Regulatory Issues for Final Disposal

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Abstract

The working committee NA 062-07-045 AA ("Criticality Safety") of the German Institute of Standardization DIN ("Deutsches Institut für Normung") is just working out a criticality safety standard for final disposal of nuclear fuel. The concept of the draft of the standard is described in the paper on hand. This concept is based on a risk-informed approach for both the criticality safety analysis of the pre-closure phase and the criticality safety analysis of the post-closure phase of a repository. Rationales for this approach are given and the related criticality safety acceptance criteria are presented.

1 Introduction

The fundamental principle in criticality safety is the Single Failure Criterion (SFC) which lays down that a single failure such as a component failure, a function control failure, a human error or an accidental event during the handling, processing or storage of nuclear fuel must not result in a criticality event.

The SFC is valid for all fuel management systems outside reactor cores. The design and operation features and characteristics of these systems shall observe the SFC.

Compliance with the single failure criterion is often achieved by applying the double-contingency principle. By virtue of this principle, a criticality event cannot occur unless at least two unlikely, independent and concurrent events (failures, errors, incidents or accidents) occur, resulting in changes of those system characteristics and conditions which are essential to criticality safety. Two events are regarded as concurrent when the second event falls into the time period required to detect the first event and to remove the consequences of the first event.

Even though applied very often, the double-contingency principle is only one method to achieve compliance with the SFC, which is the basic principle.

Non-compliance with the SFC is not totally forbidden in Germany but has to observe the following requirements: As laid down in the German criticality safety standard DIN 25403-1 (cf. Ref. [1]), in case of non-compliance with the SFC, the probability of occurrence and the consequences of a criticality event shall be determined, and it shall be demonstrated that even in case of non-compliance with the SFC a criticality event is "not credible" with respect to its probability of occurrence and its radiological risk.

Even though not laid down in Ref. [1], it is accepted in Germany that an event can be regarded as "not credible" if its probability of occurrence is not greater than 10^{-6}, cf. Ref. [2]. So, compliance with the SFC has to be demonstrated for events with a probability of occurrence that is greater than and not equal to 10^{-6}. Note that this figure shall be understood as a probability of occurrence, not as a frequency of occurrence.

Compliance with the SFC is achieved by applying safety measures which shall observe the following hierarchy [1]:

- Passive measures
- Active engineering measures automatically initiated
- Active engineering measures manually brought into action
- Administrative measures

The reliability and performance of applied safety measures has to be ensured by a safety management system which establishes controls and checks of parameters essential for ensuring criticality safety.

2 Criticality safety acceptance criterion for final disposal of fissile materials

However generally valid the definition of the SFC is, the SFC only applies to the operation of fuel management systems (outside reactor cores). With the final closure of a repository the operational phase of the repository ends, i.e. operational activities do not take place anymore. Accordingly, operational failures cannot occur anymore. The occurrence of failures of design features and characteristics cannot be excluded since the safety management ends with the final closure of the repository, so that the reliability and performance of safety measures cannot be ensured anymore.

Since the operation and the safety management end and since the repository is thus at the mercy of the development of the geological and climatic conditions in the region of the repository's site, the SFC does not apply to the post-closure phase of the repository. Because geological and climatic conditions are uncontrollable and since future political and social developments are unpredictable, events impacting the repository in the post-closure phase can only be characterized as scenarios, i.e. as situations, which are hypothetically possible in future, or as hypothetically possible and consistent sequences of future events resulting in these situations. A scenario is, by definition, not a prediction. Criticality safety assessment of the development of the repository in the post-closure phase therefore has to estimate the probability of occurrence and the consequences of a criticality event due to those scenarios which result in increases of the neutron multiplication factor of the fuel units deposited in the repository.

So, non-applicability of the SFC and non-compliance with the SFC lead to the same requirement, namely to the necessity of considering the probability of occurrence and the consequences of a criticality event. The criticality safety acceptance criterion for the post-closure phase therefore has to be a decision criterion on whether the probability of criticality under the conditions of a given scenario is acceptable or not, i.e. whether the occurrence of a criticality event caused by this scenario is incredible or not.

