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DU COMBUSTIBLE NUCLÉAIRE AUX DÉCHETS : RECHERCHES ACTUELLES

FROM NUCLEAR FUELS TO WASTE: CURRENT RESEARCH

Dealing with uncertainties in the safety of geological disposal of radioactive waste

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Note presented by Édouard Brézin.

Abstract Confidence in the safety assessment of a possible project of radioactive waste geological repository will only be obtained if the development of the project is closely guided by transparent safety strategies, acknowledging uncertainties and striving for limiting their effects. This paper highlights some sources of uncertainties, external or internal to the project, which are of particular importance for safety. It suggests safety strategies adapted to the uncertainties considered. The case of a possible repository project in the Callovo-Oxfordian clay layer of the French Bure site is examined from that point of view. The German project at Gorleben and the Swedish KBS-3 project are also briefly examined. ***To cite this article: C. Devillers, C. R. Physique 3 (2002) 935–943.***

radioactive waste / geological disposal / uncertainties / safety

Traitement des incertitudes dans la sûreté du stockage géologique des déchets radioactifs

Résumé La confiance dans l'évaluation de la sûreté d'un éventuel projet de dépôt géologique de déchets radioactifs ne pourra être obtenue que si le développement du projet est étroitement guidé par des stratégies de sûreté transparentes reconnaissant les incertitudes et s'efforçant d'en limiter les effets. Cette note met l'accent sur certaines sources d'incertitudes, extérieures ou intérieures au projet, particulièrement importantes pour la sûreté. Elle suggère des stratégies de sûreté adaptées aux incertitudes en question. Le cas d'un éventuel projet de dépôt dans la couche d'argile du Callovo-Oxfordien du site français de Bure est examiné sous cet angle. Le projet allemand de Gorleben et le projet suédois KBS-3 sont aussi brièvement examinés. ***Pour citer cet article : C. Devillers, C. R. Physique 3 (2002) 935–943.***

déchets radioactifs / stockage géologique / incertitudes / sûreté

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1. The need for safety strategies against uncertainties

Depending upon a decision of the French Parliament to be made in 2006, the principle of a deep repository for the disposal of radioactive waste may be accepted. Possible locations are the Callovo-Oxfordian clay layer at Bure (Meuse), or a granite site not yet chosen.

The multi-barrier containment system of such a repository will include waste packages containing mixtures of medium and long-life radionuclides, back-filling materials and the geological barrier, that is to say, the host rock formation and surrounding rock formations, above and below. This containment system shall be designed to hinder the migration of radionuclides in such a way that a large majority of them will have decayed, including their daughters, before reaching the biosphere. The quantities of remaining radionuclides entering the biosphere shall be small enough so that the corresponding potential risks to future generations will not be higher than today's accepted radiation risks [1].

Safety shall essentially rely on provisions made in the design, and later on during the construction and operation of the repository, to satisfy these requirements, because it is not possible to rely on surveillance and corrective actions beyond a limited period after the repository closure, say a few centuries, while the time scale of interest for safety is more than 100 000 years, according to safety assessment studies.

A safety assessment shall include [2], on one hand an analysis of the quality and robustness of containment barriers according to regulatory acceptance criteria, and on the other hand, an assessment of the performance of the multi-barrier containment system, together with a check of its compliance with regulatory requirements, taking into account uncertainties.

Performance assessments are based on calculations using models. It is not required that models describe all relevant features, events and processes with the same degree of accuracy: what is required is a comprehensive review of these elements, as well as sensitivity studies to identify which ones are important for safety and call for an estimation of their uncertainties. The task of building confidence in performance assessments will then be easier if the repository design is made, using appropriate safety strategies, robust enough so that its containment performance is little sensitive to these uncertainties. Three possible lines of actions may be combined [3] in a safety strategy, to guide the development of a repository project to an optimised robustness: minimise the occurrence of uncertainties by choosing containment barriers as reliable as possible, including the choice of a site with geological, hydro-geological and geo-chemical features and behaviour easy to understand and to model; reduce dominant uncertainties in containment barrier behaviour, through research and international exchanges; and over-design containment barriers to compensate for or to guard against uncertainties.

