Qualitative Performance Assessment of a Borehole Disposal System

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ABSTRACT

A program for disposing disused sealed radiation sources (DSRS) in a deep borehole demands, besides engineering for construction, operation and closure, great effort to characterize the site and conduct a safety assessment of the disposal system. The cost of running a safety assessment may be much greater than the costs to build and operate the facility, and expenditures with the necessary expertise and analytical infrastructure may threaten the technical and economic feasibility of such enterprise in developing countries. In this paper we propose that the safety of repositories be evaluated in terms of compliance with a set of requirements. Besides, we present an example of a preliminary list of rules, based on IAEA and ICRP guidance documents, with which disposal systems for DSRS should comply to get approval.

INTRODUCTION

In the context of radioactive waste disposal, Performance Assessment (PA) is the description of the repository and its surrounding environment, to provide a basis for decisions on the repository safety. In this sense, PA is the same as a Safety Assessment (SA). The engineered structures and the environment are regarded as an integrated system. PA thus evaluates the circumstances under which radionuclides disposed in the repository may be released and transported to the biosphere, taking into account the present state of the system and its future evolution.

Repositories for long lived sealed sources are expected to have useful life of the order of thousands of years and the acceptability of a facility or concept of repository depends on the evaluation of the radiological impact that the sources may create in the long-run and on the judgement of this impact on the basis of compliance with radiological protection objectives. Indicators to quantify radiological impact are individual effective dose rates, collective doses, and radiological risks.

Presently, estimates of doses and risks incurred by future generations, due to the existence of a given repository involve assessment of the performance of natural and engineered barriers through mathematical modeling of the features of the disposal system that may affect the release of radionuclides from the repository. Computer simulation of events and processes that may take place in the future is also necessary to demonstrate that the repository can perform according to regulatory standards.

A PA requires site investigations and the collection of a large amount of data. To run those computer simulations, it is necessary to execute an extensive program of analysis of the site in order to gain knowledge of the parameters of the repository. Parameters are variables that represent physical processes in the models used to assess the performance of the disposal system.

The site investigations provide the necessary information to decide on the suitability of the site and to get a license to proceed with the project of construction of the repository. Broad fields of investigation are: geology, hydrogeology, hydrogeochemistry, rock mechanics, ecology, geomorphology, etc in regional as well as local scale. The objective is to assess whether the site is acceptable. The knowledge obtained from the investigations is utilized to evaluate the suitability of the site for the repository and to certify that safety requirements and technical specifications are met and that environmental and social impacts are low enough.

Now, it is interesting to note two problems in that assessment of the safety of a repository for disused sealed radiation sources (DSRS). First, the PA of a geological disposal system is subject to large uncertainties because of the long range of the assessment. These uncertainties arise from lack of complete knowledge of the events and processes being simulated due to spatial and temporal variations of some parameters and due to the subjective nature of others, for instance, the behavior of future human populations. Another source of uncertainty is the random variability of measurements of most parameters. In this case, to reduce the uncertainties, more analytical work is necessary, for instance, measuring isotope's specific Kd's for all materials surrounding the wastes. Because of such uncertainties, the PA cannot provide absolute assurance that safety criteria will be met; instead, the output of the process is a reasonable guess that the system will perform as it is designed and comply with safety criteria.

The second problem is the cost of conducting the PA. Although it is difficult to find references to these costs in the literature, it is recognized that substantial site investigation efforts is needed, involving the collection of data at the surface as well as in situ, at the proposed repository location. According to some references [1,2] information necessary to estimate the potential for migration of radionuclides to the accessible environment should encompass the description of geochemical and hydrochemical conditions of the host rock, the surrounding geological and hydrogeological units, and their flow systems. The list bellow, showing the data required to describe the system thoroughly enough as to allow any estimation of future radiation doses, gives evidence that the costs of a program of site investigation can be very high. The A to Z list of site data includes:

