The Safety of Geological Disposal

Report prepared for the South Australia Royal Commission

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1 The Geological Disposal Concept

The concept of using deep geological formations to dispose of high activity radioactive wastes was first advocated in the 1950s by the US National Research Council\(^1\), when a committee of scientists proposed using caverns in rock salt formations. Since then, with 60 years of global research and development, the concept has become mature, with several deep geological disposal facilities (GDFs) in operation or scheduled to begin operation in the next few years.

Geological disposal is regarded as a permanent solution to management of the most highly active and long-lived wastes from nuclear power generation and other applications of nuclear technologies, including medicine and industry.\(^2\) It removes hazardous materials from the immediate human and dynamic, natural surface environment to a stable location where they will remain, protected from disturbance by disruptive natural processes and the activities of people.

After considerable international research, geological disposal is widely favoured by scientists. A 2008 collective statement issued by the NEA/OECD\(^3\) states that

“A geological disposal system provides a unique level and duration of protection for high activity long-lived radioactive waste. The concept takes advantage of the capabilities of both the local geology and the engineered materials to fulfil specific safety functions in complementary fashion, providing multiple and diverse barrier roles.

“The overwhelming scientific consensus worldwide is that geological disposal is technically feasible. This is supported by the extensive experimental data accumulated for different geological formations and engineered materials ..... Ethical aspects, including considerations of fairness to current and future generations, are important for the development of disposal programmes”

The Council of the European Union observes\(^4\) “It is broadly accepted at the technical level that, at this time, deep geological disposal represents the safest and most sustainable option as the end point of the management of high-level waste and spent fuel considered as waste”. Geological disposal is the official policy adopted by many nations that have radioactive wastes to be managed.

The geological disposal concept is based on placing solid radioactive wastes in robust, multi-layered engineered packages that are then carefully emplaced in purpose-constructed openings in a GDF and sealed into place. The sophisticated engineering and operation of GDFs is very far indeed from the pejorative term ‘nuclear dump’ that is often to be found in the media.

Of course, the wastes and other engineered materials that are placed in a GDF will slowly degrade and even the most stable deep geological environments will eventually change with the passage of geological time. However, the hazard potential of the wastes (their capability to cause health impacts) is also decreasing as a result of natural radioactive decay, so the long-term safety of a GDF must be evaluated by detailed assessment of how all these processes are balanced. In a properly sited and constructed GDF, the long containment times and slow movement of any released radionuclides (radioactive isotopes) will ensure that no radioactive material ever enters the biosphere in concentrations that can be harmful to people in the future. This note looks at how safety is designed into geological disposal and how it is evaluated and presented.


2 Radioactive wastes become less hazardous with time

All types of radioactive waste are at their most hazardous at the time when they are emplaced in a GDF and for some hundreds or thousands of years thereafter. Their hazard potential decreases by the process of natural radioactive decay. The figure below illustrates the declining hazard potential of spent fuel (SF) and vitrified high-level waste (HLW) from reprocessing of spent fuel (the two most radioactive and long-lived wastes destined for geological disposal) as a function of time.

The hazard potential declines by factors of many thousands over a period of some hundreds to a few thousand years. Providing isolation and containment in the GDF over this period of extremely high hazard potential is paramount and is a critical objective when siting and designing a GDF.

The figure also shows that the hazard potential of both wastes eventually declines to levels similar to natural uranium ore formations over periods from a few hundred to around a hundred thousand years. The enormous reduction in hazard potential that has occurred means that the primary isolation and containment functions of geological disposal have largely been achieved by this time, but we still need to consider the possible impacts of the residual radionuclides on people and the environment, out to around a million years. The safety analyses we discuss later thus continue to calculate risks to people for a long period after isolation and containment have done their main work and have kept the vast bulk of the radionuclides deep within the rock until they have decayed away.

3 But the timescales are extremely long....

Hazard and safety assessment of industrial facilities is usually carried out for the period over which they are operational – for most industrial activities this would be a few decades. Although we recycle much waste material, many industrial processes leave hazardous residues that need to be collected, stored and eventually disposed of. Even though many hazardous materials do not either decay or become inert with time, radioactive wastes (whose hazard, as we have just seen, does decline with time) have attracted much attention because of the time period over which their hazard is routinely evaluated. Singling them out for such special consideration is partly because the initial hazard potential of the most radioactive wastes is so much higher than many other industrial wastes.

