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APPLICATION OF THE IAEA SAFETY ASSESSMENT METHODOLOGY DURING THE DECISION MAKING AND LICENSING PROCESSES FOR THE ROMANIAN RADIOACTIVE WASTE FINAL REPOSITORY*

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Abstract. The ISAM Methodology is appropriate and was followed for safety assessment and decision making process of the Romanian Radioactive Waste Final Repository. The work performed during the development of RWFR evolution scenarios, application of the Interaction matrix method and the calculation of safety indicators using the AMBER computer code is described.

Key words: safety assessment methodology, evolution scenario, dose to human, safety indicators.

1. INTRODUCTION

Safe disposal of the radioactive waste represents one of the main objectives of nuclear policy and, at the same time, a theoretical and engineering challenge, both for national and international organizations involved. In a society which promotes, develops, sustains and manages the safe nuclear installations, this purpose is achieved based on three interdependent and important elements, namely: adequate legislative/regulatory framework, development of disposal structures, acting as barriers against the spread of radionuclides in the environment and demonstration of the safe evolution of the disposal structures.

The legislative/regulatory framework comprises the safety principles and requirements, which represent the basis of all radioactive waste management activities, as well as the practical guidance (See, for example, [1] and [2]). Regarding the disposal facilities, the international practice has as result the

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developing of the so-called disposal system, which has three components: the repository itself and its surroundings (the near field), the geosphere and the biosphere. The basic concept related to the disposal system is the defence in depth concept (multiple barrier concept), which defines the disposal system as an assembly between the disposal structures and the site. The confinement of radionuclides is ensured by the synergy of the engineered structures and the favorable site characteristics (geosphere and biosphere), the control of the waste form and content, adequate operational procedures and the institutional control.

The safety aspects of the disposal system are the purpose of specific analyses – Safety Analyses – which represent main elements in the licensing process of a repository. These analyses have to be developed systematically, following traceable and reproducible methodologies, easy to check and to justify, which allow the assessment of the long-term evolution of the repository. Some recommendations and practical examples on how to develop the safety analyses are described in the documents [3–6].

For the low and intermediate radioactive wastes resulted from the Cernavoda Power Plant operation and decommissioning, the National Strategy establishes the development of a near surface repository, with multiple barriers, which will be located in the Cernavoda area (RWFR). According the Romanian legal provisions, the Romanian National Agency for Radioactive Waste (ANDRAD) is in charge of developing and implementing the RWFR. To define and describe technical solutions and to obtain the siting licence of this repository, SITON – under the ANDRAD requests – has performed a lot of studies and analyses, regarding the site choice and characterization (a complex process, containing many steps), establishing of technical solution (based on specific technical-economic and safety assessments), as well as safety support assessments required during the decision making and licensing process of the RWFR. References [8–12] contain some of the above mentioned studies. Also, new revised safety documentation [17] was completed in May 2007 and represented the main technical documentation support to ANDRAD in order to apply for a partial siting license for RWFR, in June 2007.

The release and transport mechanisms from the repository, the specific FEPs and the preliminary system of evolution scenarios were identified in the previous work performed at SITON (see documents [10–12]). In the present paper, the work is continuing, by refining the FEP List specific for the RWFR, and the conceptual and mathematic models for the most important scenarios. The focus is on the assessment of the alternative scenarios, which are the most important in the decision making process, to establish technical solutions for the repository.

This paper approaches the following topics: the objective of our study, short presentation of the assessment methodology, our hypotheses, description of the evolution scenario modeling, are discussed in Section 2. Our major results, conclusions and future research objectives are described in Sections 3 and 4.

2. METHODS AND OBJECTIVE

THE OBJECTIVE

The objective of our study is to develop the RWFR evolution scenario system and to assess the consequences of the important ones, following the safety assessment methodology recommended by the IAEA. At the same time, the work is conducted to define and assess the main safety indicators identified for the repository in the postclosure period. This purpose is justified in the making-decision and licensing process of the RWFR, as the long-term safety assessments represent key elements, and a basis for all the future assessments. Also, the special request of CNCAN in the document NDR-05 “Norms regarding the surface disposal of radioactive waste” [2] is to identify and assess the safety indicators, which are the characteristics or consequences of a disposal system by which the potential hazards or harm can be measured, and play a specific role over different periods of the repository lifetime.

SAFETY ASSESSMENT METHODOLOGY

The International Atomic Energy Agency has coordinated, in the last years, a research project to develop a common safety evaluation methodology for the near surface disposal facilities – ISAM project [3]. The project is continuing under the name ASAM, to solve some specific problems related to near surface repositories.

The ISAM Methodology is a methodology traceable and transparent, which contains the following main steps: specification of the assessment context, description of the disposal system (near field, geosphere and biosphere), development and justification of the evolution scenarios (during the operational and postclosure period), formulation and implementation of models and data, performing calculation and interpretation of results. There is also a special back-up step, of the “stop and think” type, for control and certification of the obtained results.

To develop the conceptual model for the RWFR postclosure evolution scenarios the Interaction Matrix Method has been used. The Interaction Matrix contains a graphical layout of the disposal system compartments (as LDEs) and the specific FEPs (as ODEs). The matrix has to be developed in a traceable manner and checked against the International FEP List, to demonstrate the consistency of the model.

The mathematical model developed for long-term evolution scenarios is mainly based on the migration and transport of radionuclides from waste (sorption, diffusion, dispersion and advection), transport equation for unsaturated and saturated geological layers, biosphere pathways (uptake of radionuclides in the crops, feed of animals) and exposure pathways for human, namely contaminated water ingestion, consumption of crops and animal products (milk, meat).

HYPOTHESES

The RWFR is a near surface repository, with multiple barriers, namely waste conditioning matrix, disposal container, disposal cell, water collection system, compacted loess basement, final cover and the geological layers under repository (loess and clay). The repository is located in an unsaturated area; the saturated area is located at about 45 m depth under the facility. In the area there are also some secondary aquifers and a main one, located at about 75 m depth. The main radionuclides from the radioactive waste to be disposed are the characteristic radionuclides from a CANDU Power Plant (^{3}H, ^{60}Co, ^{137}Cs, ^{134}Cs, ^{106}Ru, ^{125}Sb, ^{54}Mn and ^{14}C).

