USING AN FEPS LIST AND A PA METHODOLOGY FOR EVALUATING SUITABLE AREAS FOR THE LLW REPOSITORY IN ITALY

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ABSTRACT

In Italy following a referendum held in 1987, nuclear energy has been phased out. Since 1998, a general site selection process covering the whole Italian territory has been under way. A GIS (Geographic Information System) methodology was implemented in three steps using the ESRI Arc/Info and Arc/View platforms. The screening identified approximately 0.8% of the Italian territory as suitable for locating the LLW Repository. 200 areas have been identified as suitable for the location of the LLW Repository, using a multiple exclusion criteria procedure (1:500,000), regional scale (1:100.000) and local scale (1:25,000 – 1:10,000).

A methodology for evaluating these areas has been developed allowing, along with the evaluation of the long term efficiency of the engineered barrier system (EBS), the characterization of the selected areas in terms of:

- physical and safety factors;
- planning factors.

The first step was to identify, on a referenced FEPs list, a group of geomorphological, geological, hydrogeological, climatic and human behaviour caused process and/or events, which were considered of importance for the site evaluation, taking into account the Italian situation.

A site evaluation system was established ascribing weighted scores to each of these processes and events, which were identified as parameters of the new evaluation system. The score of each parameter is ranging from 1 (low suitability) to 3 (high suitability). The corresponding weight is calculated considering the effect of the parameter in terms of total dose to the critical group, using an upgraded AMBER model for PA calculation.

At the end of the process an index obtained by a score weighted sum gives the degree of suitability of the selected areas for the LLW Repository location.

The application of the methodology to two selected sites is given in the paper.

INTRODUCTION

In Italy following a referendum held in 1987, nuclear energy has been phased out. A considerable amount of radioactive wastes of any kind has been produced during the about thirty years of nuclear activity. Since 1996, a major effort is being made to provide the country with a repository for LLW. A long term storage system for HLW will also be located in the same site. A near surface LLW Repository based on a vault concept is under design for a national total inventory of around 75.000 cubic meters of conditioned waste. The conceptual design has been completed and submitted to the safety authority for preliminary evaluation.

Since 1998 the ENEA Waste Disposal Program developed a Geographic Information System (GIS) to identify suitable areas for the localisation of the LLW national repository. Using the GIS a detailed screening of the Italian territory has been carried out, which allowed the elaboration of a National Map of the Suitable Areas to a scale of 1:500.000 (GIS 1). Further screening allowed the identification of 200 suitable sites (GIS 2). At present, an updated version of the GIS (GIS 3) is under development to evaluate and classify the 200 sites in terms of:

- physical and safety factors;
- planning factors.

The setting up of the GIS3 includes a definition of a system of points and weights to assess these two factors, which will attribute to each of the 200 sites a *suitability index* for the localisation of the LLW repository, defined as follows :

$$I = I_{ps} + I_p \qquad \text{(Eq. 1)}$$

where I_{ps} represents a physical and safety factors related suitability index and I_p a planning factors related suitability index. In particular, I_{ps} is given by the following expression:

$$I_{ps} = \sum_{i=1}^{n} p_i + w_i \qquad \text{(Eq. 2)}$$

where p_i represents a score linked to individual factors and w_i its weight. The I_p index is of the same nature as the I_{ps} index but refers to factors and weights related to the anthropic context of the site under evaluation. This paper deals with the method of calculating the I_{ps} index only.

The first problem to be faced has been the selection of the factors to adequately characterize the site in terms of the physical and safety suitability index. In the next paragraph the use for this goal of the list of FEPs (Features, Effects and Processes) produced by ISAM (IAEA, 2000) is described.

The second problem has been the definition of a scoring and weighting system to be associated with the identified factors. The scoring system has been defined using points ranging between 0 (site not suitable for the repository construction considering that particular factor) and 3 (optimal site for that factor). The allocation of a score of 0 even to a single factor determines the exclusion of the site from the list. The evaluation process using this scoring system will be carried out by a group of experts created for this purpose.

For the weighting system set up a methodology has been adopted which was intended to reduce as much as possible subjective considerations in this phase of the repository siting process.