As follows from section 1, in the operational (pre-closure) phase of a repository a criticality event is regarded as “not credible” if its probability of occurrence is not greater than 10^{-6}. So, at the time of closure each of the isolated fuel units or configurations deposited in the repository must meet the inequality

$$P_{crit} \leq 10^{-6}, \tag{2.1}$$

where P_{crit} denotes the probability of criticality. Therefore, to guarantee the consistency of the criticality safety acceptance criteria for the pre-closure and the post-closure phase of the repository and to thus ensure a consistent transition from the pre-closure phase into the post-closure phase, it is necessary to formulate both the criticality safety acceptance criterion for the pre-closure phase and the criticality safety acceptance criterion for the post-closure phase as a unified decision criterion on whether the probability of criticality is acceptable or not.

The probability of criticality related to an event or a scenario S is given by eq. (2.2),

$$P_{crit} = P(k_{eff}(\vec{x}, \vec{\xi}) \geq (1 - \delta k_M) \mid S) \cdot P(S). \tag{2.2}$$

P(S) in this equation denotes the probability of occurrence of the event/scenario S. $P(k_{eff}(\vec{x}, \vec{\xi}) \geq (1 - \delta k_M) \mid S)$ is the conditional probability of $k_{eff}(\vec{x}, \vec{\xi}) \geq (1 - \delta k_M)$, i.e. the probability that the neutron multiplication factor $k_{eff}(\vec{x}, \vec{\xi})$ is greater than or equal to $(1 - \delta k_M)$ under the condition that the event/scenario S is given, i.e. has occurred. $\vec{x}$ is the vector of parameters describing the material compositions, dimensions and arrangements of an isolated fuel unit/configuration under the given event/scenario S; and $\vec{\xi}$ denotes the involved nuclear data.

δk_M in eq. (2.2) denotes the administrative safety margin which can be chosen as follows:

- $\delta k_M = 0$ if the uncertainties in the nuclear data $\vec{\xi}$ are considered by means of the method described in section 8.2. of Ref. [3], continuous cross-section data are used, and the covariance matrix $cov(\vec{\xi})$ of the involved nuclear data does not include any preliminary data and is fully approved. As long as these conditions are not met, it is recommended to choose
- $\delta k_M = 0.01$, provided that $cov(\vec{\xi})$ is considered by an approved procedure applying the method described in section 8.2 of Ref. [3] or by an approved procedure using a first-order perturbation evaluation with respect to the consideration of $cov(\vec{\xi})$ (cf., for instance, section 8.3 of Ref. [3]) or to choose
- $\delta k_M = 0.02$ if uncertainties in $\vec{\xi}$ are not explicitly considered.

The δk_M values proposed are different from administrative safety margins classically chosen. This is due to the fact that δk_M refers to a criticality safety acceptance criterion

$$P_{crit} = P(k_{eff}(\vec{x},\vec{\xi}) \geq (1-\delta k_M) \mid S) \cdot P(S) \leq L \tag{2.3}$$

which applies maximum allowable probabilities L that are significantly smaller than the probabilities related to criticality safety acceptance criteria classically used. Classically a safety margin of $\Delta k_M = 0.05$ is usually used in combination with the requirement that the upper 95%/95% tolerance limit of the evaluated neutron multiplication factor does not exceed the limit $(1-\Delta k_M)$. This means that the probability that k_{eff} exceeds $(1-\Delta k_M)$ can amount to up to 0.05 with a probability of 0.95. The limit L in expression (2.3) is significantly smaller than 0.05. According to inequality (2.1), L amounts to 10^{-6} for the pre-closure phase of the repository.

In contrast to classical criticality safety analysis, however, this limit takes account of the probability P(S) of the event/scenario S which leads to that configuration for which a criticality safety assessment has to be performed. It is obvious that P(S) is usually equal to 1, (P(S) = 1, for the normal operation conditions in the pre-closure phase of the repository. But for abnormal and accidental events in the pre-closure phase, P(S) is less than 1, and the probabilities of scenarios S related to the post-closure phase of the repository can also be assumed to be less than 1, at least in most of the cases.