EVOLUTION SCENARIO MODELING PROCESS

The RWFR evolution scenarios were developed methodologically, both for operational and postclosure periods, for normal and alternative situations. The scenario development method, used in many IAEA coordinated projects, is the method of FEP List performing and analysis. From the three types of FEPs specified in document [7], the scenarios will be generated using the external FEPs, which represent the boundary conditions for the repository.

To develop the normal evolution scenarios, the FEPs which can change dramatically the repository state were excluded (for example, other disposal alternatives, accidents, changes during construction, etc.). For the operational scenarios, the FEPs which do not affect the normal disposal activities will be excluded, due to their low likelihood of occurrence in the considered timescale. For the postclosure scenarios, we took into account the FEPs which can affect the state of repository in the considered time period (for example, climatic processes and their effects, future human activities, etc.).

The conceptual and mathematical models for the long-term evolution scenarios were developed, using the interaction matrix method. The AMBER computer code v.4.7 [13] was used for scenario consequence evaluation. It uses a compartment model approach and it allows all the system components, migration processes and exposure mechanisms to be represented using a single code. The system was split into a series of assumed homogeneous compartments and the transfer processes between the compartments were expressed as transfer coefficients that represent the fraction of the activity in a particular compartment transferred from that compartment to another one per time unit. The mathematical representation of the inter-compartmental transfer processes takes the form of a matrix of transfer coefficients that allows the compartmental amounts to be represented as a set of first order linear differential equations. For the i^{th} compartment, the rate at which the inventory of radionuclides in a compartment changes with time is given by:

$$\frac{dN_i}{dt} = \left(\sum_{j\neq i} \lambda_{ji}N_j + \lambda_N M_i + S_i(t)\right) - \left(\sum_{j\neq i} \lambda_{ij}N_i + \lambda_N N_i\right) \quad (1)$$

where i and j indicate compartments, N and M are the amounts (Bq) of radionuclides N and M in a compartment (M is the precursor of N in a decay chain). $S(t)$ is a time-dependent external source of radionuclide N (Bq y^{-1}). λ_N is the decay constant for radionuclide N (y^{-1}) and λ_{ji} and λ_{ij} are transfer coefficients (y^{-1}) representing the gain and loss of radionuclide N from compartments i and j. For simplicity, the above equation assumes a single parent and daughter. However, AMBER allows the representation of multiple parents and daughters.

The solutions of the system of equations (1) (given above for all compartments and transfers in the system) provide the time-dependent inventory of each compartment. Assumptions about compartment volumes then allow estimates of concentrations in the corresponding media to be made, from which doses/intakes can be estimated. Other details regarding the contaminants transfer between different disposal system compartments are contained in the documents [8] and [9].

The end point of the assessment is the total dose received by a person from the critical group (with its main components due to ingestion of water, crops and animal products). The obtained results were presented in a sensitivity analysis, which forms the basis of the choice of technical solution for repository. The main assessed elements were the doses due to contaminated water ingestion, crop and animal products ingestion, with the following formulae:

– the dose to human due to water ingestion:

$$D_{Wat} = C_W \; Ing_{Wat} \; DC_{Ing} \quad (2)$$

where C_W is the radionuclide concentration in the abstracted water (Bq m^{-3}), Ing_{Wat} is the individual ingestion rate of water (m^3 y^{-1}), and DC_{Ing} is the dose coefficient for ingestion (Sv Bq^{-1}). The amount of the radionuclides in the aquifer depends on the transfer processes in the geological environment;

– the dose to human due to crop ingestion:

$$D_{Crop} = C_{Crop} Ing_{Crop} DC_{Ing} \quad (3)$$

where C_{Crop} is the radionuclide concentration in the crop (Bq kg^{-1} fresh weight of crop), Ing_{Crop} is the individual ingestion rate of the contaminated crop (kg fresh weight y^{-1}), and DC_{Ing} is the dose coefficient for ingestion (Sv Bq^{-1}). The C_{Crop} depends on the radionuclide concentration in the upper soil and irrigation water, crop concentration factors and the loss of radionuclides during the food preparation;

– the dose to human due to animal products ingestion (meat and milk):

$$D_{Anm} = C_{Anm} Ing_{Anm} DC_{Ing} \quad (4)$$

where C_{Anm} is the radionuclide concentration in the animal product (Bq kg^{-1} fresh weight of product), Ing_{Anm} is the individual consumption rate of the contaminated animal product (kg fresh weight of product y^{-1}) and DC_{Ing} is the dose coefficient for ingestion (Sv Bq^{-1}). The C_{Anm} depends on the animal exposure pathways (contaminated water, soil and pasture consumption, dust inhalation) and the radionuclide concentration factors in the animal products. For details regarding mathematical equations, see [8] and [9].

3. RESULTS AND DISCUSSION

In the following, we emphasize the major results obtained during the assessment process of the RWFR evolution scenarios in the postclosure period. First, our work was focused on the normal evolution scenario, describing the radionuclide migration from the repository to one of the secondary aquifers of the site. As a consequence, we assessed the influence of the repository normal evolution on a farm located nearby the repository site, considering that there are some radionuclide pathways like water consumption, water use for irrigation, etc. One of the alternative scenarios considered to be very important to define the disposal solution was the "Road construction crossing the repository area, disrupting a part of the disposal structures and accidental contamination of the farm land". For both scenarios, the end point of calculations were the safety indicators "Total dose received by the public" and, subsequently, its components due to water, crops and animal products ingestion, and the "Contributions" of the main dose components and main radionuclides to the total dose (complementary safety indicators). We emphasized, also, the difference on the shape of the total dose, as effect of the disruptive event. The complementary/support safety indicators also calculated were the concentrations of radionuclides in the geological layers, aquifer, well, soil, crops and animal products.

The calculation was performed using the AMBER computer code, version 4.7. Based on the reference [14], we assumed that the main radionuclides contained in the disposed waste are ^{3}H, ^{137}Cs, ^{60}Co and ^{14}C. The critical group is represented by farmers which have small individual farms nearby the repository site. For our calculations, the main exposure pathways are the contaminated water ingestion (from a well supplied from a secondary aquifer in the area), as well as the ingestion of contaminated agricultural products (crops, cow milk, cow meat).