Thus, safety assessments of GDFs commonly look far into the future. As noted above, the engineered barriers in a GDF are designed to contain all of the radioactivity within the waste containers for at least 1000 years. Even this relatively ‘short’ time in the context of an overall GDF safety evaluation is long in a human perspective.

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Because a GDF is no longer managed and is intentionally outside our control after its closure, it progressively becomes part of the natural environment as the engineered barriers decay and degrade by interaction with groundwaters and porewaters in the rock. This may take many thousands or tens of thousands of years – in some geological environments, or for some materials, even longer. Once water contacts the waste, some radionuclides will dissolve, but the partially degraded engineered barriers will continue to hinder the movement of these small amounts of radioactivity for hundreds of thousands of years. Any radionuclides that migrate into the groundwater system around the GDF will be in minute amounts and will be dispersed during slow movement through the geological environment. The objective of geological disposal is to ensure that, even many thousands of years hence, the presence of any such radioactivity in the groundwater system does not cause unacceptable health risks to future generations. What constitutes ‘acceptable risk’ can, of course, be a subjective matter, but those concerned with regulating radiological safety typically consider radiation doses that lead to health risks (death, or serious genetic effects) to individuals of less that one in a million per year to be acceptable. Risks less than one in ten million per year are regarded as insignificant and requiring no action to reduce or mitigate them. For comparison, the exposures that we all received from Earth’s natural background radioactivity are hundreds or thousands of times greater.

Consequently, safety regulatory authorities require that the processes that occur in a GDF are comprehensively identified, fully understood and their effects are then analysed in detail over periods of time out to about one million years. Going beyond the initial period of total containment in the engineered barriers, assessments quantify and model the physical and chemical evolution of the wastes and surrounding rock in considerable detail, out to around 10,000 to 100,000 years. Regulators typically expect to see best estimate calculations of releases that might occur into the biosphere from a GDF and the health impacts if people were to be exposed to the releases in this period. Beyond about 100,000 years, it is recognised that increasing uncertainties over the state of the system and the evolution of the natural environment make it unreasonable to continue with these detailed analyses and regulators often expect then to see broader indicators of the state of the system and how it might affect people and the environment. These different ‘indicators’ of safety are discussed in Section 10.

It can be difficult to grasp the long future timescales discussed above. One way of looking at them is to compare them with what has happened over similar time periods in the past. For example, the period over which the radioactivity of spent fuel reduces to levels equivalent to uranium ore is about the same time over which modern humans spread out of their African area of origin to populate the world. A 5000-year design life for a waste container is an equivalent period to the whole of recorded human history. Going back into the past the same length of time it takes for a particular radionuclide to diffuse through just one metre of a clay formation around a GDF would take us back to the time when modern humans first appeared in Europe and the Neanderthals disappeared.

4 The safety approach: concentrate, isolate and contain

An overarching principle of geological disposal is that we should collect and bring together highly hazardous materials to improve security and facilitate their safe management. This concentration reflects the long-held conviction that safety is best assured and environmental impacts minimised by isolating and containing the concentrated materials (see below), with these two aims being at the core of safety guidance produced by the International Atomic Energy Agency6.

A further essential aspect of geological disposal is that a GDF provides protection and safety in a completely passive manner once it has been closed – no further actions are required from people to manage the facility and the wastes, and, over immensely long times, the facility and the wastes become part of the deep, natural environment. Although the system can readily be monitored for as long as might be required, there is no burden placed on future generations to manage a GDF.

GDFs use a **multi-barrier safety system**, with a series of engineered and natural barriers acting in concert to isolate the wastes and contain the radionuclides present in them. The relative roles of the barriers at different times after closure and sealing of a GDF depend upon GDF design, which itself depends on the geological environment in which it is constructed. Consequently, the multi-barrier system can function in different ways at different times in different disposal concepts. Typical components of a multi-barrier system are illustrated conceptually below. The manufactured components are referred to as the ‘engineered barriers’ and the geological formations as the ‘natural barrier’.