a. mineralogical and petrographical composition of the geological media and their geochemical properties;
b. groundwater chemistry;
c. chemical, radiochemical and mineralogical composition of the rocks, including the fracture infilling materials;
d. sorption capacities of the minerals and rocks for ionic species of important radionuclides;
e. radionuclides content and chemical composition of the groundwater, including pH and Eh;
f. effects of radiation on the rock and the groundwater chemistry;
g. effects of organic, colloidal and microbiological materials;
h. pore structure and mineral surface characteristics of the rock, including cracks;
i. effective diffusion rate of nuclides in the rock units;
j. hydrogeological evaluation of local and regional geological units;
k. characterization and identification of aquifers and aquicludes;
l. characterization of hydrogeological units in the region, e.g. location, extent, interrelationship;
m. recharge and discharge of the major local and regional hydrogeological units;
n. hydrogeological characteristics of the host rock - porosity, hydraulic conductivity and hydraulic head gradients;
o. groundwater flow rates and prevailing directions of all aquifers in the geological environment;
p. solubility and speciation of radionuclides.

q. physical and chemical characteristics of the groundwater and host rock in the geological environment.
r. local and regional climatic history and expected future trends at regional scale;
s. tectonic history and framework of the geological setting at a local and regional scale and its historical seismicity;
t. evidence of active neotectonic processes, such as uplift, subsidence, tilting, folding, faulting;
u. any presence of faults, their location, length, depth and information on the age of latest movement;
v. in situ regional stress field;
w. estimate of the maximum earthquake physically possible at the site on the basis of its seismotectonic context;
x. estimate of the geothermal gradient and evidence of thermal springs;
y. evidence of Quaternary and possibly late Tertiary volcanism;
z. evidence of diapirism.

Construction costs of an exclusive repository for sealed sources may be low because the volume of the sealed sources, stripped out of packages and shielding, is very small – for instance, the whole inventory of sealed sources in Brazil which reaches about three hundred thousand sources, is estimated to have a volume smaller than one cubic meter [3]. In the case of a borehole three to four hundred meters deep, drilling, encasing and cementing the hole are in the cost range of a few hundred thousand dollars. This contrasts with the cost of characterizing the site in respect of all, or at least, a significant part of the quantities listed above. If the investigation work to characterize a site stops when sufficient data is accumulated for repository design, certainly the amount of data will not be enough to run a SA.

Consequently, if the strategy to dispose of sealed radiation sources apart from other institutional wastes is adopted, the structure of a repository for the sources can be small and its cost much lower than the costs of gathering data of the parameters to run the computer simulations of the SA.

There follows a description of a borehole repository for DSRS. This concept is used as an example for the line of reasoning to propose that the acceptability of the repository be based on compliance with qualitative or semi-quantitative requirements, as presented below.

DESCRIPTION OF THE DISPOSAL SYSTEM

The concept of repository is described in another paper presented in this Conference [4]. It consists of a deep borehole drilled in a crystalline rock formation. The emplacement zone is below the groundwater table, inside a granitic batholith, deep enough to accommodate all DSRS, yet providing an isolation space above the wastes and below the fractured stratum of the rock.

The hole is encased with a flush joint steel pipe, and the annulus between the pipe and the geological formation is filled with cement paste. The hardened cement paste around the casing is an additional barrier against the migration of radionuclides from the repository and is an obstacle for the flow of water between the different layers of minerals cut across by the borehole.

The sources are disposed of within lead containers, which functions as a shielded package and as a long standing barrier against the release of the radionuclides contained in the sources.

The space between the casing and the containers is left void, without grouting, and the repository can function as a retrievable storage until it is sealed off and closed. Retrievability is a controversial question but the concept is flexible allowing both conditions: in the form it is presented here, it is a retrievable storage; small changes in the design of the disposal package can render the wastes almost irretrievable.

After the capacity of the repository is reached, the space above the packages is sealed off with concrete and the site can be immediately decommissioned and released from institutional control.