This methodology has been based on a performance assessment (PA) model set up for a standard site defined to be representative, in terms of geosphere characteristics, of the 200 sites identified to be suitable for the LLW repository construction by the GIS 2 geographical analysis. Using the PA model, the importance of each factor on the total dose to the critical group has been calculated. Using this approach it was possible to evaluate the importance of each factor in terms of geosphere performance as a barrier to the migration of radionuclides in the environment. A relationship between dose variations caused by a quantitatively modified factor and related weight has been therefore established by means of a statistical approach.

PHYSICAL AND SAFETY FACTORS

In order to choose the factors for the evaluation of the 200 sites considered suitable for the construction of the LLW repository, a list of FEPs (features, events and processes) has been analysed. The considered FEPs list was developed in the framework of the Programme on

Improvement of Safety Assessment Methodologies for Near Surface Disposal Facilities (ISAM) of the International Atomic Energy Agency (IAEA) (IAEA, 2000). The list consists of 137 FEPs relevant to the assessment of long term safety of near – surface disposal facilities. The FEPs list was originally developed to be used as a common first approach in a manyscenario generation procedure. In the context of this study the FEPs have been instead extremely useful in the definition of an objective siting procedure of the repository.

The first phase in defining physical and safety factors consisted in screening FEPs to obtain a list of factors able to cover all important aspects to be considered in the LLW repository siting process. Therefore, the screening procedure has been done considering the IAEA listed FEPs:

- which were related to physical and safety factors which play a part in the construction of a near-surface LLW repository;
- for which data were available in the GIS 2, using which the scoring system previously described could be applied;
- which could be somehow implemented in the PA model.

At the end of the screening process, the following FEPs have been identified, for each one of them the scoring criteria is also described:

Site investigation: evaluation related to the investigations that must be carried out at a potential site in order to characterize the site both prior to the repository construction and during construction and operation;

Seismicity: evaluation related to the seismic danger of the site expressed in terms of maximum acceleration that may happen in the site with a return time of 3000 years and a 90% probability of not exceeding this acceleration.

Hydrothermal activity: site evaluation related to its safety performance capacity not to be negatively influenced by high temperature groundwater, including processes such as density driven groundwater flow and hydrothermal alteration of minerals in the rocks through which the high temperature groundwater flows.

Hydrological and hydrogeological response to geological changes: site evaluation related to its safety performance capacity not to be negatively influenced by large scale geological changes (i.e. changes of hydrological boundary conditions due to effects of erosion on topography, changes of hydraulic properties of saturated and unsaturated zones due to changes in rock stress or fault movements, etc.)

Periglacial effects: site evaluation related to its safety performance capacity not to be negatively influenced by physical processes and associated landforms in cold but ice-sheet-free environments (i.e. permafrost, soil-flow (movement) – solifluction, etc.).

Warm climate effects (tropical and desert): site evaluation related to its safety performance capacity not to be negatively influenced by warm tropical and desert climates, including seasonal effects and meteorological and geomorphological effects special to these climates.

Drilling activities: site evaluation related to its safety performance capacity not to be negatively influenced by any type of drilling activities near the repository. These may occur with or without knowledge of the repository existence.

On site geology: site evaluation related to its safety performance capacity not to be negatively influenced by the properties and characteristics of the host lithology as it may evolve both before and after repository closure in terms of the geochemical and hydrodynamic barrier to radionuclide transport in the geosphere.

Alteration of the direction of transport and migration of pollutants in the geosphere: site evaluation related to its safety performance capacity not to be negatively influenced by the properties and characteristics of smaller discontinuities and features within saturated and unsaturated zones that are expected to be the main paths for contaminant transport through the geosphere, as they evolve both before and after repository closure.

Lithology of the unsaturated zone: site evaluation related to its safety performance capacity not to be negatively influenced by a lack of capacity of the unsaturated zone to act as a barrier to the migration of radionuclides in the geosphere as a consequence of a failure of the repository engineered barrier system.

Unconfined aquifers*:* site evaluation related to its safety performance capacity not to be negatively influenced by the presence of unconfined aquifers used as a main resource for human drinking water supply.