Two sources of uncertainties will be considered: the first one, external to the project, is linked to possible energy, social, economical or regulatory policy changes; the second one, internal to the project, reflects limits of the current understanding and modelling of the behaviour of the repository itself.

In the following, examples will be given of suggested safety strategies against selected sources of uncertainties of external or internal origin, that may help building confidence in the post-closure safety of a possible repository, with a view to decision-making.

2. Safety strategies against external uncertainties

2.1. Uncertainties in waste inventory due to possible changes in the fuel cycle policy

French policy makers have made the decision to keep the nuclear energy production rate at a constant level of 400 $TWh \cdot y^{-1}$. During the next ten years, the utility, EDF, in charge of providing this service, intends to reprocess about 85% of the 1000 tons of UOX spent fuel unloaded each year. The extracted plutonium will be recycled in MOX fuel whereas the unprocessed 15% UOX spent fuel and 100% MOX spent fuel will be stored, waiting for future recycling. Reprocessing waste produced at the La Hague COGEMA plant will be stored, waiting for disposal in a possible geological repository which ANDRA would have to provide. Such a repository would have to accept both waste existing at the time of its conception and waste that might be produced later on, from several decades of nuclear energy production. Therefore, it is necessary, when designing the repository, to take into account possible policy changes concerning the fuel cycle. A prudent safety strategy should therefore consist in disconnecting as far as possible waste disposal management safety from fuel cycle policy by over-designing the repository so that it would be able to accept, throughout its operating period, any type of possible high activity radioactive product without expected use, including unprocessed UOX and MOX spent fuel that might in the future be redirected towards disposal. Direct disposal of spent fuel is, as a matter of fact, the worse case as concerns long-life radionuclide inventory: a factor 10 more actinides and a factor 100 more iodine-129 compared with reprocessed solid waste, iodine in the case of reprocessing being discharged and diluted safely into the sea [4]. Decay heat is also higher for spent fuel than it is for reprocessing waste.

2.2. Uncertainties in retrievability requirements

The principle of retrievability has been introduced at first for political reasons. Retrievability means making provisions to allow corrective actions in a repository, including the possible recovery of waste packages during a certain time after being deposited in the repository. The recovery process may be of various degrees of difficulty, from an easy reversibility along open pathways, to more complicated interventions like re-mining a sealed repository. From a safety point of view, retrievability should be considered as a possible supplement to the robustness of the repository design, not as an alternative to it. Moreover, its limits and possible drawbacks for long term safety have to be made clear. The first limit is the time during which institutions may keep the memory of the repository; this time is generally taken as no more than 500 years. The second limit is related to the feasibility of monitoring and intervention, a question that deserves attention.

It seems reasonable to allow a relatively easy retrievability during the operating time of a repository, the period during which waste is being deposited, when accidents may happen (fire, flooding, discovery of unexpected barrier defects) which would call for corrective actions. On the other hand, providing means for easy retrievability beyond that operating time is questionable from the point of view of safety. As will be discussed in Section 3, leaving access pathways open during an extended time would lead to permanent damage of the geological barrier, especially if it is made of clay materials, because of their mechanical properties and because of the influence of their water content on these properties. In addition, more time would be necessary for the repository to return to equilibrium after closure, while this transition phase may last centuries and its description is affected by large uncertainties.

For the reasons indicated above, making provisions to leave pathways open beyond the operating time to facilitate retrievability would most likely increase uncertainty in the assessment of the long term safety of a repository located in a clay formation. At the same time, monitoring the transition phase after closure, together with offering possibilities of corrective actions in the closed repository, may increase confidence in the behaviour of the containment system and will certainly facilitate public acceptance. Such a monitoring would imply the use of remote and non perturbing measurement devices.

From the above considerations, the suggested safety strategy, for a repository located in a clay formation, should favour an early back-filling of deposition cavities, galleries and shafts. On the other hand, the suggested safety strategy should also aim at reducing uncertainties, firstly in the possibility of remotely monitoring safety-relevant parameters during the transition phase after closure, and secondly in the possibility to safely re-mine the repository area for intervention purposes during the same phase.