Two principal objectives underpin GDF safety:

- **ISOLATION**: which ensures that the wastes have no direct contact and interaction with people and the environment. A GDF environment must be deep, inaccessible and stable over many tens of thousands of years. Rapid uplift or erosion and exposure of the waste must not occur. The site should be unlikely to be drilled into during exploration for natural resources in the future.

- **CONTAINMENT**: means retaining the radionuclides within the multibarrier system until natural processes of radioactive decay have reduced the hazard potential considerably – for many radionuclides, GDF designs provide complete containment until radioactive decay reduces their hazard potential to insignificant levels, within or close to the waste package. However, the engineered barriers in a GDF will degrade progressively over thousands of years and lose their ability to provide complete containment. Because some radionuclides decay extremely slowly and/or are mobile in deep groundwaters, their complete containment is not possible. Assessing the safety of geological disposal involves evaluating the fate and impact of these extremely low concentrations of radioactivity that might eventually reach people and the surface environment, even though this may not happen until many thousands of years into the future.

5  **How can one show convincingly that a GDF is safe?**

Proving the safety of a GDF involves understanding and demonstrating the way in which the various barriers in the GDF system provide isolation and containment. The way in which this is done has been developed over many years by the OECD Nuclear Energy Agency and the IAEA, based upon internationally accepted Safety Standards produced by the IAEA.  

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jargon employed by specialists for the approach used is “developing a Safety Case”; more technical descriptions of this are contained in companion documents to this note.

To assess the safety of the GDF, it is necessary to show that the host geological environment and the engineered barriers have been selected and designed to ensure that multiple physical barriers or chemical processes (referred to as safety functions) work together to prevent releases. This provides assurance that, even if one safety function does not perform fully as expected (e.g., owing to an unforeseen process or an unlikely event), others will ensure that overall safety is nevertheless provided.

A safety function can be provided by one of the multi-barrier components of the GDF, such as the waste form, waste package, the backfill or the host geological formation, or by a chemical property or process, such as solubility of radionuclides in water, the corrosion rate of containers, or the dissolution rate of waste materials. Safety functions for a barrier or component in the GDF system will vary from one GDF concept to another, from time to time after closure and between different geological environments, meaning that there is not a unique set of safety functions that applies to all GDFs. Once a safety function has been identified for a GDF component, then one can lay down specific requirements on how it must work (these are called quantitative performance targets) in order to assure that it contributes as intended to increasing safety.

In designing a safe system, emphasis is usually placed on system robustness. This can be achieved by keeping the system as simple as possible – avoiding features that are poorly understood or difficult to characterise, and preferring GDF sites and designs that are insensitive to potentially detrimental phenomena (e.g. climate change or geological events).

It is important to be able to demonstrate with confidence that all the safety systems will function as intended. This is done by a mixture of physical tests and experiments, analysing the sensitivity of barrier performance to both natural variability and to uncertainties that cannot be fully removed by measurements, observations on analogous systems that represent larger physical scales and time periods than can be addressed by testing, and by thorough and transparent scientific review by independent experts.

The arguments and evidence regarding system safety will be refined and strengthened as a GDF project progresses – that is, a safety case has to be developed progressively and elaborated. It is therefore to be expected that a project will have multiple iterations of safety case production, with different levels of formality and detail.

6 The core of safety demonstration: quantitative analysis of system behaviour (safety assessment)

Safety assessments are a major component of a safety demonstration. They use mathematical models to frame and describe possible mechanisms that could lead to releases of radioactivity to the biosphere, then calculate their health and environmental consequences.

Because they involve ‘computer modelling’ and ‘long-term forecasting’ of consequences, safety assessments are sometimes treated with scepticism. After all, they involve making forecasts of how the GDF and the natural environment could behave over many thousands of years. However, they are not aiming to make precise predictions of the future – only to scope the likely range of outcomes of what are mostly very slow processes that are rather well understood. Most scientists are entirely comfortable with modelling, which is a common method used to interpret observations (e.g., of how natural systems behave) or the results of experiments. All scientists agree, however, that the models must be structured around accepted and testable physical processes, must be built on sufficient quantities of high quality data and must identify and capture scientific uncertainties transparently, so that we can obtain a proper feeling for the validity of model results and forecasts.