Estimation of the probability P(S) in cases P(S) < 1 requires application of the methods of Probabilistic Safety Analysis (PSA). The results of PSA studies of abnormal or accidental pre-closure phase events as well as the outcomes of PSA studies of post-closure phase scenarios are usually based on models characterizing the conditions under study as realistically as possible, rather than the conservative models typically used in classical criticality safety analysis. In fact, for the post-closure phase scenarios in particular it is usually required to reduce the analysis conservatism as far as possible, otherwise one is very quickly faced with the problem to miss compliance with the acceptance criterion eq. (2.3). For instance, it is well known that the use of burnup credit in the criticality safety analysis of final disposal of spent fuel is a necessity for any viable disposal scheme. However, it has to be considered that the use of the actinide-plus-fission-product burnup credit level, for instance, makes it necessary to study post-closure phase events which result in a separation of actinides and fission products due to the very different geochemical properties of actinides and fission products.

2.1 Criticality safety acceptance criterion for the pre-closure phase

As already stated above, the limit L amounts to 10^{-6} for the pre-closure, i.e., operational phase of the repository. The criticality safety acceptance criterion for the pre-closure phase is thus given by inequality (2.4)

$$P_{crit} = P(k_{eff}(\vec{x},\vec{\xi}) \geq (1-\delta k_M) \mid S) \cdot P(S) \leq L_{op} = 10^{-6}. \tag{2.4}$$

For normal operation conditions, i.e. for P(S) = 1, expression (2.4) reduces to

$$P(k_{eff}(\vec{x},\vec{\xi}) \geq (1-\delta k_M) \mid S) \leq L_{op} = 10^{-6}. \tag{2.5}$$