The safety indicator "Total dose" was calculated performing a sensitivity analysis, to determine the optimal duration for the institutional control, optimal depth for waste disposal, optimal size of final cover and the adequate location of all types of waste (assuming that there are many waste types, containing long-lived or short-lived radionuclides, namely ^{60}Co, ^{3}H or ^{14}C). In order to determine these parameters, we assume, for example, the variation of the following input data: time of occurrence of the alternative scenario (100 or 300 years after the closure of repository), the quantity of disrupted radioactive material, different crops grown-up in the contaminated area (pasture, grains, green vegetables or root vegetables).

The input data regarding the radionuclide inventory are illustrative only. The input data regarding the site, concentration factors, dose factors, drinking water rate or ingestion rates, etc, are chosen from the literature [15] or from the previous work performed in SITON [10–12]. We can mention that the obtained results have no purpose to be the object of a comparison against the regulatory dose criteria, in order to license the RWFR. They serve, in the context of this paper, only to illustrate an assessment methodology, the management of alternative scenarios possible in the post-closure phase of RWFR and the specific sensitivity analysis necessary in the safety indicators evaluation process.

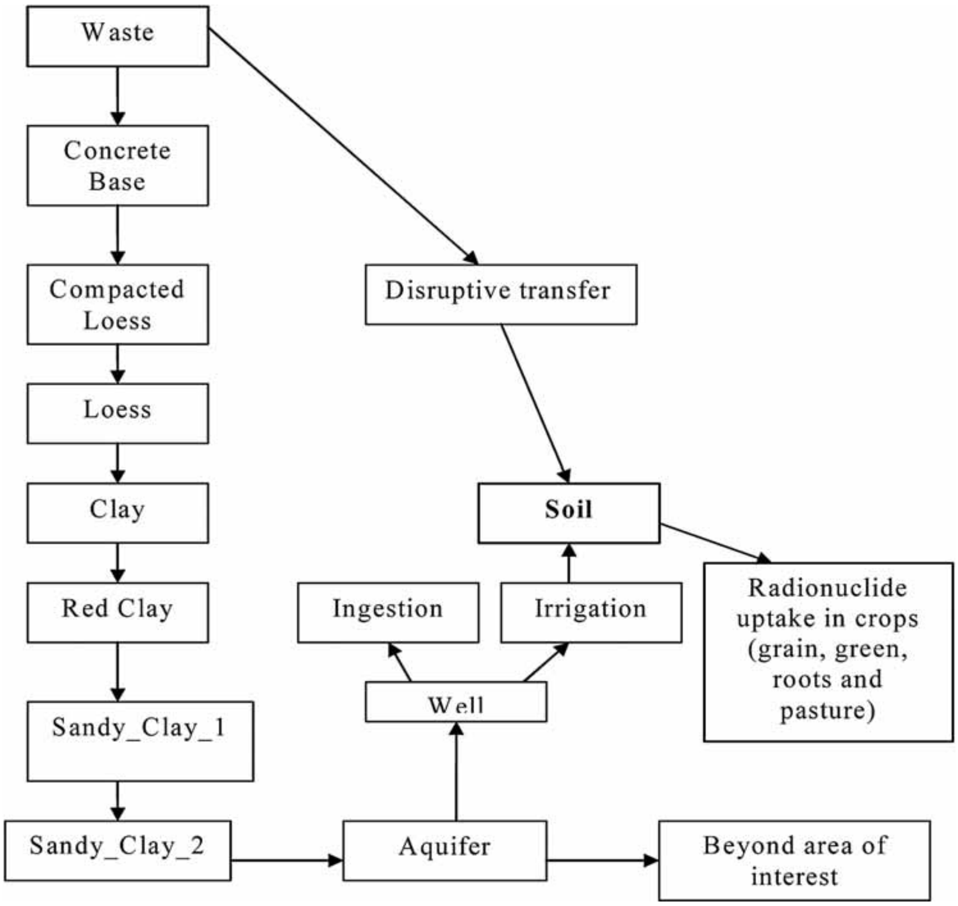

Fig. 1 – Conceptual model of repository.

For the sensitivity analysis, the following three variant scenarios were assessed, namely: "Road construction after 100 years and 0.0001% of the radioactive material was removed from the repository" (Variant 1), "Road construction after 300 years, and 0.001% of the radioactive material was removed from the repository" (Variant 2) and "Road construction after 300 years and 0.0001% of the radioactive material was removed from the repository (without ^{14}C)" (Variant 3). The percents are calculated from the residual amount of radionuclides, at the moment when the event occurs.

One of the main approaches was the partitioning of the disposal system in a lot of compartments, assumed to be homogenous, and, also, to define the transfer processes between them. The conceptual model (represented simplified in Fig. 1) was implemented in the AMBER code, using its friendly graphical interface. The modeling of source term was performed using the ramp up function, assuming appropriate degradation time periods for the engineering barriers and considering different variables for each radionuclide. It will be a subject of the future refinements in our work. The total dose resulted from the normal evolution scenario (Fig. 2) reflects the normal and predictable radionuclide transfer processes. Then, the early peak values are produced by ^{3}H, while the radionuclides ^{137}Cs and ^{14}C have a long-term important contribution. A challenge was to model the leaching of radionuclides from the waste form.