A safety assessment of a GDF will normally begin with modelling a ‘reference evolution’ of the system – that is, it will assume that most of the physical and chemical processes that could affect future GDF behaviour continue to operate as they do today. This analysis is then complemented by postulating various ‘scenarios’ of alternative ways the system could evolve:

- **Reference evolution**: typically consists of the best estimate of scientists about how the engineered barriers, the geological environment and the surface environment will
evolve after the GDF is closed. This needs to consider how heat is dispersed in the GDF and the surrounding rock, how water moves from the rock into the engineered barriers, how stresses change in the GDF, how barriers degrade and how radionuclides might be mobilised and start to migrate through the barriers. A central, ‘reference case’ is often defined, with a number of alternatives or ‘variants’ reflecting different possible behaviour of some component or process. All of the cases tend to be conservative, in that they assume generally pessimistic performance of the barriers, so they would overestimate the potential releases of radionuclides and hence the health impacts of geological disposal.

- **Scenarios:** owing to the long time periods involved, it is important to consider how the GDF might respond to mainly external or internal processes or events that are regarded as generally of low probability. These typically include natural events such as earthquake faulting, different trajectories for Earth’s future climate and the possible impacts of people, who might be unaware of the presence of the GDF in the far future. Highly pessimistic ‘what-if?’ scenarios are often modelled too, to explore how resilient the system would be if one or more of the barriers failed completely for an unknown cause, either locally in part of the GDF, or across the whole facility.

Safety assessments model a large range of conditions and outcomes and then use information generated on releases of radioactivity to evaluate possible health and environmental impacts. These can then be compared to regulatory requirements that are imposed to protect both people and other species. Inevitably, safety assessments and the ways of presenting their results – aimed at other scientists and regulatory authorities – can be extremely complex. Typical safety assessment reports comprise hundreds of pages of analysis, covering numerous variants and cases, and use multiple means of presenting the results.

### 7 Where does the information come from?

Demonstrating safety in the above manner requires a large amount of information about the properties of the wastes and the engineered materials in a GDF and their long-term behaviour, and about the natural environment in which the GDF is located – in particular, the characteristics of the host rock formation and the surrounding geological formations. Because forecasts are being made far out into the future, information is also required about how the natural environment (e.g., Earth’s climate) could change and evolve.

Scientists have been gathering and analysing information on material properties specific to GDFs for more than 50 years by laboratory testing and by experiments carried out in deep underground laboratories in different rock formations around the world. This is supplemented by the enormous database from general materials science studies in other industries. Of course, tests are limited in duration compared to the long times considered in safety evaluations and the information on physical and chemical processes has to be extrapolated into the future.

To give confidence in these extrapolations, scientists have turned to studies of archaeological materials (such as iron, steel, glass, copper, cement) to identify conditions that favour preservation and to verify their understanding of degradation mechanisms and rates (see Section 10.5 below). Because the engineered barriers in many GDF concepts are conservatively assumed to provide complete containment for only some thousands of years, the condition of archaeological materials of similar age preserved in environmental conditions similar to the deeper underground can provide very useful information.

The second major area of information required for safety demonstration concerns the physical and chemical properties and behaviour of the geological environment. Around the world, there has been a huge effort to characterise the deep geological environment using remote sensing geophysical techniques, drilling, sampling and testing in deep boreholes, and testing and experimentation in underground research laboratories. Scientists need to know how water moves through the rocks, how the rocks respond to the hundreds of years of heat emission from some of the wastes, how excavation of the GDF openings affects the natural properties of the rocks and how contaminants from the waste might interact with the rock and move through it if they escape from the waste packages.
As a result of intensive investigations of several planned or prospective GDF sites around the world in granites, metamorphic rocks, clays and volcanic rocks, there is now a thorough understanding of all these factors and scientists are confident that safety assessments can be based on sound principles and robust models and credible calculations.

In the same way that archaeological materials provide support to materials science investigations, the natural environment can provide support to estimates of long-term behaviour in the geological surroundings of a GDF, such as the movement of contaminants through the rock. Detailed study of uranium ore deposits, for example, provides direct evidence of the processes whereby uranium (a major component of some wastes) interacts with water in the rock and can migrate through it over millions of years, or be fixed, on or in minerals in the rock. A major international study of this nature took place in the 1980s at the Alligator Rivers uranium ore body in Northern Australia.