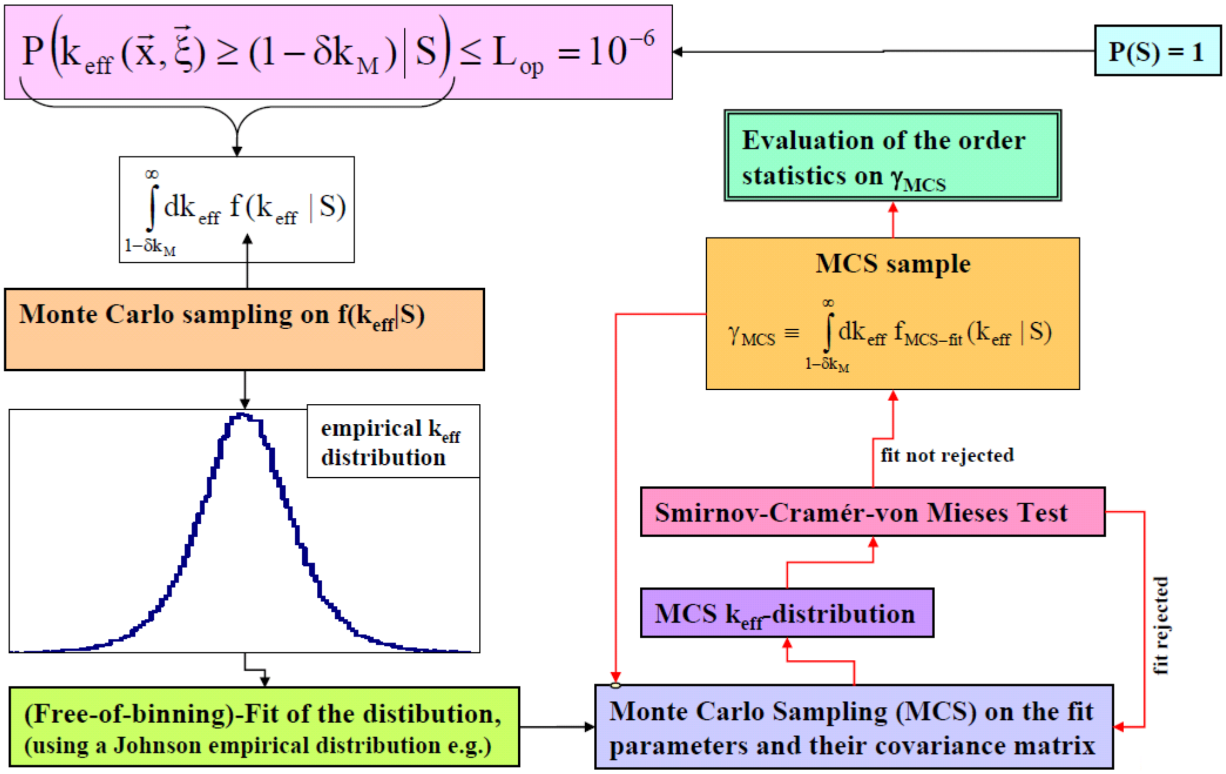

Figure 1: *Illustration of the solution of the integration problem eq. (2.7), cf. Ref. [3]*

Estimation of the probability P(S) is obviously required for those abnormal or accidental events S only, which do not meet inequality (2.5). One may, of course, base the analysis of abnormal and accidental events on the conservative assumption P(S) = 1 as it is done in classical criticality safety analysis. One is then forced, however, to demonstrate that inequality (2.5) is met.

The solution of the integration problem

$$P(k_{eff}(\vec{x},\vec{\xi}) \ge (1-\delta k_M) \mid S) = \int_{1-\delta k_M}^{\infty} dk_{eff}\, f(k_{eff} \mid S) \qquad (2.6)$$

has already been described in detail in sections 1 and 9 of Ref. [3]. Since inequality (2.5) requires the demonstration that the inequality

$$\int_{1-\delta k_M}^{\infty} dk_{eff}\, f(k_{eff} \mid S) \le 10^{-6} \qquad (2.7)$$

is met, the integration problem eq. (2.7) has to be solved by means of the procedure described in section 9 of Ref. [3]. This procedure is illustrated in Figure 1. As indicated, it consists of the steps:

- Monte Carlo sampling (MCS) on $f(k_{eff} \mid S)$ taking account of all uncertainties in k_{eff} as described in detail in Ref. [3]

- Free-of-binning-fit of the resulting empirical distribution $f_{\mathrm{fit}}(k_{\mathrm{eff}} \mid S)$
- MCS on the fit parameters and their covariance matrix and Smirnov-Cramér-von Mieses test (cf. Ref. [4]) of the resulting distribution $f_{\mathrm{MCS-fit}}(k_{\mathrm{eff}} \mid S)$
- Calculation of the value γ_{MCS} of the integral (2.6) for $f_{\mathrm{MCS-fit}}(k_{\mathrm{eff}} \mid S)$
- If a sufficient number of samples γ_{MCS} is achieved, evaluation of the order statistics of the γ_{MCS} values by means of the procedure described in section 1.2 of Ref. [3].

2.2 Criticality safety acceptance criterion for the post-closure phase

For the post-closure phase inequality (2.3) is written as follows:

$$P_{\mathrm{crit}} = P(k_{\mathrm{eff}}(\vec{x},\vec{\xi}) \geq (1-\delta k_M) \mid S) \cdot P(S) \leq L_{\mathrm{clos}}(t - t_{\mathrm{clos}}) \qquad (2.8)$$

where t_{clos} denotes the time of closure of the repository.

The elaboration of scenarios for the post-closure phase of a repository has to be based on estimations of hypothetically possible future developments of the geological and climatic conditions in the region of the repository's site, in particular of those conditions which determine the hydrogeological conditions at the repository's site and which may result in the intrusion of water into fuel units deposited in the repository. Figure 2 gives a rough overview of the tectonic processes and climatic conditions determining the geomorphology at the repository's site. This overview gives an indication of how complex the elaboration of post-closure phase scenarios is; and the complexity probably increases in the course of time after closure. More detailed overviews of the tectonic processes end climatic conditions including representations of the effects of tectonic processes on the climatic conditions as well as representations of the interactions between geomorphological and climatic conditions and interactions between geomorphological conditions and tectonic processes will be given in the DIN criticality safety standard for final disposal of nuclear fuel which is currently in development by the working committee NA 062-07-045 AA ("Criticality Safety") of the German Institute of Standardization DIN ("Deutsches Institut für Normung").