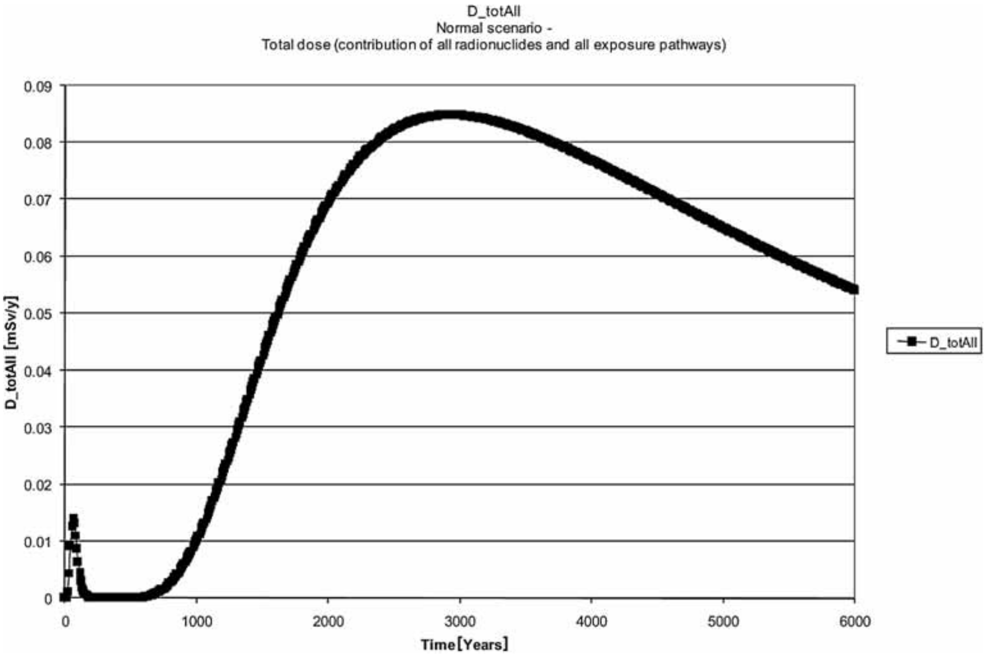

Fig. 2 – Total dose resulted from the normal evolution scenario. The two peak values can be emphasized (the early and the long-term ones), due to tritium and ^{14}C migration, respectively.

The shape of dose due to contaminated water ingestion is not affected by the disruptive scenario (Figs. 3 and 4). From the inventory, only ^{3}H has an early major contribution. The other radionuclides migrate slowly, due to retardation process in the geological layers (clay), and they have a low contribution to the above mentioned dose. We can also emphasize the long term contribution of ^{14}C. After the refinement of the conceptual/mathematical models in accordance with the new obtained data [14], the concentration of this radionuclide will be the subject of a double check, in order to be reduced.

The doses due to crop (Fig. 5), cow meat and cow milk ingestion (Fig. 6) are strongly affected by the disruptive event, because our assumption is that the disrupted material from the repository structures was spread on the farm soil. Regarding the doses due to crop ingestion (Fig. 5), before the occurrence of the disruptive event, the contribution of each crop is decreasing as follows: D_grain > D_root > D_green. In this period, the major contribution is resulting from ^{3}H migration (early peak values). After the event occurrence, the importance of each crop is D_root > D_grain > D_green. The peak values are resulting from ^{137}Cs and ^{14}C migration (long term peak values).

Fig. 6 (the doses resulted from animal products ingestion) shows that, before the event occurrence, the milk ingestion is more important than meat ingestion,

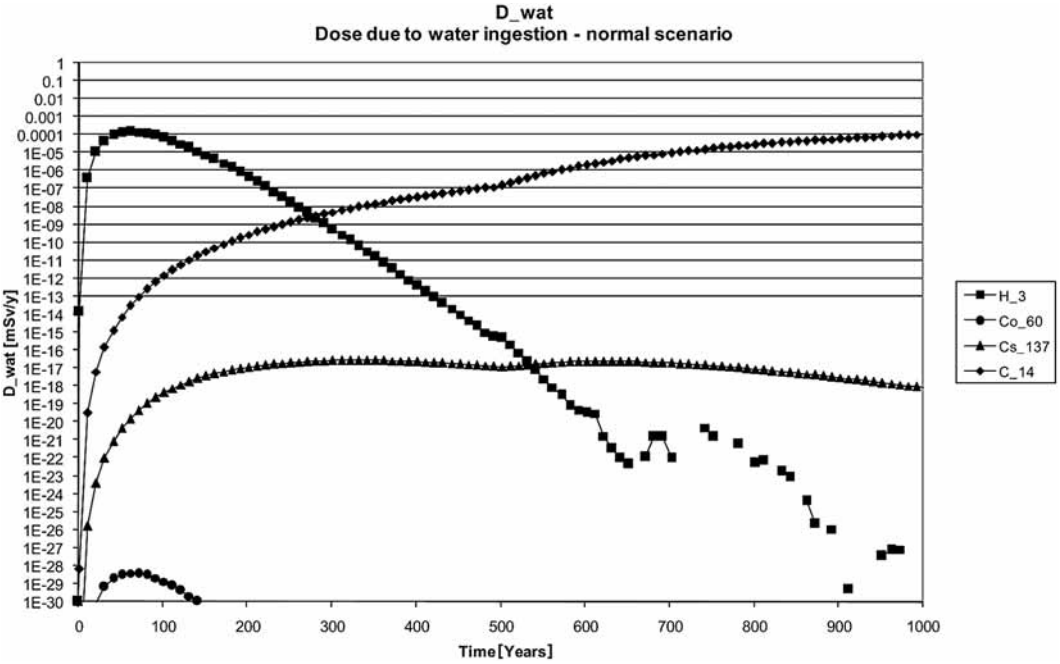

Fig. 3 – Dose due to water ingestion. Normal evolution scenario. Comment: the un-discontinuities are due to very small concentration values of tritium and ^{60}Co.

