never moved far beyond their place of origin. They remain contained in the sedimentary rocks that kept them from being dissolved or spread by groundwater.

Archaeological analogue studies are designed to study the many materials used in radioactive waste management, including metals, cement, bitumen, glass and clay. As it was shown already they are important for the engineered barriers from the deep repositories. Several examples are very instructive in the context [2]:

1. Cooper: The bronze (96% cooper) cannon from the warship Kronan, which sank in the Baltic Sea in 1676, was found in the clay sediments of the sea bottom. The corrosion over 300-year period was only about 50 microns. The environmental conditions were similar to those expected in the Swedish...
KBS3 disposal concept, which envisages the encapsulation of spent fuel in a 0.1-m-thick copper canister surrounded by bentonite clay;

2. Iron: Many iron artefacts do not survive long-term burial in soil. However, a huge intact hoard of Roman iron nails found in Scotland had some of the nails in remarkably good state of preservation.

3. Cements: The Romans used cement in structures such as harbours, thermal baths—Fig. 4.

![Figure 4 Typical lime mortar and stone construction from the Roman Fort and Bath House at Glannoventa, UK.](image)

and the dome of the Pantheon in Rome. Studies of ancient cements, concretes and mortars have found that their alkaline components are stable over a long period of time, implying that chemical containment of radionuclides in a repository would also be long-lived.

4. Bitumen: The earliest recorded use of bitumen goes back more than 5000 years and has been used as a waterproof mortar for stabilizing natural and artificial riverbank walls. The good preservation of the ancient inscription on bitumen attests to its stability on a millennial time scale.

5. Glass: It is a naturally occurring material. A well-known example is volcanic obsidian, used as early as Neolithic period as an alternative to flint. Obsidian is common in the 50 to 55 million-year-old Tertiary volcanic rocks of western Scotland. The existence of these and similar rocks suggests that natural glasses can resist devitrification for million of years.

6. Clay: Some disposal concepts have plastic clay surrounding the waste containers, e.g., bentonite clay or mudrock. Perhaps the best known natural analogues for clay forming a barrier to migration of radionuclides is at Cigar Lake in the Canadian Shield, where a high grade uranium ore body was formed some 1300 million of years ago. This ore body is surrounded by a clay-rich envelope 10-50 m thick, that has helped to keep the ore body intact over much of this time—Fig. 5.
4 IMPACT OF THE NATURAL ANALOGUES ON PUBLIC ACCEPTANCE

Due to the complexity of natural geological systems and the difficulty for human understanding to apprehend geological time, the main emphasis is on building confidence by demonstration rather than providing quantitative data. The implicit link in the public’s mind between natural analogues and manmade repository should have a positive impact on public acceptance. For apprehending the repository challenge, natural analogues have two decisive qualities: 1) they provide valid long term data and 2) they may help to increase the confidence of the public.

The first aspect was already debated in the previous section, so here we focus on the second one regarding the public acceptance.

Public acceptance is one of the key factors influencing the feasibility of implementation of nuclear waste repositories. The general antipathy against anything “radioactive” is further compounded by the difficulty of presenting a simple, transparent safety case for a facility deep underground [9]. We have to recognize that the demonstrations of the performance of geological, hydrological, mechanical and geochemical barriers are difficult to be followed by the large public. The challenges for communication are: 1) to identify the essential parts of the “safety case” which need to be discussed with key audience groups (on a site- and repository concept-specific basis) and 2) to develop an approach which makes them accessible and attractive.

In the context of the first aspect of the communication strategy, some of the important characteristics of such a strategy are: 1) demonstration of high levels of competence, openness and honesty of involved organisation (both regulators and implementers), 2) ensuring consistency of policy, procedures and utilisation of technical arguments, 3) recognition of the importance of reacting to feedback from all involved parties. Further, another essential part of safety case, is for instance, that many people fear that a repository could explode! Although, the experts consider such fears silly, the question is how can dialogue be initiated? The best
approach is: illustrating that legitimate concerns are addressed and demonstrating that some fears are groundless.

Starting point in the approach is that the explosion risks do exist, but with the following remarks: 1) explosions are a common risk in mines (methane); generally repositories will be in areas containing little gas but, in any case, gas will be monitored continuously and ventilation rates set high enough to avoid explosion risks, 2) explosives are used in underground construction, but all construction work will be rigorously separated from any area containing radioactive waste by very clear zoning rules, 3) combustible or explosive materials / fuels will be strictly excluded from areas containing waste, 4) SF of HLW in a thick steel canister is inherently stable and cannot possibly burn or explode.

However, very unlikely scenarios can be imagined in the distant future when glass or canister dissolve and a critical mass of fissile material accumulates. Even if a critical mass is obtained, it is extremely unlikely that self-sustaining chain reactions could occur and even if chain reaction did occur, it would be self-limiting as it would stop as soon as temperatures increased sufficiently to boil water and hence remove the essential moderator in the system. Even if chain reaction did occur, it would be self-limiting as it would stop as soon as temperatures increased sufficiently to boil water and hence remove the essential moderator in the system. We observe immediately that this is just the case of the natural nuclear reactors, from Gabon.

So, concerning the second aspect of communication strategy, the natural analogues could be successfully used to convince the public. Indeed, we have to observe that the natural analogues could very easily: 1) catch attention and 2) bring messages clearly to a wide audience range. In this order of ideas, if we put the question, how can we know about the future of a deep man-made repository, the best answer is probably: by studying the past- Oklo Fossil Nuclear Reactors!

So, we can learn that the natural chain reaction has occurred in the past - but only under very special conditions; there were no explosions, although the ore body boiled dry; waste was produced but was contained in the ore. All these are circumstances similar in some measure to the actual deep repository concept.

5 CONCLUSIONS

Natural analogues can play an important role in explaining some of the essential components of the safety case.

It is important to ensure that emphasis is on opening dialogue – not discounting concerns as unscientific.

Natural analogues can attract very large audiences. The challenge is to build and maintain an integrated programme including face-to-face presentations during site visits, publications for technical and non-technical audiences, radio, TV, film and, especially now, the Internet.

REFERENCES (TIMES NEW ROMAN, 12PT, BOLD, ALL CAPS)