Note that such a strategy would not allow an easy recovery of previously disposed off spent fuel, as, for example, in case of a policy change from disposal towards reprocessing. If the possibility of saving spent fuel having no immediate use were to be guaranteed, for example as a measure of precaution against energy shortage, it would be preferable to store it safely rather than putting it in a deep repository located in a clay formation.

2.3. Uncertainties in waste conditioning

Although the disposal environment is not yet precisely defined, waste continues to be produced in a form that is favourable to its safe storage, handling and transport. Progress has been made and will continue to be made in reprocessing plants to reduce the cost and the volume of waste, in particular through the incorporation of a larger fraction of radionuclides into glass matrixes. However, later adjustments of waste packages to actual disposal environmental conditions will most probably be necessary. Among the possibilities of adjustment, the encapsulation of waste in robust containers is one of the most commonly foreseen technique, as it is done for spent fuel to be disposed off. Moreover, waste to be produced and disposed off from now on will be in larger quantities than the existing waste. Therefore, the suggested safety strategy should, on one hand avoid conditioning the waste in materials which may be incompatible with the safety of deep geological disposal in clay or granite, on the other hand standardise as much as possible waste dimensions to facilitate their encapsulation into robust containers of a small number of types.

2.4. Uncertainties in radiation protection rules

The radiation protection rules referred to when checking compliance of long term potential risk estimates with regulatory requirements use safety indicators expressed in terms of individual doses or risks, in accordance with international recommendations [5]. Regulatory requirements are defined in reference [2]. In particular, an acceptance criterion of 0.3 $mSv \cdot y^{-1}$ limits individual doses to hypothetical critical groups, calculated for the most probable repository evolution scenario during the first 10 000 years. Beyond that time scale, this dose level should no longer be considered as a strict limit, but as an objective to be met. This rule results from the acknowledgement of growing uncertainties in the long-term behaviour of the containment system, the performance of which cannot therefore be studied otherwise than using simplified pessimistic models. Consequently, the acceptability of the estimated potential risk should not be judged only according to its distance from the objective, but also in accounting for the conservatism of the calculations. Moreover, the precise value of the objective, as long as it remains a small fraction of the natural background dose level has not a strong influence on the safety of a repository. It can therefore be considered as robust with respect to possible future changes in the regulation. Consequently, it should be homogenised between the interested countries in order to avoid misinterpretation. More worrying are the possible changes in the values of the dose factors (the committed effective dose per unit intake) proposed by the competent international body [6]. Significant changes have been observed in the past between successive publications of these data sets. However, information on the uncertainties about these data is lacking, a situation that does not allow a safety strategy to be defined. A demand for obtaining such information, especially for long-life radionuclides, should be forwarded to the competent bodies, as a contribution to building confidence in the safety of deep geological disposal.

3. Safety strategies against internal uncertainties

3.1. Background

The Bure site has been selected for further characterisation, by means of an underground laboratory, and for feasibility studies of a possible repository in the Callovo-Oxfordian clay layer, 130 m thick and 500 m deep. Investigations from the surface in the selected zone have shown favourable properties as concerns its permeability, hydraulic head gradient, geological stability and retention of radionuclides. Moreover, geological studies have shown the absence of valuable resources.

However, this favourable geological barrier will be perturbed due to construction works and due to the presence of the repository itself, to an extent that will depend on the precautions taken. Therefore, the assessment of the containment system performance must take into account, among others, two main sources of uncertainties affecting the description of these perturbations, which have been already mentioned above when discussing the retrievability issue. The first one corresponds to the description of the return to equilibrium transition phase following closure, which may last centuries, a period when the radioactivity of the waste is maximum. The second one corresponds to the description of the damage inflicted on the clay material properties in the vicinity of the repository, which may permanently affect the long term containment properties of the geological barrier in the near field. Each of these two sources of uncertainties deserves strong safety strategies within the development of a possible repository project in the clay layer of Bure. The case of a possible repository in granite will not be addressed below due to the lack of site specific data.