Hydrological balance: site evaluation related to its safety performance capacity not to be negatively influenced by morphological conditions which can cause flood or stream water stagnation during critical meteorological events.

Erosion and sedimentation: site evaluation related to its safety performance capacity not to be negatively influenced by local scale removal and accumulation of rocks and sediments, with associated change in topography and geological/hydrogeological conditions of the repository host lithology.

MODEL OF CALCULATION OF THE DOSE

As mentioned above, the weight of each previously identified factor has been evaluated depending on the variation, caused by the same factors, on the maximum total dose value calculated by the PA model for the so called *standard scenario*.

In this scenario, the Repository EBS is assumed to remain intact for a post-closure institutional control period of 300 years, during which the basic features of the site (such as the cover integrity, the drainage system, etc.) would be maintained. After this period, radionuclides are assumed to leach from the Repository at a rate that will increase in time in accord with an EBS degradation rate calculation based on that of Berner (1992), which reaches the natural infiltration rate after 5,580 years.

The conceptual radionuclide transport model is shown in Fig. 1. Only the water pathway has been considered.

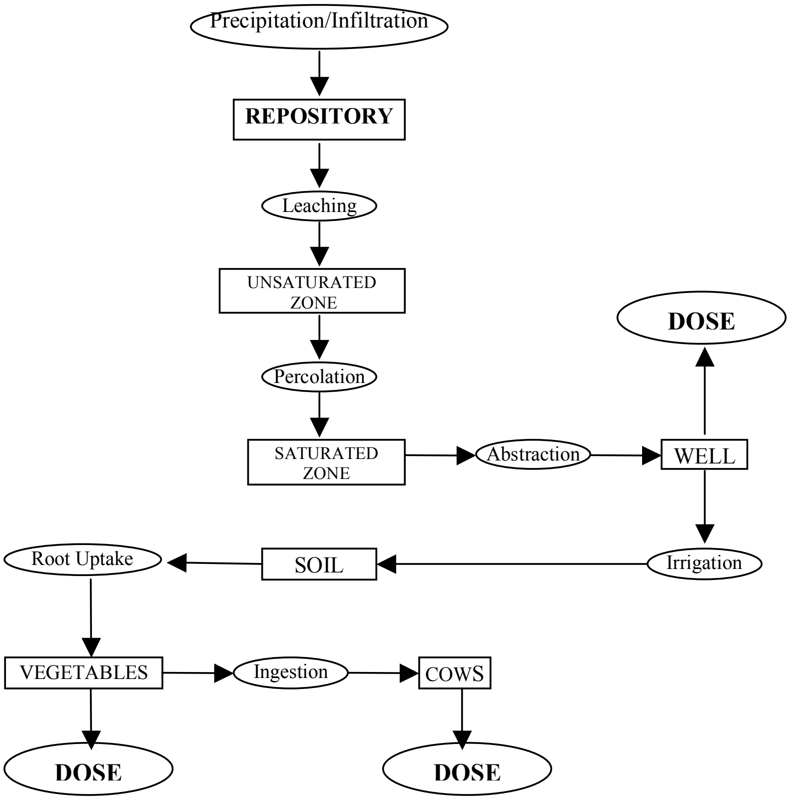

Fig. 1. Water pathway conceptual radionuclide transport model

A number of assumptions were made with respect to flow and transport in this model:

- steady-state flow in the vadose and saturated zones;
- depleting source release from the repository with a step increase at the stipulated time of failure of the concrete barriers:
- one dimensional flow and transport in the unsaturated zone with no lateral spreading owing to diffusion/dispersion;
- one dimensional flow and transport through the saturated zone with no diffusion or hydrodynamic dispersion;
- credit for sorption where appropriate in the repository (cement/concrete) and on the porous media for the unsaturated and saturated zones;
- complete mixing of radionuclides in compartments;
- no solubility constraints.

It has been assumed that an individual of the exposed group either:

- uses a well drilled 1000 m downstream the repository for the consumption of 2 l of water per day;
- uses groundwater also for irrigation of vegetables;
- consumes fish from the contaminated sea with an annual intake of 20 kg.