Once a post-closure phase scenario S is given, there is no problem to estimate the conditional probability $P(k_{\mathrm{eff}}(\vec{x},\vec{\xi}) \geq (1-\delta k_M) \mid S)$, but due to the complexity with which one is confronted in formulating scenarios, there is a problem in estimating the probability P(S) of the scenario S. For some cases, P(S) may virtually become 1 in the course of time after closure of the repository. A candidate for such a case is, for instance, the scenario that the repository is breached during exploratory drilling for prospecting because the knowledge of the location of the repository is lost, which will certainly be the case after a glacial epoch, for instance. But in other cases the uncertainty in determining the probability P(S) increases with increasing time $(t - t_{\mathrm{clos}})$ and it cannot be excluded that there may finally be a scenario-specific time t_S, such that it will not be possible to give a reasonable estimate of P(S) for $t > t_S$.

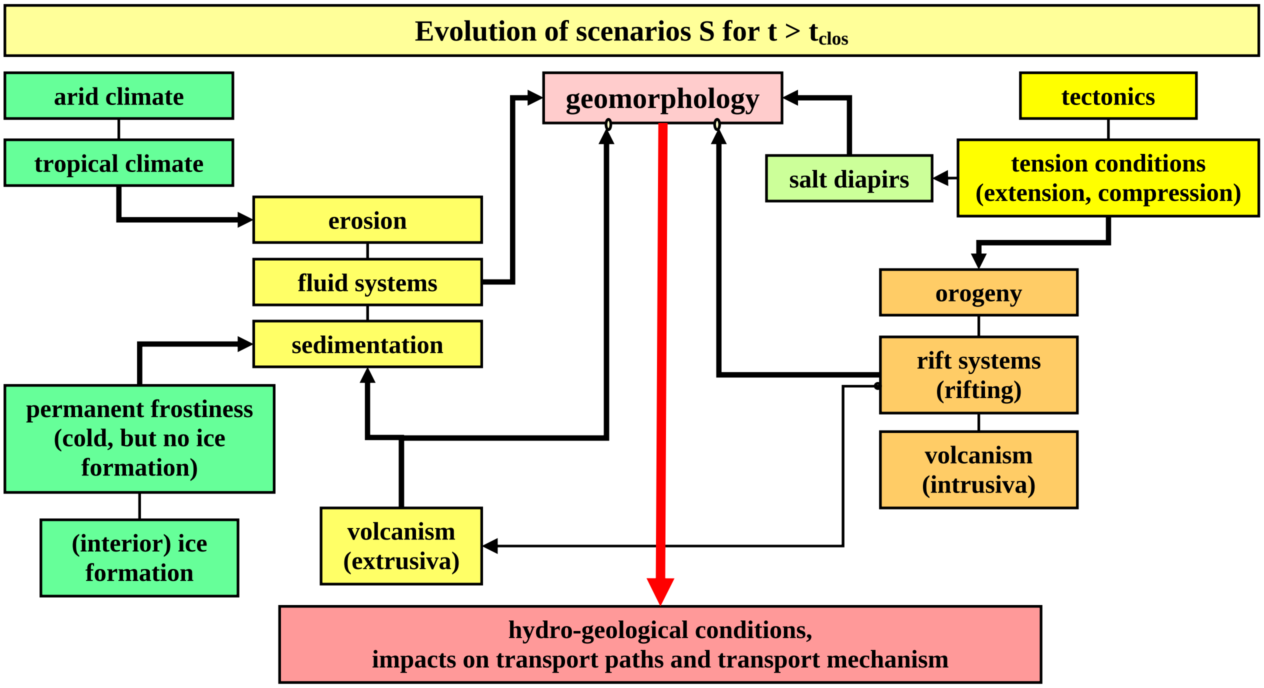

Figure 2: *Rough overview of the tectonic processes and climatic conditions determining the geomorphology at the repository's site*

