RETRENKING REGULATIONS FOR DISPOSAL CRITICALITY

ABSTRACT

This paper provides the basis for the position that the current U.S. Nuclear Regulatory Commission (NRC) criticality regulation is in need of revision to address problems in implementing it for the postclosure period in a geologic high-level waste repository. The authors believe that the applicant for such a facility should be able to demonstrate that postulated postclosure criticality events will not cause unacceptable risk of deleterious effects on public health and safety. In addition, the applicant should be expected to take practical and feasible measures to reduce the probability of a criticality occurring, even if (as expected) the consequences of such a criticality for repository performance and public health and safety would be negligible. This approach, while recognizing the probabilistic nature of analyses of events and conditions in the distant future, is also arguably consistent with the defense in depth concept that has been successfully applied to nuclear reactor regulation. The authors believe regulations for postclosure criticality control should support this dual approach, rather than require a deterministic prohibition of criticality as does the current rule. The existing rule seems appropriate for the preclosure period, as long as it is clearly specified to apply only to that period.

I. INTRODUCTION

The purpose of this paper is to discuss uncertainties with regard to application of the NRC rule for criticality in a geologic repository [10 CFR Part 60.131(h)] and to suggest how the uncertainties could be resolved.

NRC rules for control of criticality events during storage and transportation of fissile nuclear waste have been used and interpreted extensively in the nuclear industry. These rules are deterministic in nature and prohibit criticality absent two unlikely, independent, and sequential or concurrent changes occur in conditions essential for a criticality. The rules require that the margin to criticality be maintained at a value that accounts for uncertainties and reflects an additional administrative margin to ensure criticality does not occur.

The same type of regulation applied to storage and transportation is also contained in 10 CFR Part 60, the regulations applicable to a geologic repository in the United States. An established interpretation of application of this type of regulation to the postclosure period of regulatory concern for disposal of high-level waste does not exist. This situation is not unexpected, no disposal facility having yet sought a license under Part 60. But there are likely to be problems with the rule’s application, and the lack of interpretations has led to uncertainty and concerns about how to interpret and comply with the rule.

One reason for concern is that the rule is worded in a manner that could be interpreted to require a deterministic demonstration of compliance. Licensing precedent to date with NRC regulations has generally been consistent with deterministic compliance demonstration. However, uncertainties inherent in the
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long period applicable to waste disposal are likely to make a deterministic prohibition of criticality (or many other events or conditions) infeasible. Just as it is very difficult to state with complete assurance how the configuration of an object or material will change as it degrades over time, it is very difficult to support, in a licensing arena, the statement that a repository containing significant amounts of fissile material will never experience a criticality condition. It is certainly feasible to place a probability on such an event and to require that repository and waste package design make that probability low during the extremely long period of postclosure containment and isolation (thousands of years). And it is also feasible to analyze the risk (probability times consequence) of potential criticality events and thereby to determine the magnitude of the threat they pose to the health and safety of the public. A reasonable argument may be made that compliance with the existing disposal criticality rule can be demonstrated using a probabilistic risk-based argument, but such an interpretation has not to date been advanced to or accepted by the NRC.

Another issue with the deterministic criticality regulation as applied to disposal criticality is the "double contingency criterion" that requires two unlikely, independent events for criticality to occur. If criticality is addressed through risk-based analysis, the double contingency criterion becomes arguably superfluous. Probabilities and consequences of all postulated changes in conditions that contribute significantly to risk can be predicted using this approach, regardless of whether two or more changes are dependent or independent. The risk-based approach does not include, for reasons previously discussed, absolute prohibition of postclosure criticality events, so a criterion prohibiting such an event absent two changes in conditions would be inappropriate in conjunction with a probabilistic rule.

A third aspect of the incompatibility of the current criticality rule with disposal criticality analysis concerns the five percent $k_{eff}$ administrative margin to criticality. If analysis of the risk of criticality begins with an assumed critical configuration that would in fact be five percent subcritical or more, the result of this analysis would be unrealistic. Where a deterministic result is sought (e.g., criticality shall not occur), adding a margin to make up for possible inadequacies in the characterization of calculational biases and uncertainties makes sense to add confidence in the calculated result. However, a risk-based approach uses probabilities (calculated in a manner that accounts for biases and uncertainties) of an undesirable event and consequences of the event. Typically, a probabilistic analysis does not employ an arbitrary, additional conservatism to the end result. Instead, the probabilistic approach is intended to incorporate conservatisms into the probability distributions used for risk assessment, commensurate with the levels of uncertainty in the various aspects of the analysis models. This approach avoids consequence analyses based on fictitious configurations (i.e., consequences of criticality in a subcritical system).