The AMBER (QuantiSci, 1998) code has been used for the implementation of the conceptual model described above in a mathematical model for the calculation of doses. AMBER is a flexible software tool that allows the user to build their own dynamic compartmental models to represent the migration of contaminants in a system, for example in the surface and sub-surface environment.

In AMBER the contaminants are assumed to be uniformly mixed in a series of compartments between which transfers can take place. A compartment is any specific part of the system being modeled. Each transfer is donor controlled, depending directly on the amount of material present in the compartment from which the material is moving, and can change with time.

Mathematically, the amount of contaminant in any compartment is determined by Eq. 3. If the total amount of contaminant m in compartment *i* is I_i^m (moles) then this must satisfy the expression:

$$\frac{dI_i^m}{dt} = -\left[\lambda_r^m + \sum_j \lambda_{ij}\right] I_i^m + \lambda_r^{m+1} I_i^{m+1} + \sum_j \lambda_{ji} I_j^m \qquad \text{(Eq. 3)}$$

where λ_{ij} is the exchange rate per year between compartment i and compartment j, λ_r^{m+1} is the decay rate per year of the parent contaminant m+1 , and λ_r^m is the decay rate per year of contaminant m.

The main parameters implemented in the AMBER model are reported as follows:

- *I* – precipitation rate (m/y);
- *Inv* – radionuclide inventory (Bq);
- *L* – length of pathways (m);
- *D* – irrigation rate (m/y)
- *theta_w* – water content (adimensional);
- *q* – flow velocity in compartments (m/y);
- *Kd* – distribution coefficient of radionuclides in compartments (m^3/Kg);
- *S* – width of the compartments (m);
- *rho_gr* – bulk density of compartments (Kg/m^3).

The value of the maximum total dose calculated for the standard scenario was 3.9×10^{-1} mSv/y, 150,000 years after the repository closure.

WEIGHTING SYSTEM EVALUATION

Once the maximum total dose for the standard scenario has been calculated, model parameters to be modified and their ranges of modification have been identified. This process has been summarized in Table I.

Table I – Variation of the parameters of the model

Factor (FEP)	Model parameter changes with respect to the standard scenario	Total dose for the most unfavorable variant
Site investigation	• geosphere compartments Kd is increased and decreased one order of magnitude; • geosphere compartments q is increased and decreased two orders of magnitude.	2.2 mSv/y at 500,000 year

Seismicity	• geosphere compartments Kd is increased one order of magnitude and decreased two orders of magnitude by the end of the institutional control period; • geosphere compartments q is increased and decreased two orders of magnitude by the end of the institutional control period; • repository compartment assumes the 5,580 year value of q by the end of the institutional control period.	2.4 mSv/y at 80,000 years
Hydrothermal activity	• geosphere compartments Kd is increased and decreased one order of magnitude; • geosphere compartments q is increased and decreased two orders of magnitude.	2.2 mSv/y at 500,000 years
Hydrological and hydrogeological response to geological changes	• unsaturated zone compartment L is increased up to one order of magnitude; • geosphere compartments q is increased and decreased of one order of magnitude.	4.7E-1 mSv/y at 100,000 years
Periglacial effects	• I is increased up to 5 times; • S of the repository compartment becomes nil after 300 years and 1000 years.	5.4E-1 mSv/y at 60,000 years
Warm climate effects (tropical and desert)	• I is decreased of 2 times and increased of 2 times; • S of the repository compartment becomes nil after 300 years.	4.8E-1 mSv/y at 80,000 years
Drilling activities	• Distance between repository and well is decreased up to one order of magnitude; • D is increased up to 5 times.	1.1 mSv/y at 100,000 years
On site geology	• Unsaturated compartment L is decreased up to one order of magnitude; • geosphere compartments Kd is increased and decreased ,one order of magnitude; • geosphere compartments q is increased and decreased one order of magnitude.	2.6 mSv/y at 300,000 years
Alteration of the direction of transport and migration of pollutants in the geosphere	• geosphere compartments Kd is increased and decreased one order of magnitude; • Distance between repository and well is decreased up to one order of magnitude;	2.2 mSv/y at 500,000 years
Lithology of the unsaturated zone	• unsaturated compartment Kd is increased and decreased one order of magnitude; • unsaturated compartment q is increased and decreased two orders of magnitude.	1.3 mSv/y at 100,000 years