Gathering information on the evolution of the geological and surface environments over tens and hundreds of thousands of years, scientists begin with the well-established knowledge of geological history that shows how long the rock formations have been stable at a GDF site. Rates of tectonic processes and erosion can be established by direct observations based on a thorough understanding of the mechanisms involved in shaping Earth’s surface. The overall goal is to provide evidence that conditions at depth in the rock will remain more-or-less as they are today for at least the next 100,000 or a million years. This means that areas that are tectonically active (characterised by active faulting, nearby volcanism or rapid uplift of the rocks) need to be avoided when selecting a GDF site.

To provide the basis for some of the scenarios discussed in Section 6, scientists will look at the recorded seismic history of a region, observations of ancient faults and evidence for earth movement, and the tectonic stresses to which an area is subjected. This allows them to develop estimates of the frequency with which earthquakes of different magnitudes might occur. Forecasts of Earth’s future climate states, which affect surface conditions and might also affect deeper conditions in the rock, tend to be made conservatively, by simulating conditions that have already occurred in the last million years (global cooling during glaciations, long dry or wet, or warm or dry periods, different rainfall patterns etc.) for which evidence of their impacts is preserved in the geological environment.

Overall, there is now considerable experience in several countries in assembling all this information and using it to understand and forecast how the GDF will behave over hundreds of thousands of years and how it might affect the health of people and the environment in the distant future, many generations hence.

8 What levels of impacts are expected?

The baseline finding of safety assessments is that a well-sited, properly constructed, operated and sealed GDF will have no health impact on people or the environment over the next million years.

During that period, it will have become part of the natural environment and, in the more distant future, many millions of years hence, a GDF for spent fuel might be expected to resemble a deep uranium ore body in many respects.

However, safety evaluations tend to be highly conservative, taking account of all uncertainties and assuming imperfect materials or engineering, or poor properties or behaviour. Effectively, safety assessment scientists tend to focus on the more extreme scenarios in which releases of contaminants into the rock can occur and then assess how those might reach people, and in what concentrations.

The typical output of a safety assessment is thus a calculation of the rate at which each radionuclide or chemical contaminant in the wastes moves through each part of the barrier system and the rate at which those that do escape engineered and geological confinement might reach people in the future. The assumed pathway to people is often chosen to be a water-well in an aquifer above or close by the GDF. It is then possible to make simple assumptions about people’s lifestyles and behaviour and calculate the radiation exposures (‘doses’) they could receive if they used the water from the well. This type of output is useful, because it can be compared directly to regulatory standards, which, internationally, are usually in the form of ‘annual dose limits’ to hypothetical individual persons who might be
exposed to releases from the GDF. The word ‘hypothetical’ is important, because the times at which releases might be predicted to occur are many hundreds of generations, or tens of thousands of years into the future.

The figure below shows a typical output of this type of safety evaluation – in this case, for the disposal of spent fuel in a deep clay formation in Switzerland. It shows estimated radiation doses to a hypothetical person exposed to releases from a GDF as a function of time (years) after closure of the GDF. Note that both the time and the radiation dose scales are logarithmic, meaning that each division shown is ten times larger or smaller than the previous one. The bottom of the dose axis is a factor of one hundred billion times smaller than the top; the time axis starts at 100 years and goes out to 10 million years.

It can be seen that some releases (for example, of the most mobile radionuclides that might escape from a breached container after the initial period of complete containment) are forecast to occur after several thousand years, but the doses that they might produce are hundreds of thousands of times lower than the Swiss regulatory guideline. Regulatory standards are set so as to protect members of the public exposed to radiation from the nuclear industry and are considered to be quite conservative. For example, the regulatory limit shown on the diagram is tens of times less than the accepted annual radiation exposure limits for people working in the nuclear industry. So, with these dose limits, people are considered to be very well protected and doses very much lower than this (such as those arising from a GDF) are considered to have no impact on health.