3.2. Uncertainties in the behaviour of the containment system during the return to equilibrium transition phase

After the waste packages have been deposited in the disposal cavities within the clay formation, the repository will be back-filled and sealed. Water is expected to progressively re-saturate the repository so that the clay containing engineered barriers can swell, counter-balance rock stresses and reduce voids in the geological barrier. However, this process may develop with different speeds in the different parts of the repository, depending on water availability, so that voids may be reduced in an inconsistent way and only the final equilibrium state may be amenable to modelling. At the same time, the radioactivity is maximum, especially due to caesium-137 and strontium-90, two mobile radionuclides which, if easily available from the waste packages, could be rapidly transported to the biosphere through a not yet ready containment system. The suggested safety strategy, in addition to a minimisation of the amplitude and duration of the transition phase, in particular by limiting de-saturation, should include: firstly a reduction of the uncertainties in the estimated duration of the transition phase, secondly an encapsulation, using robust containers, of waste that need to be strengthen to remain tight during the transition phase.

3.3. Uncertainties in the extent and description of permanent damages to the geological barrier

Beyond the transition phase, the uncertainties in the range and description of permanent damages to the clay material, due to the perturbations caused by the repository, will, to a large extent, determine confidence in the assessment of the long term containment performance of the geological barrier at Bure. The modelling of the effects on the clay containment properties of mining works, de-saturation, mechanical stresses, heating, oxidation, chemical interactions with foreign materials are still far from being satisfactory. Although such effects are expected to be limited to a few meters around disposal cavities, galleries and shafts, the fact that they may result in continuous weak pathways is a cause of concern when assessing long term containment performances, if one considers the total length of galleries (hundreds of kilometres) and the possible connections of disposal cavities with aquifers through such pathways.

The suggested safety strategy should therefore include several lines of action. Above all, minimise uncertainty by a prudent design and construction process limiting perturbations, and characterised by: soft mining techniques, deposition cavities of limited size, a temperature lower than 100 °C at the rock interface, limited amounts of foreign materials, and early back-filling. The second line of action should aim at reducing uncertainties in the modelling of the damages to the geological barrier as well as in the functioning of buffer, sealing or support equipment designed to limit or to compensate for the weakening of the geological barrier containment properties. This should constitute an important item for underground laboratory full scale experiments. Finally, the third line of action should consist in studying the possibilities of strengthening the less durable waste packages. Encapsulation in long-life canisters is a way of doing so; for fuel cycles including reprocessing, improvement of waste matrixes is another possible way.

However, encapsulating waste in metal canisters might, if not carefully studied, cause adverse effects in the geological barrier due to corrosion gas production and possible chemical action of iron on the containment properties of clay materials. The safety strategy should in such a case be completed by a reduction of the uncertainties in these adverse effects together with the development of corrosion resistant canister materials.

Note that strengthening waste packages as much as reasonably achievable, as illustrated by the past or ongoing development of glass matrixes and canisters, is generally considered a useful precaution against remaining uncertainties in the quantification of damages to the geological barrier caused by any event or process, including those of natural origin such as seismic activity, climate change or erosion. Specific safety strategies should be defined for each family of events or processes in a way similar to the one described above for the damages caused by the repository itself.

Of course, the safety strategies shall be adjusted to the evolution of uncertainties during the repository design process, relaxing unnecessary conservatism or strengthening insufficient one; however one should insist on the necessity of maintaining, for each safety strategy, a sufficient redundancy between the different lines of action just described.

3.4. Examples from abroad

Similar safety strategies can be identified in foreign countries repository designs, even if the respective roles assigned to the different containment barriers may differ from one project to another, for example, as between the German Gorleben project and the Swedish KBS-3 concept.

The Gorleben project assigns to the geological barrier, a salt dome, the main role in the containment system because uncertainties in its containment behaviour are considered relatively small due to its long geological history, its self-sealing properties and its low permeability. However, the risks of water flooding during the transition phase has led the designer to adopt the encapsulation of waste in steel canisters. This, in turn, emphasises the question of how to cope with corrosion gas, a question that is currently being examined.