Fortunately, the limitations of deterministic regulation of the postclosure disposal period are fairly widely recognized. The National Academy of Sciences (NAS), in its 1995 report on Yucca Mountain standards, recommended that postclosure repository performance standards be risk-based. That is, the standard should be that the risk to the health and safety of the public posed by a potential repository is acceptable to society. In the case of radioactive waste, that risk is posed by the potential exposure of members of the public to ionizing radiation. The appropriate result of analyses to demonstrate compliance with risk-based regulations is the overall risk posed by the repository, defined by the NAS as the expected value of a probabilistic distribution of health effects. Risks posed by potential criticalities are considered along with risks posed by other potential events and conditions, as contributors to the overall risk. The Department of Energy's Yucca Mountain Site Characterization Project is pursuing this performance-based approach on the grounds that it is the most appropriate and most practical method of ensuring the health and safety of the public are protected against the probability and consequence of a potential criticality in a disposal facility after closure.
To address the problems discussed above, this paper advocates that either: (1) criticality control regulations applicable to long-term disposal of high-level radioactive waste be revised to be explicitly compatible with the risk-based approach that is appropriate for analysis of risks posed by a nuclear waste repository, or (2) an interpretation of the existing rule that clearly allows risk-based demonstration of compliance be made by the NRC. The Department of Energy has recommended to the NRC a change to a risk-based criticality rule\(^3\), and the NRC has replied that they recognize the need to deal with “uncertainty” with respect to the application of the existing criticality rule to the postclosure time period.\(^4\)

II. BACKGROUND: CRITICALITY REGULATIONS FOR HIGH-LEVEL WASTE

The NRC has established a set of criticality regulations pertinent to the storage, transportation, and disposal of high-level waste. The 10 CFR Part 72 regulation for storage reads as follows:

"Design for criticality safety. Spent fuel handling, packaging, transfer, and storage systems must be designed to be maintained subcritical and to ensure that, before a nuclear criticality accident is possible, at least two unlikely, independent, and concurrent or sequential changes have occurred in the conditions essential to nuclear criticality safety. The design of handling, packaging, transfer, and storage systems must include margins of safety for the nuclear criticality parameters that are commensurate with the uncertainties in the data and methods used in calculations and demonstrate safety for the handling, packaging, transfer and storage conditions and in the nature of the immediate environment under accident conditions."\(^5\)

Numerous independent spent fuel storage installations (ISFSI) have been licensed under Part 72. Deterministic criticality analysis, supported as appropriate by probabilistic analyses, can be used to demonstrate compliance with these regulations for the licensing period (typically 20 years for an ISFSI). Such analyses are not extraordinarily difficult or complex by nuclear industry standards, and there is a large body of experience for guidance in how they can be performed.

In developing 10 CFR Part 60 (regulations for disposal of high-level waste), the NRC used a similar wording to that in Part 72. The current criticality regulation in 10 CFR Part 60 reads as follows

"Criticality control. All systems for processing, transporting, handling, storage, retrieval, emplacement, and isolation of radioactive waste shall be designed to ensure that nuclear criticality is not possible unless at least two unlikely, independent, and concurrent or sequential changes have occurred in the conditions essential to nuclear criticality safety. Each system must be designed for criticality safety assuming occurrence of design basis events. The calculated effective multiplication factor \(k_{\text{eff}}\) must be sufficiently below unity to show at least a 5 percent margin, after allowance for the bias in the method of calculation and the uncertainty in the experiments used to validate the method of calculation."\(^6\)

This rule reads very similarly to the one in Part 72. Although the Part 60 (disposal) rule specifies an administrative safety margin of 5% to be applied to \(k_{\text{eff}}\) while the Part 72 (storage) rule requires unspecified "margins of safety," precedence has set the margin at 5% for Part 72 licenses. Both rules incorporate the so-called "double contingency criterion," which states that a criticality shall not be possible unless two or more unlikely, independent, and concurrent or sequential changes have occurred. A common thought process in the development of the two rules is very evident.