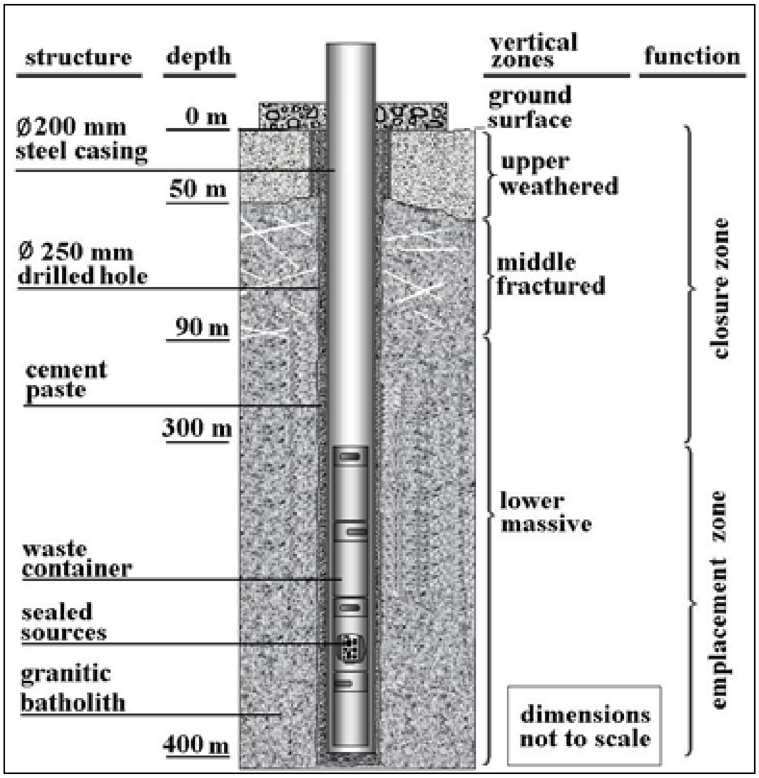

Fig. 1. Concept of the repository for disused sealed radiation sources

REQUIREMENTS FOR THE DISPOSAL SYSTEM

In the long run, the relevant risks to human health or the environment from the disposed sources are of radiological nature only. So, the safety of the repository can be reasonably assured if: 1) dispersion of the radionuclides into the biosphere, driven by natural processes, is retarded until they have decayed to safe levels; 2) human intrusion into the repository, be it inadvertent or intentional, is unlikely and an arduous endeavour.

Nevertheless, during construction, operation and closure of the repository other risks are present and, as a consequence, general industrial safety must be observed in all activities besides radiation protection guidelines.

These broad requirements are detailed below to focus on all aspects of a repository project, from operational procedures to the geological setting characterization. The set of requirements are based on guidance documents issued by the International Atomic Energy Agency (IAEA) [5,6,7,8,9,10] and by the International Commission on Radiological Protection (ICRP) [11]. The requirements are grouped in five categories: general requirements, concept of the repository, geological medium, structure & materials of the facility, and waste form. They are presented and discussed in the Tables I through V below.