In the KBS-3 concept [7], the main containment role is entrusted to a long-life robust copper canister. For the canister to fulfil its function, the granite formation has to maintain reducing conditions in the underground water and prevent mechanical damages to the canister in case of tectonic movement. In addition, the geological barrier shall contribute to limiting the consequences of possible initial defects in the canister's welds. In that respect, the safety strategy is based on a full scale development of reliable canister fabrication processes and on stringent quality control programs. The Swedish have also examined the questions associated with the transition phase after the repository closure, during which temporary by-passes within the containment system may exist and favour oxidising water transport towards the canisters or radionuclide migration from possible faulty canisters towards the biosphere. An acceptance procedure for individual deposition holes is currently being studied that should, at the same time, ensure a sufficient water availability for buffer material to swell in a timely fashion, and prevent excessive water flows.

4. Conclusions

In conclusion, the examples presented above show that safety strategies against different sources of uncertainties should be defined and implemented to guide the development of a possible repository towards more robustness, so that confidence in its safety will be increased with a view to decision-making.

Uncertainties external to the project, which may result from possible future changes in energy, social, economical or regulatory policies, have to be estimated and dealt with at the very beginning of the repository design process to facilitate its smooth development. In particular, the repository should be over-designed to be able to accept spent fuel, even if today the utility does not expect to direct it towards disposal. The option of allowing an easy retrievability beyond the repository operating time should not be favoured, especially for a repository located in clay. Uncertainties about the possibilities of remotely monitoring safety relevant parameters and of interventions in a closed repository during the transition phase after closure should be reduced. Future developments in waste conditioning should avoid materials that could be incompatible with the safety of a repository in clay or granite and should favour the standardisation of waste dimensions to facilitate waste encapsulation. A demand should be forwarded to the competent bodies to obtain information on the uncertainties in dose-factors data sets for long-life radionuclides.

Among other internal sources of uncertainties, those related to the perturbations caused by a repository in the host rock, especially in clay materials, should be controlled as far as possible to allow a convincing safety demonstration to be provided. Over-designing remains however a supplementary mean of building a reasonable confidence. During the transition phase after the repository closure, when the repository returns to equilibrium, uncertainties may be difficult to control, so that the encapsulation of waste in corrosion resistant canisters having a life time of a few centuries might be necessary to obtain confidence. Survival of such canisters beyond the transition phase might not be necessary if a reasonably high confidence in the containment performance of the perturbed geological barrier can be obtained. This would, however, imply imposing a number of strong constraints on the repository design, which can be summarised as follows: use soft mining techniques, limit the size of cavities, limit the temperature at the rock interface below 100 °C, reduce the amount of foreign materials, qualify at full scale the performance of seals and favour early back-filling. An alternative to the encapsulation of waste in long-life canisters would be, for reprocessing waste, the improvement of matrixes to reduce their radionuclide release rate.

On the other hand, encapsulating waste in long-life corrosion resistant canisters, might be judged a useful precaution against remaining uncertainties in the quantification of the effects on the geological barrier of the seismic activity, climate change and erosion, depending on the reduction in uncertainties that will result from corresponding research programs.

In any event, as confirmed by the French, German and Swedish cases analysis, the role of the geological barrier will remain essential for the long-term protection of waste and engineered barriers against stresses from the surface, including inadvertent intrusions, and for the mitigation of the consequences of radionuclide releases from faulty waste packages.

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Discussion

Question de J. Dercourt

La réversibilité s'impose dans l'état actuel d'étude du laboratoire en cours d'installation en France, car elle est affirmée aux autorités politiques qui ont accordé les autorisations de creusement. La prévision géologique est en croissance régulière dans les domaines à considérer (les climats à venir, la circulation des eaux, ...) ce qui justifie pour une longue durée la réversibilité. Prenez-vous en compte (dans la démarche de sûreté) que l'acceptabilité sociale des installations de stockage passe par la garantie à long terme de la réversibilité affirmée par la loi ?