Unconfined aquifers	- Distance between repository and well is decreased up to one order of magnitude; - Inv is decreased up to 5 times.	3.6 mSv/y at 100,000 years
Hydrological balance	- I is increased up to two orders of magnitude; - saturated compartment q is increased two orders of magnitude.	3.9E-1 mSv/y at 150,000 years
Erosion and sedimentation	- geosphere compartments Kd is increased and decreased two orders of magnitude; - S of the repository compartment becomes nil after 300 years.	5.0E-1 mSv/y at 400,000 years

For each factor, each variation of the parameters has defined a variant of the standard scenario. The result is a matrix of maximum total doses (Table II). For each matrix, and thus for each factor, a most unfavorable variant has been identified. This has been characterized by the greater value of the maximum total dose and has been used for the calculation of the factor's weight. The evaluation of the weight has been made taking into account both the value of maximum total dose and time in which this dose is registered (Table I).

As an example, in Table II the matrix of maximum total dose and time for the *on site geology* factor is presented.

Table II – Matrix of maximum total doses for different combinations of parameters for the *on site geology* factor

		L (***)					
		0.1		0.5		1	
q (*)	**Kd(**)**	Dose (mSv/y)	Time (year)	Dose (mSv/y)	Time (year)	Dose (mSv/y)	Time (year)
10	10	5.3E-2	100,000	4.9E-2	100,000	4.7E-2	150,000
	1	8.7E-2	70,000	8.7E-2	80,000	8.3E-2	90,000
	0.1	7.5E-2	50,000	7.6E-2	50,000	7.7E-2	50,000
1	10	4.7E-1	400,000	4.2E-1	500,000	3.4E-1	70,000
	1	4.6E-1	100,000	4.2E-1	100,000	**3.9E-1**	**150,000**
	0.1	7.1E-1	70,000	7.2E-1	80,000	6.9E-1	90,000
0.1	10	1.8	1,000,000	2.8E-1	1,000,000	8.7E-2	1,000,000
	1	**2.6**	**300,000**	2.1	400,000	1.51	600,000
	0.1	1.78	100,000	1.6	90.000	1.5	100,000

(*) Flow velocity of the geosphere compartments
(**) Distribution coefficient of the radionuclides in the geosphere compartments
(***) Length of transport pathway in the unsaturated compartments
The most unfavorable variant is highlighted in bold characters.

Calculation of Weight

A procedure has been developed to define a weight for each one of the factors described in table A. This weight is the sum of two *relative weights*, the first one related to the maximum total dose and the second one related to the time at which this dose occurs for the most unfavourable variant (see Table II).

The weight calculation procedure has been carried out by means of the following steps:

1. The values of the maximum total dose relative to the most unfavourable variant for each factor and for the standard scenario to define the *maximum total dose relative weight function* have been distributed along the X axis of a Cartesian system;
2. The values of the time relative to the most unfavourable variant for each factor and for the standard scenario to define the *time relative weight function* have been distributed along the X axis of a Cartesian system;
3. A maximum total dose relative weight linear interpolation function has been calculated (Fig. 2). In this function a relative weight of 0 has been assigned to a maximum total dose of 0 mSv/year and a relative weight of 1 has been assigned to the higher values of maximum total dose obtained for all the considered factors;
4. A time relative weight exponential interpolation function has been calculated (Fig. 3). In this function a relative weight of 0 has been assigned to an arrival time of the total maximum dose of 1,000,000 years and a relative weight of 1 has been assigned to an arrival time of the total maximum dose of 0 years for all the considered factors;