Therefore, in order to avoid compensation for the increasing uncertainty in P(S) by implementing measures such as the use of smaller storage capacities of the fuel units (which increases the frequency of fuel handling processes and transports) or measures for decreasing the fissile content (which requires plants for processing the spent fuel and which leads to an increase in the total mass that has to be stored in the repository), the maximum allowable probability of criticality $L_{clos}(t-t_{clos})$ is chosen as follows:

$$L_{clos}(t-t_{clos}) = \begin{cases} 1-(1-L_0)\cdot e^{-\varphi_S\cdot(t-t_{clos})},\ t_{clos} \le t \le t_S \\ 10^{-4}, t > t_S \end{cases} \tag{2.9}$$

with

$$L_0 \equiv L_{clos}(0) = L_{op} = 10^{-6} \tag{2.10}$$

and φ_S chosen such that

$$L_{clos}(t_S - t_{clos}) = 10^{-4} \tag{2.11}$$

which leads to

$$\varphi_S = -\frac{1}{t_S - t_{clos}}\cdot\left(\frac{1-10^{-4}}{1-10^{-6}}\right). \tag{2.12}$$

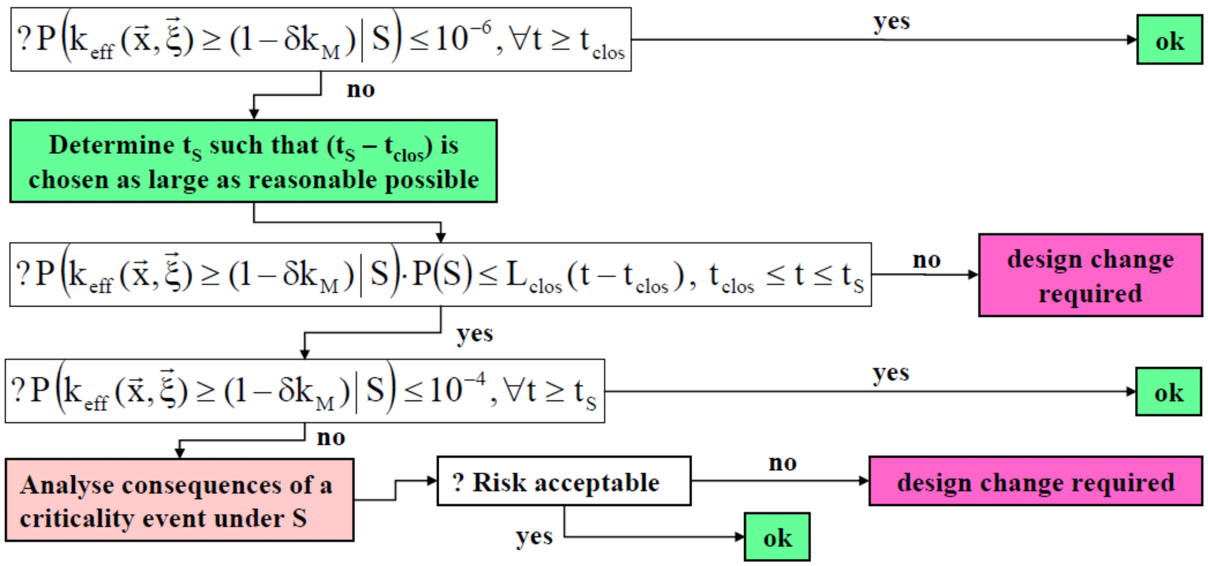

Figure 3: *Post-closure phase safety criteria for t ≤ t_S and t > t_S*

The limit of 10^{-4} is chosen for all $t \geq t_S$ because an event which has a probability of occurrence of $P > 10^{-4}$ is usually regarded as “credible”.