The authors of this paper believe that these, deterministically worded regulations, which are clearly compatible with criticality analysis for facilities subject to a 20- to 40-year license term, are incompatible with
postclosure disposal (repository) criticality analysis. The incompatibilities, which concern the deterministic wording of the regulation applicable to the repository, the double contingency criterion, and the administrative safety margin, are discussed in turn below.

III. DETERMINISTIC VS PROBABILISTIC ANALYSIS

The disposal criticality regulation is deterministically worded. For example, it states: “All systems... shall be designed to ensure that a nuclear criticality accident is not possible...” This wording could reasonably be interpreted to forbid criticality (absent two unlikely conditions), though another reasonable interpretation is that criticality must be incredible (of so low a likelihood as to be not worthy of further concern). The problem with this deterministic wording is that it implies a level of certainty must be obtained. Depending on the period of regulatory concern for disposal (currently unspecified but assumed to be 10,000 years or more), there may be significant uncertainties as to the conditions in a repository and the waste packages emplaced therein. The NFX has recognized this in 10 CFR Part 60.101:

“While these performance objectives and criteria are generally stated in unqualified terms, it is not expected that complete assurance that they will be met can be presented. A reasonable assurance, on the basis of the record before the Commission, that the objectives and criteria will be met is the general standard that is required. For § 60.112, and other portions of this subpart that impose objectives and criteria for repository performance over long times into the future, there will inevitably be greater uncertainties. Proof of the future performance of engineered barrier systems and the geologic setting over time periods of many hundreds or many thousands of years is not to be had in the ordinary sense of the word. For such long-term objectives and criteria, what is required is reasonable assurance, making allowance for the time period, hazards, and uncertainties involved, that the outcome will be in conformance with those objectives and criteria.”

Licensing experience and the above-referenced text lead the authors to believe the NRC would likely be inclined to accept a demonstration that postclosure criticality events are possible, though not credible. However, two questions should be asked:

1. Is it necessary and appropriate that a license application for a high-level waste repository demonstrate that any criticality event in the postclosure period be incredible, even if the consequences for repository performance and public health and safety of such a criticality would be minimal?

2. What are the implications for geologic disposal of fissile material if the answer to the first question is affirmative?

To answer the questions in reverse order: The authors believe it is possible that a repository can be constructed to allow demonstration that any and all criticality events in the postclosure period are extremely unlikely. Would they be incredible? If a probability figure can be identified and agreed upon as the threshold for credibility over the period of regulatory concern, it may be possible to design a repository and waste package (i.e., engineered barrier system) to achieve that figure. Depending on the figure chosen (which would likely be the subject of debate in a licensing arena), the repository might need to be substantially expanded and/or the waste packages designed to have smaller capacities, such that concentration of enough fissile material to support criticality would become highly unlikely (incredible). In the worst case, the capacity of a proposed repository might be reduced enough to require eventual development of a larger number of repositories to accommodate the entire high-level waste inventory, a result that would have substantial financial, political, and environmental consequences. A probability threshold for postclosure criticality has not been
established, and a determination of how much expansion would be necessary in a given repository environment (e.g., Yucca Mountain) has not been performed. However, the authors consider it likely that a repository designed to make postclosure criticality incredible would be very large, with small, widely spaced waste packages. Possible emplacement of more highly enriched spent fuels such as some DOE-owned spent fuel types would tend to further spread out the waste packages if criticality is to remain incredible. The cost to the nation of such an approach would likely be substantially larger than the projected cost of the current repository design concept, which includes relatively large waste packages spaced relatively close together. There might also be repository performance implications of a larger repository. For example, the current concept is intended to use waste decay heat to drive moisture away from the vicinity of the waste packages and thereby maintain them dry for a substantial period of time. Waste package corrosion would be expected to be much slower in a dry environment than in a moist one. This “dry, hot” repository design approach would not be feasible in a repository with widely spaced, small waste packages.