Réponse de C. Devillers

Le terme réversibilité recouvre des possibilités très diverses, depuis une reprise aisée des déchets, via des voies d'accès laissées libres, jusqu'au « re-mining » d'un dépôt scellé. Ces possibilités sont ouvertes tant que la mémoire du stockage est conservée. Les exigences de réversibilité n'étant pas aujourd'hui précisées, l'analyse de sûreté étudie de façon paramétrique les avantages et les inconvénients pour la sûreté à long terme des différents degrés de réversibilité techniquement envisageables. En effet, le stockage doit in fine pouvoir être fermé dans des conditions assurant la sûreté à long terme.

Il me semble que vouloir prolonger au-delà de la période d'exploitation du dépôt des possibilités de reprise aisée des déchets, par exemple en retardant le scellement des cavités de stockage et des voies d'accès aux déchets présenterait à cet égard plus d'inconvénients que d'avantages. En particulier, pour un stockage en formation argileuse, les effets de la désaturation, de l'oxydation, de la fissuration et la présence de matériaux de soutènement supplémentaires pourraient dégrader les performances de confinement de la barrière géologique, sans bénéfice notable par ailleurs pour la sûreté à long terme, comme je l'explique dans mon texte. Par conséquent, sans autre précision sur sa signification, le terme réversibilité ne peut pas s'identifier à un principe de sûreté.

Commentaire et question de C. Thegerström

Je voulais faire une remarque et puis j'ai une question.

Ma remarque, c'est que dans le système suédois, le conteneur est bien sûr un élément majeur parmi les barrières mais c'est aller trop loin de dire que nous mettons « toute la sûreté sur le conteneur ». Les autres barrières sont aussi importantes et le système doit fonctionner d'une façon sûre même avec des conteneurs imparfaits.

Ma question : y a-t-il une limitation dans le temps pour l'obligation, en France, de faire des calculs quantitatifs de risques des stockages profonds ?

Réponse de C. Devillers

Pour des questions de temps de parole limité, j'ai simplifié, mais je suis d'accord avec votre remarque puisque la longévité du conteneur ne peut être assurée sans le rôle protecteur de la formation granitique, tant au plan du risque de corrosion par des eaux oxydantes que du risque de dommage mécanique pouvant résulter de mouvements tectoniques.

Pour ce qui concerne votre question, l'autorité de sûreté française n'a pas introduit de limitation dans le temps pour l'obligation de faire des calculs quantitatifs de risques. Cependant, elle a considéré qu'au-delà de 10 000 ans, les critères de limitation de dose pourraient être utilisés non plus comme des limites absolues mais comme des valeurs d'objectifs.

Commentaire G. de Marsily

Il me semble que la prévision du comportement à long terme d'un stockage est, du point de vue de la géologie, beaucoup moins incertaine que pour les autres composantes plus artificielles (c'est-à-dire construites par l'homme) du stockage.

Les géologues sont en effet capables de reconstruire avec beaucoup de finesse des histoires géologiques sur des durées de millions d'années, et peuvent donc s'avancer à proposer des prévisions sur 10 000, 100 000 ou 1 million d'années, certes avec des incertitudes, mais sans outrepasser les bornes de leur discipline.

En revanche, les comportements dégradés des stockages du fait d'interventions humaines futures, imprévues et délétères (forages par exemple) est bien plus aléatoire. C'est d'ailleurs ce que montrent de nombreuses analyses de sûreté déjà réalisées à ce jour (WIPP, Yucca Mountain, Suède, etc.).

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Réponse de C. Devillers

Il est vrai que la prévision du comportement d'une formation géologique vierge est relativement fiable jusqu'aux périodes de temps éloignées que vous mentionnez, encore que les effets des changements climatiques ou des mouvements tectoniques soient sources d'incertitudes. Mais on ne peut en dire autant d'une formation géologique contenant un stockage, qui aura toujours un comportement dégradé du fait des interactions entre les ouvrages et le milieu géologique, et de leurs conséquences possibles sur les performances de confinement de la barrière géologique. Cette question se pose en particulier pour les formations argileuses et fait intervenir des processus difficiles à modéliser. Comme je l'évoque dans mon texte, les incertitudes correspondantes pourraient conduire à surdimensionner les conteneurs de déchets, notamment pour passer la phase délicate du retour à l'équilibre du stockage.