So therefore, as illustrated in Figure 3, the following steps have to be taken in the criticality safety analysis of post-closure phase scenarios:

- For a given scenario S the conditional probability of criticality under S, $\gamma_S = P(k_{eff}(\vec{x},\vec{\xi}) \geq (1-\delta k_M) \,|\, S)$, is calculated. If $\gamma_S \leq 10^{-6}$ for all times $t \geq t_{clos}$, no further analysis is required for the scenario S, i.e. criticality safety is ensured for this scenario for $t \geq t_{clos}$.
- If $\gamma_S \leq 10^{-6}$ is not met for all $t \geq t_{clos}$, one has to determine t_S such that $(t_S - t_{clos})$ becomes as large as reasonably possible.
- It has to be checked then if the criterion eq. (2.8) together with eq. (2.9) is met for $t_{clos} \leq t \leq t_S$. If this is not the case, the design features and characteristics are regarded as not adequate for ensuring criticality safety in the scenario-specific time period $[t_{clos}, t_S]$ and have to be modified, therefore.
- If the criterion eq. (2.8) together with eq. (2.9) is met for the time period $[t_{clos}, t_S]$, it has to be checked if this criterion together with eq. (2.9) is also met for all $t > t_S$. If this is the case, no further analysis is required, i.e. criticality safety is ensured for the scenario S.
- If the criterion eq. (2.8) together with eq. (2.9) is not met for all $t > t_S$, the occurrence of a criticality event has to be postulated since an event with a probability of occurrence greater than 10^{-4} is regarded as a credible event. If the radiological risk related to the worst conse-

quences of the postulated criticality event is acceptable, it is ensured that the design features and characteristics guarantee safety against criticality. Otherwise, design modifications are required.

A central question in the safety analysis of a repository is the length of time over which the various scenarios have to be analyzed with respect to ensuring safety against criticality. It is observed that there are tendencies to define a time period of conformance and to restrict this period to 10 000 years after closure, or 1 000 000 years after closure, etc. However, because of physics, a time period of conformance cannot be prescribed but has to be derived from

- the nuclide inventories of the fuel units deposited in the repository,
- the changes in these inventories due to radioactive decay and
- the changes in these inventories caused by long-term changes in the geological, geohydrological and geochemical conditions at the repository site.

So, the required time of conformance depends on the fuel units, i.e. may vary from fuel unit to fuel unit.

3 Some remarks on the use of burnup credit

It has already been mentioned that the use of burnup credit for disposal of spent fuel is considered to be a necessity for any viable disposal scheme. The objective of a burnup credit criticality safety analysis usually is to generate a loading criterion, named as “loading curve”, which the fuel has to meet to be acceptable for loading in the storage casks to be used for disposal.

A loading curve is based on a reactivity equivalence condition which is usually defined as follows: P(S) in inequality (2.3) is set to 1, P(S) = 1. Under a given event/scenario S and based on the given isotopic composition of the fuel, that burnup of the fuel is determined which leads to the equality

$$k_{eff}(\vec{x},\vec{\xi})_{\gamma} = 1 - \delta k_M \text{ under the condition that } \gamma = P(k_{eff}(\vec{x},\vec{\xi})_{\gamma} = (1-\delta k_M) \mid S) = L. \qquad (3.1)$$

As appears from the preceding sections, the maximum allowable probability L depends on the time t_{LC} for which the reactivity equivalence condition (3.1) and hence the loading curve (LC) is generated. In addition, the reactivity equivalence condition on which the loading curve is based is bounded to the event/scenario S used to determine the loading curve, since this event/scenario determines the reactivity equivalence condition [5]. In other words, the reactivity equivalence condition does only hold for $t = t_{LC}$. Therefore, it has to be demonstrated that a loading curve meets the criticality safety requirements at all times t different from t_{LC}, taking into consideration the following issues:

- Change of the isotopic content and its spatial distribution due to the radioactive decay.

- Change of the isotopic content and its spatial distribution due to the impacts of the events and scenarios to be studied.

However, it is obvious that these issues have also to be taken into account (at least to some extent) if no burnup credit is taken.

References

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