Given that the repository could possibly be designed to make criticality events incredible by a reasonable standard, albeit at a potentially significant resource expenditure and at possible cost for overall repository performance, should the repository be designed to support a demonstration that criticality is incredible? From an objective, scientific standpoint, the authors believe the answer is no. The postclosure period is fundamentally different from the preclosure period in the repository and from any facility dealing with use, storage, or transportation of nuclear fuel in that the waste is hundreds of meters underground and virtually inaccessible. Therefore, exposure of human beings to high direct radiation levels, airborne radioactive contamination, or energy release near a criticality event in the postclosure underground repository is not possible unless a truly catastrophic event occurs that would involve major disruption of the hundreds of feet of rock overlaying the waste. The authors believe such a disruption can be demonstrated to be highly unlikely, and its probability and consequence can be addressed using risk-based analysis. Furthermore, consequences of such an event not related to criticality would be expected to overshadow any criticality-related consequences.

Ultimately, what should matter is whether repository performance meets requirements levied on that performance and whether there is reasonable assurance that the health and safety of the public are protected against any and all adverse consequences of disposal of the high-level waste. A postclosure criticality would cause, for some period of time, an incremental increase in the radionuclide inventory inside the repository area. Such an increase would not by itself threaten public health and safety. The extent to which the increased inventory would affect the release of radioactive materials from the repository is and should be of concern. It is the consequence of the criticality and not its potential existence that should be the focus of concern. Probabilities and consequences of postulated postclosure scenarios (such as the recently postulated “autocatalytic criticalities” that could theoretically involve a significant energy release) will need to be addressed. Assessing the risk (probability times consequence) of a scenario will allow it to be captured in the overall risk posed by the repository as a result of all postulated processes, conditions, and events (of which criticality is involved in only a small fraction). Very preliminary assessments of the consequences of postclosure criticality indicate that the consequences of one or even several criticality events would be negligible. For example, a very conservative analysis predicted that a criticality in the waste package filled with the most reactive two percent of the expected commercial spent nuclear fuel might have a maximum power of two kilowatts and an expected maximum duration of 10,000 years. If the criticality started 15,000 years after emplacement (the approximate time after closure when the spent nuclear fuel will be the most reactive), the increase in inventory of radioisotopes of interest to repository performance assessment (measured in curies and with respect to the same waste package at the same time without the criticality) would be only 24%. Most of that increase would be due to
relatively short lived isotopes, which would decay within the next 10,000 years, so that by 20,000 years following criticality shutdown (45,000 years after emplacement) the increment in radioactivity would be reduced to 10 percent, and by 40,000 years after criticality shutdown the increment would be reduced to 8.5 percent. Therefore, the impact of a criticality on the overall repository radionuclide inventory would be exceedingly small.

The above discussion summarizes a sound approach to addressing postclosure repository safety issues. Use of a probabilistic or risk-based approach allows incorporation of the ever-increasing level of uncertainty with increasing time after closure into the analysis, and it focuses on what is really important - the “bottom line” risk of unacceptable exposure of the public to doses of ionizing radiation.

The authors recognize that the objective argument stated above will not likely sway all parties to a repository licensing proceeding and that unplanned criticality as a phenomenon is likely to be of concern to some members of the public. In addition, the applicant will, appropriately, be expected to demonstrate “defense in depth” in the repository design. This concept, which seeks to have multiple barriers to undesirable events, has been the NRC’s philosophy in licensing of reactors; it is also evident in the existing disposal criticality rule. The authors believe defense in depth is appropriate for criticality and other postclosure issues to compensate for the uncertainty inherent in predictions of repository performance. The issue is in how to provide defense in depth in a probabilistic context. One way to help address this issue is, in addition to demonstrating that the risk of criticalities is very small (performance-based analysis), to demonstrate that feasible steps have been taken to minimize the likelihood of criticalities, even if their consequences are negligible. Determination of what is feasible could be based on a similar thought process to the “As Low as Reasonably Achievable” (ALARA) concept that has been widely used and accepted in the nuclear industry for addressing radiation exposure issues. As applied to criticalities, the concept might include a tradeoff such as, “The applicant will expend a certain amount of resources (to be determined) to reduce the likelihood of a criticality event in the repository by a factor of ten.” The logic process for this effort might consist of determining the scenarios that would contribute most to the overall probability of a criticality event, and then developing cost-effective design measures to substantially reduce the likelihood of those scenarios. Ultimately, the measures to be taken would be based on the value placed by society on driving down the likelihood of an event probably not of major importance to public health and safety. The repository license applicant could propose a number, and that number’s acceptability would be determined in a repository licensing proceeding if NRC guidance on the subject has not been promulgated.