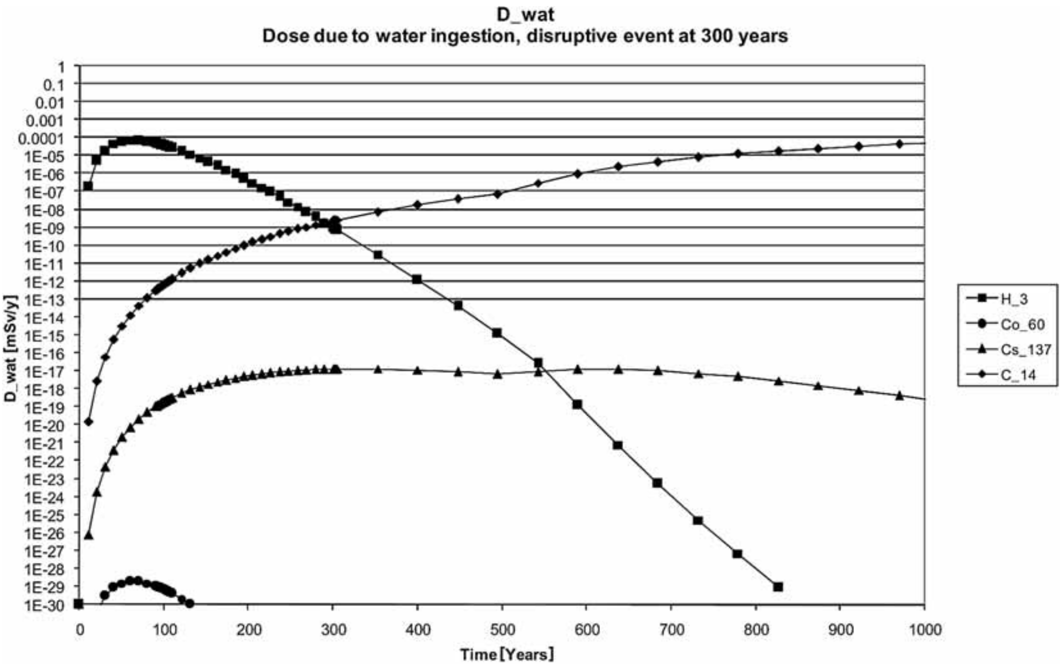

Fig. 4 – Dose due to water ingestion. Alternative Scenario at 300 years (Variant 3).

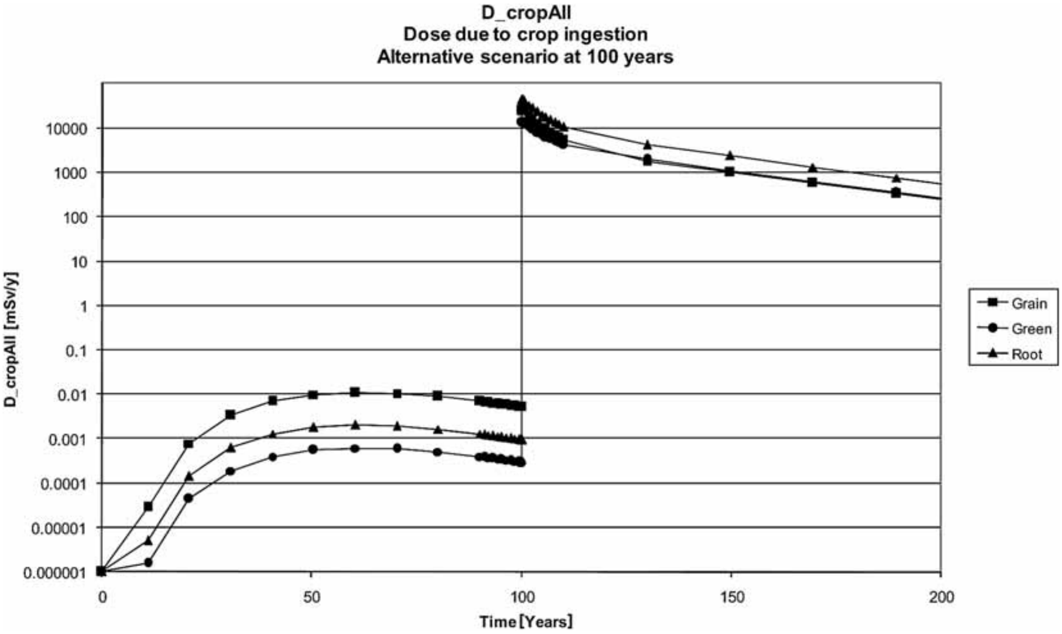

Fig. 5 – Dose due to crop ingestion. Alternative Scenario at 100 years (Variant 1). The important contribution of the disruptive event can be emphasized in the moment of occurrence. The shape of dose components, before the event occurrence, is the same as the normal scenario dose, with early peak values due to tritium migration.

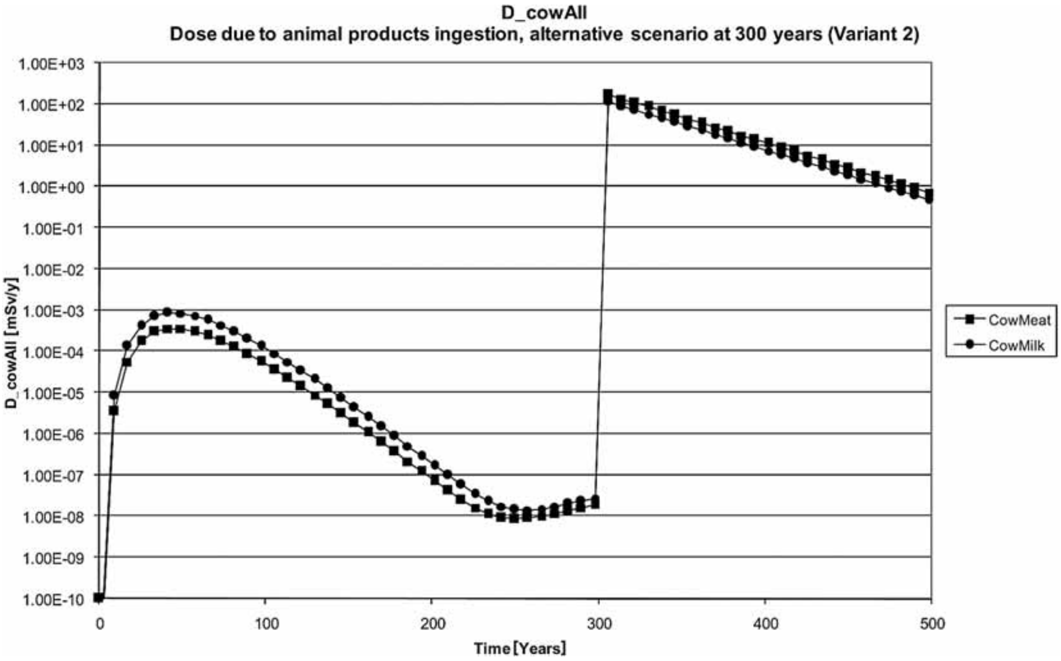

Fig. 6 – Dose due to animal products ingestion. Alternative Scenario at 300 years (Variant 2). The important contribution of the disruptive event can be emphasized in the moment of occurrence. The shape of dose components, before the event occurrence, is the same as the normal scenario dose, with early peak values due to tritium migration. Due to the late moment of disruptive event occurrence, we can emphasize also the decreasing of dose component values before the disruptive event.