There is some lively discussion among scientists on this last point. Some consider that any radiation dose, no matter how small, has a health impact. Others challenge this, considering that either there is a threshold, below which there is no harm, or even that some level of radiation dose has a positive effect on our immune system. In either case, the dose levels estimated to arise from a GDF are acknowledged by all scientists to be so low as to have undetectable health impacts in an exposed population – that is, if there were any impact from these extremely small exposures, we could not see it. Many scientists also point out that we live in a naturally radioactive environment and are constantly exposed to radioactivity. The human species has evolved in a background of natural radioactivity. As can be seen from the diagram, our natural exposures are tens of times (to many hundreds of times, depending on where we live) higher than the dose limits set by regulators for nuclear activities such as a GDF and hundreds, thousands or millions of times higher than doses that are estimated actually to come from a GDF in the far future.

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It is easy to see why most scientists are confident that geological disposal in a suitable facility at a well-chosen site will be very safe.

9 Impacts of low probability scenarios

As discussed above, evaluating GDF behaviour only for the expected evolution is not sufficient; a safety case will also consider potentially damaging events and processes that have low probabilities of occurrence. The circumstances under which these might occur are described in the form of ‘scenarios’ and the potential radiological impacts are calculated, just as for the expected evolution of the GDF.

The figure below shows an example of how the results of many different scenario analyses can be presented⁹. This case is from the safety case that accompanied the construction licensing application for the national GDF for spent fuel in Finland, which obtained approval from the regulatory authorities in 2015 and will be the world’s first GDF for spent fuel.

The diagram is quite complicated, so let’s see what can be learned from it. The labelled points show the calculated peak release rates of radioactivity from failure of a single canister of fuel and the times (years into the future) at which they are estimated to occur, for a range of adverse scenarios. It uses the same type of logarithmic presentation as the previous diagram. The scenarios include rock and container shearing in a major earthquake at the GDF site (RS), accelerated corrosion (AIC) and base scenarios (BS) in which the highly pessimistic assumption is made that one or more SF canisters have undetected defects at the time of emplacement in the GDF, such that they leak immediately.

The diagram also illustrates a point made earlier about regulatory requirements. In Finland, the regulator recognises that calculating doses to hypothetical people entails increasing uncertainty with time, so it requires this detailed analysis only over the first 10,000 years. After this, the regulations are framed in terms of admissible fluxes of radioactivity to the biosphere. The blue line shows this limit. It can be seen that, apart from the ‘initially failed’ BS scenarios, all the scenarios evaluated have estimated peak releases that occur tens or hundreds of thousands of years into the future. All the scenarios lead to releases of radioactivity that are well below the regulatory constraints.

10 How else can we judge the safety provided by a GDF?

Because radiation exposure calculations focus principally on regulatory standards of dose or risk, a range of other measures has been developed to illustrate more broadly the performance of the difference barriers in a GDF and how they contribute towards safety.

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Some of these are based on quantitative calculations – others provide more qualitative evidence. Taken together, these ‘safety indicators’ can provide a fuller picture of how a GDF performs.

10.1 Comparative radiation exposures

The natural radioactivity that surrounds or passes through us all comprises a range of sources: cosmic radiation from beyond the Earth, radioactive gases released from rocks, soils and buildings (our biggest source of exposure) and the food that we eat (for example, coffee and nuts contain higher levels of radioactivity). Two examples have been widely used to compare the very small calculated doses from a GDF to our natural radiation exposures.

- flying on a holiday or business trip: taking three typical intercontinental jet flights (say, 36 hours of flying) exposes us to around 0.1 mSv of cosmic radiation. This is the same as a typical dose limit we have seen in previous Sections, set by regulators for as the limit for releases from a GDF over a full year, and is hundreds to thousands of times higher than the actual estimated doses we have just seen from a GDF. A few minutes of high altitude flight exceeds the doses that might arise over a whole year from a GDF.

- the ‘banana equivalent dose’ (BED) is a rather whimsical comparison made to the radiation dose that we receive from the radioactive potassium contained in many foodstuffs (also in our own bones), and particularly in bananas. The BED is about 0.001 mSv, from eating one banana. Comparing with the peak dose levels from the Swiss GDF shown in Section 9, this suggests that the radiation health impacts over a whole year are about the same as those of eating just one banana every ten years.