IV. DOUBLE CONTINGENCY CRITERION

As previously explained, the current repository criticality rule requires that criticality be impossible unless two unlikely and independent changes in conditions essential to criticality safety have occurred. This requirement is consistent with the “multiple barriers” or “defense in depth” philosophy imposed in NRC regulations and guidance for many different facility types. However, the risk-based approach planned for use in postclosure criticality analysis will comprehensively address features, events, and processes that pose the potential for criticality, with focus on the risk of criticality rather than on prohibiting its occurrence. In this type of analysis, prohibition of an unwanted event (criticality) is out of place. Therefore, prohibition of criticality unless two events occur is also incompatible with a risk-based approach.

An adaptation of this criterion to a probabilistic analysis environment could possibly be made. However, as previously pointed out, defense in depth can be provided by expecting the applicant to drive down the probability of a criticality event to the lowest practical level. Again, the definition of “practical” could be proposed by the applicant based on an ALARA-like standard, and accepted by the NRC. This is admittedly a “soft” requirement at this point in time. But repository postclosure issues are new and very
challenging; they involve tradeoffs of projected risks against the practicality of reducing those risks in a meaningful and significant manner. Rather than attempting to arbitrarily set a standard that might be inappropriate for any geologic repository, it would seem preferable for the applicant for a repository to show what the risks and tradeoffs are. If the risk to the health and safety of the public is very small and considered acceptable in a licensing proceeding, and if the applicant has demonstrated a good faith effort to drive the (likely very small) risks as low as can be reasonably expected, the intent of the regulations would seem to be met.

V. ADMINISTRATIVE MARGIN TO CRITICALITY

As stated in the introduction to this paper, the issue regarding the administrative margin is whether such a margin should be applied to criticality analysis to provide additional confidence that, even beyond the uncertainties and biases in the analysis, the results of the analysis will be conservative. The existing disposal criticality rule, 10 CFR 60.131(h), states that $k_{\text{eff}}$ must be sufficiently below unity to show at least a 5% margin, after allowance for bias in the method of calculation and the uncertainty in the experiments used to validate the method of calculation.

A reactivity or $k_{\text{eff}}$ margin is not particularly meaningful in a probabilistic analysis, because such an analysis is intended to calculate the probability and consequence of a criticality event, rather than to demonstrate deterministically that the event will not occur or is incredible. The justification for an engineering margin is usually that it allows for any unknown factors/effects in the performance or reliability of a designed component or system. The margin is most appropriate when there is no quantitative assessment of the probability of occurrence of the failure event or its consequences (i.e., for deterministic preclosure analyses). In contrast, a comprehensive probabilistic evaluation will include consideration of all known factors/effects and estimation of their probabilities.

The margin in the current rule exists to provide additional conservatism. As stated earlier in this paper, the risk-based method incorporates conservatism in the probability distributions used for risk assessment. In addition, this paper has argued that the combination of the risk-based, "bottom-line" analysis and the additional measures to further reduce the probability of criticality provide defense in depth. Therefore, the additional margin is arguably not necessary. Should still more conservatism ultimately be determined necessary, however, it can be provided through some type of administrative margin compatible with the probabilistic nature of the compliance demonstration. For purposes of estimating the number or frequency of postclosure criticality events and determining resulting source terms, the authors believe that the analysis should be based on "best estimate" physics, $k_{\text{eff}}$ of 1, less bias and uncertainty, and should not include the 5% margin. This method incorporates conservatism (through biases and uncertainties) without forcing consequence analysis based on an unrealistically conservative condition. The method would ensure the design is conservative for criticality control, while eliminating from performance assessment calculations an arbitrary distortion of the already conservative physics.

VI. PRECLOSURE CRITICALITY

The assertions of this paper are in no way intended to apply to preclosure criticality in a geologic repository. There is no problem with using a deterministic criticality analysis approach for preclosure analyses, since the time frame is short (on the order of 100 years), conditions in the repository are controllable and verifiable, and there is much experience in this type of calculation for spent fuel storage. Very importantly, the repository will be occupied by workers in the preclosure period, and deterministic prohibition of credible criticality events is clearly mandatory.

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2. Ibid., p. 65.


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