Table I. General Requirements of a Repository for Disposal of DSRS

Requirement	Notes on compliance
1 – Non-radiological impact in the environment The construction of the facility has to comply with relevant regulations of non-radiological nature. Among possible adverse effects a geological disposal system may have on the environment, the following may be mentioned: (a) degradation of the environment due to mining, excavations, and other industrial operations in the area of interest; (b) impact on areas of significant public value; (c) degradation of public water supplies; (d) impact on plant and animal life, particularly endangered species.	The construction of the repository generates a small amount of soil and rock debris of excavated material. The volume of excavated material is about 20 m^3, for a 400 m deep borehole, which can be disposed of along with drilling fluids with acceptable impact; The small footprint of the repository and small-scale surface buildings allows the facility to be sited in a way that do not impact significantly any area of interest, nor disturb water supplies, nor endanger plant or animal species. There is no expected discharge of toxic effluents or emission of noxious gases, the use of energy, water and raw materials is limited, and the area of land required is small.
2 – Industrial safety During construction and operation of the geological disposal facility, like in any other industrial facility, due attention to occupational safety and health risks has to be given.	The technology used in drilling, encasing, and cementing the borehole is common to water exploitation engineering projects. Occupational risks during operation of the facility are mostly related to loading and unloading heavy waste packages.
3 – Radiological safety Protection measures of exposed individuals as a result of the operations at the repository shall be optimized and the exposures of workers and members of the public shall be kept within dose limits.	In regard to radiation protection, waste emplacement operations are similar to the routine operations of production, transportation and use of sealed sources. The doses to workers will be greater during the transfer of sources to disposal container and the doses incurred by individuals of the public will be greater during transportation of the sources to the disposal site. All these doses usually meet radiological protection principles and regulatory limits with present technologies.
4 – Control of disposal The emplacement of waste in the repository must be subject to the issuance of an appropriate authorization	The emplacement of the DSRS in the repository will begin only after sanction of the licensing authority and will be based on approved operating procedures and institutional controls.
5 – Record keeping Traceable records of the repository operations shall be kept by the responsible person entitled in the license.	Traceable records of the disposed wastes can be easily maintained throughout the operational phase of the repository with present technologies.
6 – Post closure control of the repository Institutional control of the repository shall be exercised after ending the operational phase and the safety in the post decommissioning phase shall be achieved without active institutional controls.	After wastes are emplaced in the repository, the operator continues to control the site until the borehole is sealed and the site is decommissioned, to prevent human intrusion. After closure, any sign of the repository is removed to a depth of some tens of meters and the site released to unrestricted use.
7 – Quality assurance A quality assurance program for all components of the disposal system shall be established to ensure compliance with relevant standards and criteria.	The construction of the repository only requires already mature and well proven technologies. Internationally accepted engineering and mining codes and applicable regulations, standards and specifications are available.

Table II. Requirements for the Concept of a Repository for Disposal of DSRS

Requirement	Notes on compliance
1 – Multiple natural and engineered barriers The long term safety of the disposal system shall be attained by application of the principle of safety in depth, and shall rely on multiple independent barriers.	Five barriers block the release and dispersion of the radionuclides in the environment: one is a natural barrier, the geological medium, and four are engineered barriers, the metal capsules of the DSRS, the lead castle packages, the metal casing of the borehole and the cement paste annulus interfacing with the geological medium.
2 – Robustness of the concept The concept of the repository must be strong enough to withstand credible natural or man induced events that can affect the repository. Situations in which exposure could arise as a result of the occurrence of disruptive events with low associated probabilities, shall also be considered.	Robustness is achieved through the multiple barrier concept and through the implementation of sound technical and managerial principles. Failure of any structure of the repository does not imply a preferential route to the release of the radioactive material. Migration of the radionuclides will only occur after the failure of all engineered barriers and bypass of the natural barrier.
3 – Long term isolation of the wastes Considering that it is impossible to keep the wastes isolated indefinitely from the biosphere (soon or later the material that composes the wastes will disperse in the environment), the purpose of a repository is to keep them isolated until the radioactivity has decayed to safe levels.	A decay time of ten half-lives reduces the radioactivity by a factor of one thousandth. Half lives vary from 30 years to 1620 years for more relevant DSRS and so the necessary isolation time is many thousands years. International experience indicates that ten thousands years of isolation is achievable in geological formations.
4 – Deep emplacement zone This requirement is related to the possibility that natural or man induced phenomena remove the overlying layer and expose the waste at the earth surface in shallow repositories.	Stability of a granitic batholith allows expect that erosion processes and uplift of the crust will make wastes to crop out only millions of years from now. In regard to man induced phenomena, the emplacement zone is beyond the depth of usual engineering projects.
5 – Repository induced changes in geological setting The construction of the repository shall not decrease the ability of the medium to function as a barrier against the migration of radionuclides.	Drilling a borehole will not induce the appearance of any significant fracture in the rocks. The cement paste around the casing will prevent the flow of fluids between different strata.
6 – Flexibility of the concept The concept of the repository shall have sufficient flexibility to accommodate future changes and fluctuations in the demand for disposal capacity.	The capacity of one borehole is defined at the project phase, however additional holes can be inexpensively drilled at the same site, allowing for future expansion of the sealed radiation source market and growing of the demand for disposal space.
7 – Retrievability Retrievability must be examined carefully. Retrievability allows for decisions to be reverted and for developments in waste management to be implemented in the future. The objection is in the security side, whether sources could be retrieved without regulatory consent.	As presented here, the concept allows for the sources to be retrieved during the operational phase. Small changes in the design of the disposal package can render the sources irretrievable. In any case, after the cavity is sealed with concrete, it is very improbable that the sources can be inadvertently or intentionally released.
8 – Impact on land use Activities on the land surface above the repository that can adversely affect the safety of the disposal system such as drilling, blasting, impoundment of liquid waste, etc. may be restricted.	A borehole plus administration and waste processing buildings occupy an area the size of a city block. After closure, the site can be decommissioned immediately. Buildings may be demolished, all tracks of the borehole removed and the site released for unrestricted use.
9 – Security The concept of repository shall enhance the security of the disposed wastes.	Disposed DSRS secured in the bottom of the repository could hardly be retrieved without the operator’s consent.