10.2 Containment provided by each barrier in the GDF system

Safety assessments typically find that over tens and hundreds of thousands of years, most of the radioactivity present in the wastes decays without moving outside the degraded waste containers and surrounding engineered barriers, or is not released because physical and chemical processes trap it, even after the waste material itself may have dissolved and degraded. Those releases that do get into the surrounding rock formations are attenuated by various processes, including trapping in pores and on minerals in the rock, dispersion over large volumes of rock and dilution in deep groundwaters.

One way of showing these various aspects of containment is to look at where radioactivity is to be found in a degrading GDF, far out into the future. An example is shown below, for vitrified high-level waste (HLW) disposed in a GDF located in a geological environment in which there is no effective groundwater flow in the rock formations 100 metres above and below the facility. This would be representative of a thick clay formation or an environment where there are no natural gradients driving deep groundwater movement.

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Examination of the diagram, which shows the total radioactivity (here expressed as radiotoxicity) present in different parts of the system at different times in the future (here, out to 100 million years), reveals a number of interesting features. First, the model has assumed that the HLW glass is completely dissolved after about 100,000 years. Before this time, almost all the radioactivity remains in the glass or in mineral precipitates formed in the engineered barriers around it. The remainder is contained with the 100 m ‘natural diffusion barrier’ provided by the immediately surrounded rock formations. After a few thousand years, this fraction is about a millionth of the total activity in the system – the rest is still in the engineered containment.

Radioactivity does not begin to escape into the overlying rock formations and the biosphere (labelled ‘outside’ on the diagram) until a million years into the future. At this time, this partially ‘released’ fraction is only one ten-billionth of the total radioactivity, most of which is still inside the engineered barriers.

10.3 Migration time compared to radioactive decay rate

As radionuclides move through the degraded engineered barriers and the surrounding rock their radioactivity is decreasing as a result of the natural process of radioactive decay that we have already mentioned. This decay in activity is different for every radionuclide and is characterised for each by a ‘half life’ – the time it takes for radioactivity levels to reduce by a half. After one half-life, the original radioactivity will be reduced to a half, after two half-lives have passed, to a quarter and so on. After 10 half lives have passed the residual radioactivity will be about one thousandth of the original activity and after 20 half lives have passed, only about one millionth.

Radionuclides have an enormous range of half-lives. Those found in wastes in the GDF typically have half-lives from a few years up to tens of millions of years. If we take a radionuclide with a 30-year half life (e.g., some isotopes of caesium and strontium, common in many waste types), then during 1200 years of containment in the engineered barriers, around 40 of its half-lives will have passed and natural decay will have reduced the radioactivity to around one billionth of what it was at the time of disposal. This means that the hazard potential of such short-lived radionuclides is to all intents and purposes reduced to insignificance if they can be contained for even a short period in a GDF. In comparison, iodine has a very long-lived isotope with a half-life of more than 10 million years, so no amount of engineered containment will help to reduce its radioactivity.

The diagram above\(^\text{11}\) shows the effect of containment times on some different radionuclides found in wastes that might go to a GDF. It plots half-life against the time it would take the

\(^{11}\text{European Commission PAMINA Project: Performance Assessment Methodologies in Application to Guide the Development of the Safety Case: Report: Safety Indicators and Performance Indicators: Deliverable (D-N°:3.4.2), 2009.}\)
isotopes to diffuse through a clay formation in which a GDF might be located. All those isotopes plotting in the green area are effectively completely contained by the clay and those in the brown area would pass through the clay with largely undiminished activity.

It is clear that safety assessors will then be most interested in what happens to those radionuclides that are not effectively contained. For these radionuclides, numerous analyses have shown that safety is assured because any eventual releases from a GDF at source are initially distributed across long time periods and large spatial scales, and any radionuclides that do migrate out of the GDF are then widely dispersed and diluted by natural processes in the overlying rock formations and the biosphere before they reach people. This means that concentrations in groundwaters when radionuclides reach the environment would be very low.