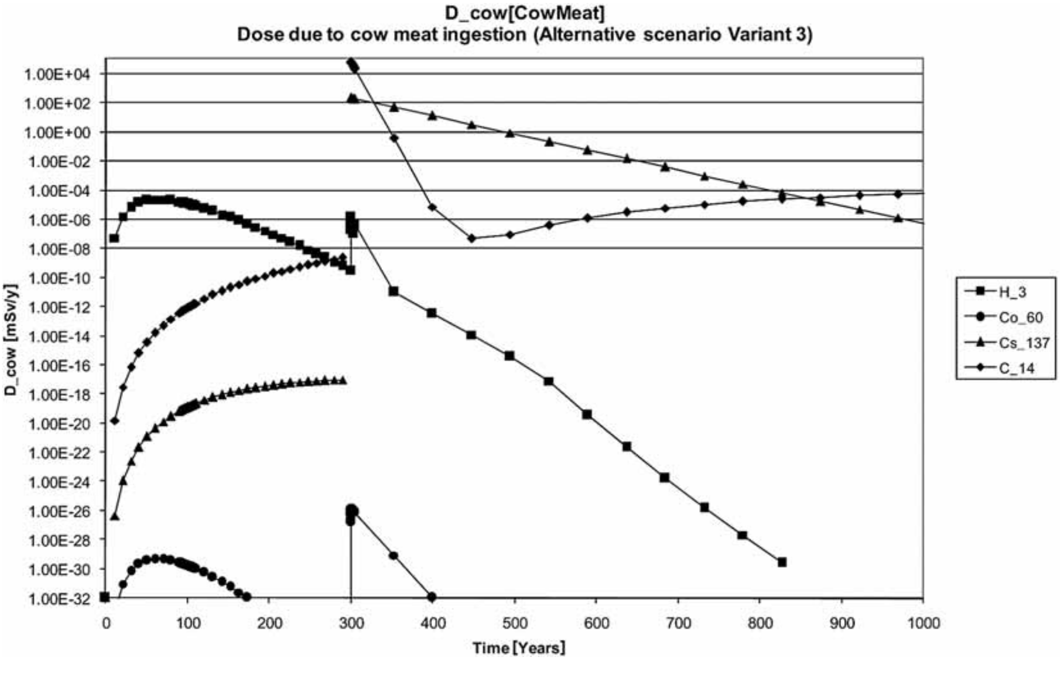

Fig. 7 – Dose due to cow meat ingestion. Alternative Scenario Variant 3. The important contribution of the disruptive event can be emphasized in the moment of occurrence. The shape of dose components, before the event occurrence, is the same as the normal scenario dose, with early peak values due to tritium migration. Due to the late moment of disruptive event occurrence, we can emphasize also the decreasing of dose component values before the disruptive event. We can emphasize, also, the low contribution of ^{60}Co.

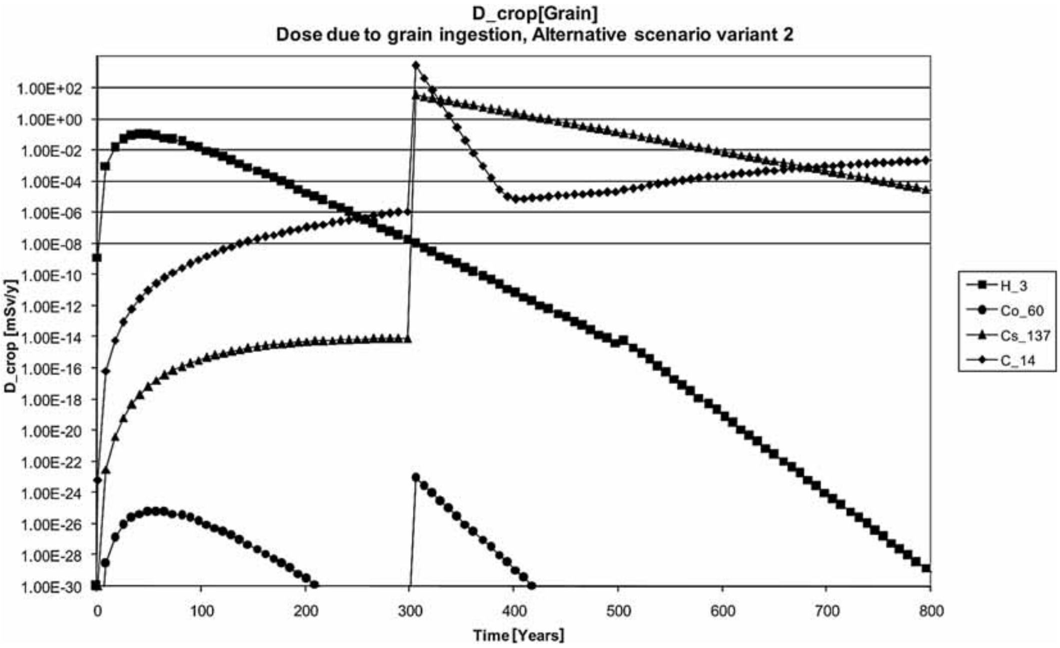

Fig. 8 – Dose due to grain ingestion. Alternative Scenario Variant 2.