Table III. Requirements for the Geological Setting in a Repository for Disposal of DSRS

Requirement	Notes on compliance
1 – Natural barrier The geological environment of the repository shall function as the main obstacle to the movement of radionuclides contained in the wastes into the biosphere.	Granite presents low permeability, contains little or no flowing water, occurs in massive, homogenous, and long standing formations.
2 – Rock type The geological setting of the repository shall have properties that tend to restrict movement of radionuclides from the site to the accessible environment.	Granite has suitable characteristics: high mechanical strength to rupture, low solubility, physical and chemical stability, homogeneity, chemical compatibility with wastes and engineered barriers, and low economical value of minerals
3 – Formation size The geological unit at a candidate site must have enough width and vertical thickness in order to provide a protection zone around the repository.	Batholiths are a huge expanse of continuous plutonic rock with no floors that covers an area larger than 100 square kilometers. Drilling a borehole in the middle of a batholith assure compliance with this requirement.
4 – Tectonics and seismicity Significant tectonic processes and events such as faulting, seismic activity or volcanism can not be expected to occur with intensity that would compromise the necessary isolation capability of the repository.	This is a site specific requirement, but the kind of rock is very common and offers plenty of candidate sites for selection in most places.
5 – Mineral deposits of economical value The repository must be sited far from valuable mineral deposits and sources of geothermal energy, to assure that future generations are not denied the right to sources of raw material, and to avoid that the exploitation of mineral resources disturbs the isolation of the waste.	It is expected that mining of granites will continue in the future but one considers that this material can be obtained easier in more accessible outcroppings than in mineral bodies hundreds of meters deep.
6 – Hydrogeologic environment The underground water flow must be small and the rock must have low permeability at the level of waste emplacement in the repository. Open fractures in the geological setting must be limited with little flowing water.	A hard rock environment has irregular distribution of pathways of groundwater flow, typically consisting of three vertical zones, upper weathered, middle fractured and lower massive. The emplacement of the wastes in the lower, massive zone, assures compliance with this requirement.
7 – Geochemical characteristics The medium must have high adsorption coefficients in order to limit the transport and diffusion of radionuclides toward the biosphere.	The granite has variable adsorption rates, with high values for americium, but low to moderate values for strontium and cesium.
8 – Geomorphology The site of the repository must be not subject to extreme weather conditions that may affect the surface of the terrain and the site must be geomorphologically stable.	The repository must be sited in places where there is low potential for flooding or catastrophic torrent of rainwater during the operation phase. After closure, events at the surface will have low or no impact at the depth of the repository.