10.4 Radiotoxicity compared to radioactivity in substances we use

Another form of safety indicator is to compare the flux of radioactivity from a GDF to the biosphere with the radioactivity arising from everyday processes in which people are engaged. This is useful, given the inevitable uncertainty about future lifestyles. The figure below shows the calculated rate of release of radioactivity from spent fuel in a GDF in a clay formation in Belgium (one of the potential targets for the national GDF) as a function of time, again using a logarithmic scale. Here, radioactivity is expressed as ‘radiotoxicity’, the highly hypothetical radiation dose that would result if a person were to ingest all of a particular radioactive substance released from the GDF in a particular time period. The upper curve shows the total radiotoxicity from all the radioactive substances released into the environment from a GDF for spent fuel in the Boom Clay. The contribution to the total made by individual radioactive isotopes (of technetium, chlorine, iodine etc.) is also shown.

The ‘Reference Value’ line shows, for comparison, the radiotoxicity of agricultural fertilizers (which are naturally radioactive) that are applied on farmland in the Flanders region of Belgium: about 10 Sv/km² per year. A square kilometre is about the size of the GDF, so it can be seen that this is more than ten times higher than the total releases from the GDF.

10.5 Natural analogues

Perhaps the most compelling support for the safety case comes from ancient examples of materials that are central to the containment and isolation functions of geological disposal. Although analogues of materials and processes from archaeology and from nature have been used for decades to generate quantitative, safety-related information on the nature and rates of processes such as corrosion, alteration and mobility. Much useful scientific information

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has arisen from studying, for example, how naturally radioactive elements in deep geological systems can be mobilised by groundwaters and fixed by interaction with the rock. As noted earlier for example, the Alligator Rivers uranium ore body in Northern Territories has been extensively studied with this objective.

Another example that has often been used is the Cigar Lake uranium ore body that lies deep under the rocks of the northern Canadian Shield. The illustration below shows the geometry of the ore body, which lies at a depth of about 450 m beneath the surface, compared to an early Canadian concept for a GDF for spent fuel, which is mineralogically similar to this uranium ore body. Both the ore body and the GDF concept feature a clay ‘envelope’ around the uranium – in the GDF, as one of the barriers in the system design. The depths of GDFs are also typically around 400 to 1000 m.

Cigar Lake is one of the richest uranium ore bodies known and contains around 100,000 tonnes of uranium (much larger than many national GDFs). The fascinating aspect of this ore body for GDF safety evaluators is that it has been stable for over 1000 million years and represents a potential source of mobile uranium (as does a GDF), yet it exhibits no radiometric signature at the land surface. This gives considerable confidence that, even very far into the future, an ancient GDF would be causing no radiological health impacts to people, even if they were living above it.

However, it is perhaps simple physical examples of the longevity of preservation of material properties that can be the most compelling, when it can be shown that the environment in which they have been preserved is analogous to deep underground conditions. The illustrations below show some examples of materials that have been studied over recent years. They include:

- Iron (the material from which many waste containers and other GDF components are made) in 1900 year-old Roman nails, found among a huge hoard of around 7 tonnes

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of iron objects, showing very little corrosion in the centre of the mass. In similar wet, anoxic conditions, waste containers are conservatively assumed to have lost their integrity after about 1000 years.

- Glass (analogous to some of the properties of vitrified HLW) in small, intricate, 3500 year-old Egyptian artefacts that have survived in the surface environment of soils, have been useful analogues for disposal of HLW in desert conditions in the USA, where the safety assessment conservatively assumes complete dissolution of massive glass blocks weighing hundreds of kilograms within a thousand years.

- Wood is not, of course, a component of wastes but examples of how clay formations provide excellent preservation environments for materials in a GDF are provided by ‘fossil’ forests in Italy and Belgium. At Dunarobba in Italy, 1.5 million year-old wood is preserved in close to its natural state in a clay formation – it can still be cut and burned, like modern wood.

11 So, how safe is a GDF?

Based on the kind of evidence and studies outline in this note, scientists who have looked into the details GDF safety cases would agree that a well sited, constructed and operated GDF provides more than adequate protection of people and the environment for as far into the future as we can make reasonable forecasts.

Perhaps the most compelling argument is that, under every case and scenario analysed, the doses that might affect hypothetical people only occur in the most distant future and are so small that their effects would be undetectable among those of the natural background radiation in which we all live. We could receive considerably higher doses by spending a couple of weeks holiday in an area with slightly higher background radioactivity or by stepping onto a short aircraft flight to a nearby town – things that we would not think twice about.