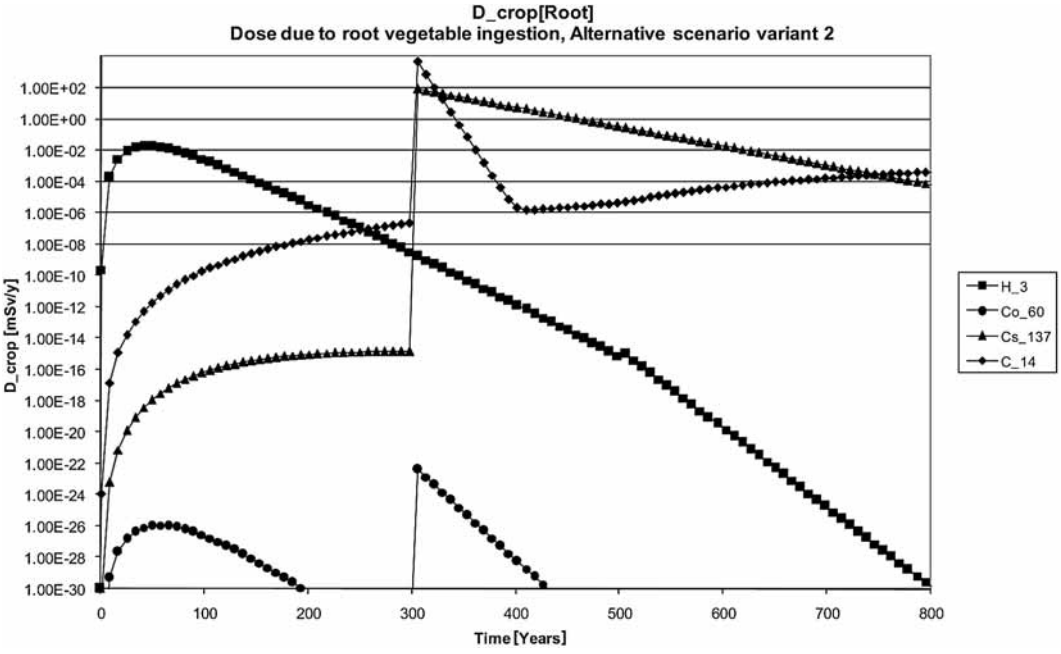

Fig. 9 – Dose due to root vegetable ingestion. Alternative Scenario Variant 2. We can emphasize the sensible resemblance with Fig. 8, except for the slow decreasing of ^{137}Cs concentration on the root vegetables, by comparison with the concentration of the same radionuclide in grain vegetables.

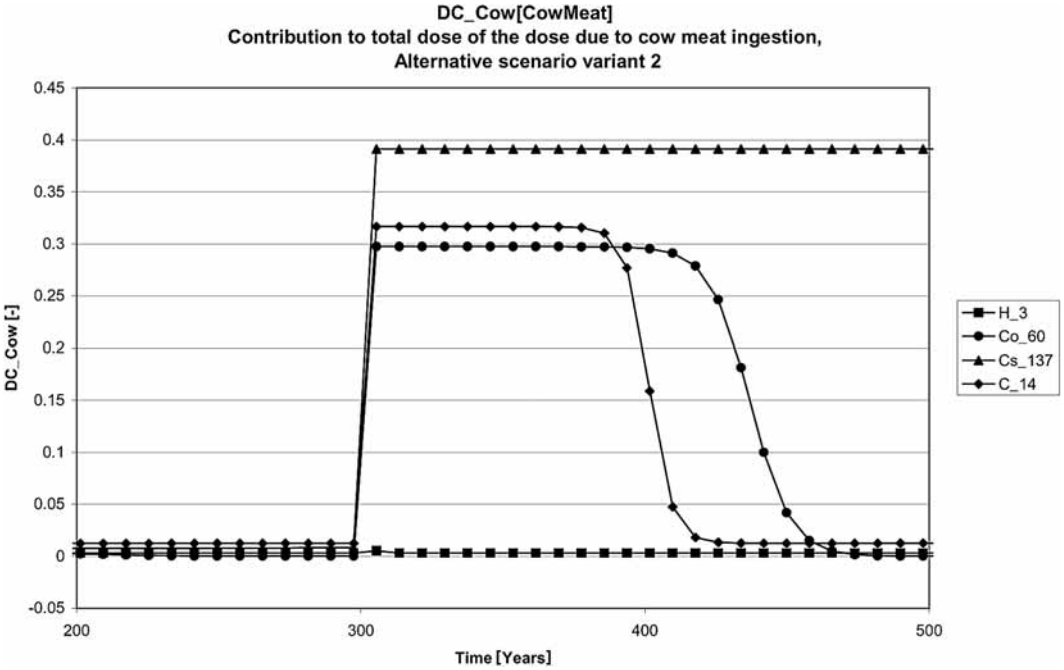

Fig. 10 – Contribution to the total dose of the dose due to meat ingestion. Alternative Scenario Variant 2. The different contribution of each radionuclide in the different time periods, before and after the disruptive event occurrence, can be emphasized. Also, the moment of disruptive event occurrence is very important for the evolution of this complementary indicator.

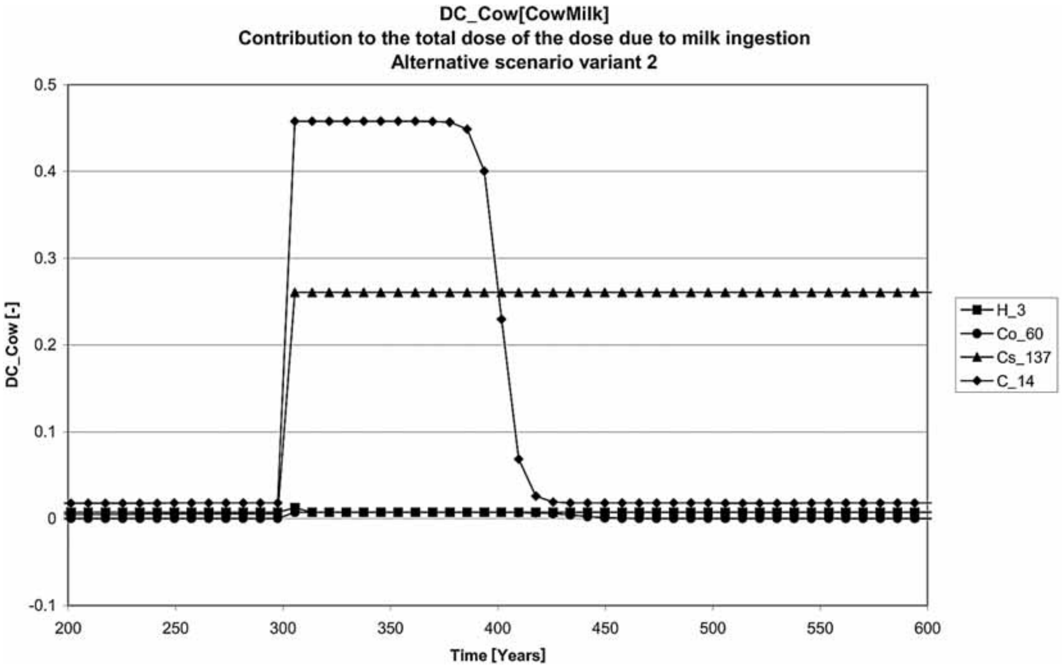

Fig. 11 – Contribution to the total dose of the dose due to milk ingestion. Alternative Scenario Variant 2. The different contribution of each radionuclide in the different time periods, before and after the disruptive event occurrence, can be emphasized. Also, the moment of disruptive event occurrence is very important for the evolution of this complementary indicator.