Table IV. Requirements for the Borehole in a Repository for Disposal of DSRS

Requirement	Notes on compliance
1 – Engineered barriers The environment that surrounds the repository shall be protected from the wastes by multiple independent barriers.	Three engineering barriers will isolate the radioactive sources: the lead containers, the steel casing of the borehole, and the cement paste around the casing. Each barrier is independent and tends to prevent the escape of radioactive material.
2 – Construction materials Structures of the repository shall be made with long standing, chemically compatible materials, thermally and radiolytically resistant, capable of withstanding the permanent mechanical loads foreseen.	The metal casing of the borehole is a common material in service under harsher conditions in the oil and gas exploitation industry. The alkaline environment created by cement paste forms a passivation layer on the surface of the metal that further protects it against corrosion. The lead of the packages is one of the most stable metals. Hydrated cement forms a stable and long standing mineral.
3 – Engineering codes and standards The design, construction and operation of the repository shall be carried out under well established engineering standards and codes.	The proposed borehole is drilled and encased using the well established technologies developed in groundwater exploitation and gas and petroleum mining industry. A project will identify and follow the requirements of the relevant industrial standards.
4 – Thermal and radiolytic stability The structures of the repository shall withstand the anticipated mechanical loads under the prevailing temperature of the deep geological medium and under the radiation field created by the wastes.	Tests with samples of cementitious materials show only small changes in the mechanical strength after irradiation to 100 kGy. Temperatures expected at the depth of emplacement of the sources are in the range of 10 to 20 degrees Celsius above surface temperatures.

Table V. Requirements for the Waste Form in a Repository for Disposal of DSRS

Requirement	Notes on compliance
1 – Function as a barrier Disposed wastes shall be in a form that tends to blockade the spread of the radioactive material.	Most sealed sources are strong metal capsules that prevent leakage of the radioactive substance contained in and only a small fraction has the radioactive material loosely bound to the metal structure of the source.
1 – Solid waste form Disposed wastes shall be in a solid form.	Almost all sealed sources are solid substances enclosed in a metal capsule or adhered to a metal plate. Current exceptions are short lived Kr-85 and some H-3 sources that are gases enclosed in strong metal capsules.
2 – Waste form stability Wastes must be in a form that is mechanically, thermally, chemically and radiolytically stable.	The metal capsules of the sealed sources can easily withstand the environmental conditions in the repository because of the resistance of metals to radiation and heat.
3 – Absence of hazardous products Waste forms are required to have no hazardous products like explosive, inflammable, or corrosive materials.	The metal capsules of the sealed sources satisfy all this requirements.
4 – Waste package Waste disposal packages shall resist the mechanical load in the repository and the normal or accidental conditions during transport and emplacement.	The disposal package is a robust, monolithic block of lead that is tested under accident conditions for transport of radioactive materials and that can withstand the weight of the packages stacked above it.
5 – Low economical value of waste package material Waste disposal packages shall be made of materials of low commercial value.	Lead is a relatively common material and is deemed to be too cheap to attract future mining activities in searching for raw materials at the depth of the repository.
5 – Accuracy of composition The waste packages shall have the composition of the contained radioactive materials accurately measured.	Each package can be identified and its content known exactly because in the packing operation each source will be accounted and recorded.

CONCLUSION

In the long run, risks to human health and the environment posed by a geological repository for DSRS are of radiological nature and the safety will be assured if dispersion of the radionuclides into the biosphere, driven by natural processes, is retarded until they have decayed to safe levels and if human intrusion into the repository is unlikely.

In this paper, these two requirements were detailed in all aspects of a repository, from operational procedures to the characterization of the geological setting. The requirements were grouped in five categories: general requirements, concept of the repository, geological medium, structure and materials of the facility, and waste form. For each requirement, the components of the repository must be evaluated in order to demonstrate that the system performs in conformity to the safety objectives.

More work is needed, however, to refine the wording of the requirements, to verify the consistency of the line of reasoning used in the notes on compliance, to rule out redundancies and inconsistencies between different requirements, and to extend the list of requirements to get a thorough set of prerequisites for a repository to be considered safe.

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