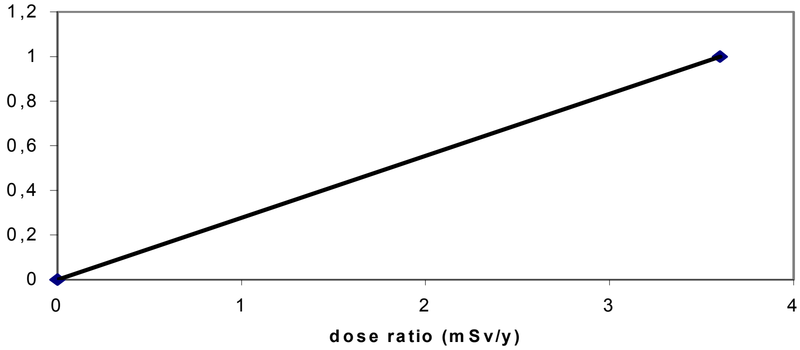

Fig. 2 – Interpolative curve of the values of the dose ratio

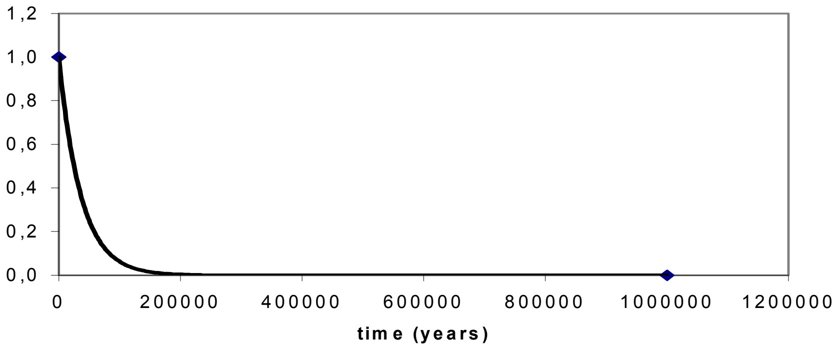

Fig. 3 – Interpolative curve of the values of the peak time

5. Once the maximum total dose relative weight function has been defined, relative weight ($PR_{\text{dose ratio}}$) has been calculated for all the values of the all factors on the X axis;
6. Once the time relative weight function has been defined, relative weight ($PR_{\text{peak time}}$) has been calculated for all the values of the all factors on the X axis;
7. The sum of maximum total dose and time relative weights has been then calculated for each factor and for the standard scenario to obtain a total weight, as indicated in the following equations.

$$P\_std\_scenario = PR_{dose\_ratio} + PR_{peak\_time} \qquad \text{(Eq. 4)}$$

$$P\_fact\_i = PR_{dose\_ratio} + PR_{peak\_time} \qquad \text{(Eq. 5)}$$

where:

- *P_std_scenario* is the total weight for the standard scenario;
- *P_fact_i* is the total weight for the *i* factor;
- PR_{dose_ratio} is the maximum total dose relative weight;
- PR_{peak_time} is the time relative weight;

8. The *weight* has been calculated for each factor using the following equation

$$w_i = \frac{P\_fact\_i}{P\_std\_scenario} \qquad \text{(Eq. 6)}$$

The results of calculation are shown in Table III.

Table III. Weight of the analyzed factors

FACTORS	WEIGHT
Site investigation	4.9
Seismicity	6.2
Hydrothermal Activity	4.9
Hydrological and hydrogeological response to geological changes	1.6
Periglacial effects	2.7
Warm climate effects (tropical and desert)	2.0
Drilling activities	3.0
On site geology	5.8
Alteration of the direction of transport and migration of pollutants in the geosphere	4.9
Lithology of the unsaturated zone	3.5
Unconfined aquifer	8.6
Hydrological balance	1.0
Erosion and sedimentation	1.1

CONCLUSIONS

The described procedure has led to a more objective definition of weights to be associated to physical and safety factors to be used for the evaluation of the 200 sites identified as suitable for the location of the LLW repository in Italy (Table III).

The most important aspects of the weights calculation procedure are:

1) It is coupled with the Performance Assessment (PA) methodology, the technique applied for the evaluation of the safety of a LLW repository;
2) In the context of the PA application, this procedure applies FEPs that are confirmed and accepted worldwide. FEPs have not been used here to define the possible evolutionary context of the repository system, but to classify sites on the basis of their radiological impact.
3) It leads to a uniform and objective evaluation process for different areas and sites.

This procedure has been applied to a typical but not real site, which is thought to be representative of a large number of sites divided into macroareas by the use of GIS methodology.

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