while after the event occurrence, the meat ingestion becomes more important. Also, the earlier peak values are due to ^{3}H, while the long term peak values are due to ^{14}C and ^{137}Cs (see also Fig. 7). The Figs. 8 and 9 emphasize also the long-term contribution of ^{14}C and ^{137}Cs and the highest values of dose due to root vegetable ingestion, after the disruptive event occurrence.

Another safety indicator evaluated in our study was "Contribution" to the total dose of each dose components. Figs. 10 and 11 present the contribution to the total dose of the doses due to meat ingestion and milk ingestion, respectively. The long-term contribution of ^{137}Cs is the most important regarding the meat ingestion pathway. These safety indicators are very important to establish the concentration limits for radionuclides, in order to avoid high dose values.

4. CONCLUSIONS

The results obtained till now (in the research work at SITON) are useful in the site licensing process for the RWFR, as well as to establish technical details regarding the disposal concept. The results allow the comparison between the calculated values for the total dose and the dose limits specified in the appropriate norms and regulations (*i.e.*, the Romanian Fundamental Norms of Radiological Safety, ICRP 81). More confidence on the assessment methodology is given by the fact that the results of our scenarios are consistent with those in the literature [16].

Application of the IAEA safety assessment methodology for the RWFR allow the alignment to the wordwide practices in this area and, at the same time, offer the certainty that all important data/information are taken into account in the analysis process. A very important step of the ISAM methodology – the feed-back step – allows the self-assessment of the evaluation process, as a whole and each step in turn.

We have also many problems to solve, to refine, to explore and to detail the conceptual and mathematical model of the RWFR, according to the new obtained site characteristics and inventory data. Also, the future research will focus on the development and evaluation of an enlarged system of safety indicators, to offer a complete view of the safety evolution of the repository.

LIST OF ABBREVIATIONS

The following definitions and symbols were used in this paper:

RWFR	–	Romanian Radioactive Waste Final Repository
SITON	–	Subsidiary of Technology and Engineering for Nuclear Projects
CNCAN	–	National Commission for Nuclear Activities Control
IAEA	–	International Atomic Energy Agency
ISAM	–	Improvement of Safety Assessment Methodologies for Near Surface Disposal Facilities
ASAM	–	Application of Safety Assessment Methodologies for Near Surface Disposal Facilities

FEP List	–	Features, Events and Processes List
D_ing	–	Dose received by human, due to ingestion pathways
D_wat	–	Dose received by human, due to water ingestion
D_crop	–	Dose received by human, due to crop ingestion
D_cow	–	Dose received by human, due to animal products ingestion (meat and milk, in our paper)
D_grain	–	Dose received by human, due to grain ingestion
D_root	–	Dose received by human, due to root vegetable ingestion
D_green	–	Dose received by human, due to green vegetable ingestion.

REFERENCES

1. Fundamental Norms for safe management of radioactive waste, NDR-01, approved by CNCAN Order no. 56 from 2004, March, 25.
2. Norms for near surface disposal of radioactive waste, NDR-05, approved by CNCAN Order no. 400/2005, and published in Official Bulletin no. 345/17.04 (2006).
3. Safety Assessment Methodologies for Near Surface Disposal Facilities – ISAM, Results of a co-ordinated research project, IAEA (2004).
4. R. H. Little, C. Torres *et al.*, Postdisposal safety assessment of toxic and radioactive waste: Development and testing of the SACO methodology and code, European Commission, Contract No. FI2W-CT90-0042, Final Report EUR 16871 EN (1996).
5. R. H. Little, K. J. Clarke *et al.*, Application of procedures and disposal criteria developed for nuclear waste packages to cases involving chemical toxicity, European Commission, Contract No. ETNU/CT93/0106, Final Report EUR 16745 EN (1996).
6. M. W. Kozak, Decision analysis for low-level radioactive waste disposal safety assessments, *Radioactive Waste Management and Environmental Restoration*, **18**, 209–223, (1994).
7. A generic List of Features, Events and Processes (FEPs) for Near Surface Radioactive Waste Disposal Facilities, DRAFT-TECDOC –XXX, IAEA, February (2004).
8. Support Study for Preliminary Safety Report of RWFR. Scenarios due to disruptive events and processes, RI-1461/14.11.2005, SITON, (2005).
9. Technical and Safety Documentation required to license the Saligny site for RWFR, Code 05.08.08, SITON (2006).
10. Water infiltration analysis in the repository, in accident conditions or due to engineered barrier degradation, ST-2126/01 SITON (1998).
11. Support Analysis for Preliminary Safety Report for RWFR. Developing and evaluation of evolution scenarios for RWFR and RWTP, RI-1039, SITON (2000).
12. Support Analysis for Preliminary Safety Report for RWFR. Evaluation of safety case using AMBER computer code, RI-1035, SITON (2000).
13. AMBER 4.4 Reference Guide, version 1.01e, 2003, Enviros Consulting Limited & Quintessa Limited, UK.
14. Safety Evaluation for Saligny site for RWFR, Contribution of SCN Pitesti, Doc. no. 6867/27.04 (2006).
15. J. Ashton, T. J. Sumerling, Biosphere Database for Assessments of Radioactive Waste Disposals. UK Department of the Environmental Report DoE/RW/88/083 (1988).
16. IAEA, Safety Assessment of Near Surface Radioactive Waste Disposal facilities: Model Inter-comparison using Simple Hypothetical Data (Test case 1), First Report of NSARS, IAEA-TECDOC-846, Vienna, (1995).
17. Safety Report for Siting a Near Surface Repository at Saligny Site, RI-1547, SITON (2007).