CONSIDERATIONS FOR NEGLECTING WATER LEAKAGE IN THE CRITICALITY ANALYSIS OF INDIVIDUAL PACKAGES

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SUMMARY

Current transport regulations specify that the criticality analysis of an individual package shall assume that water can leak into or out of all void spaces in the package, including those within the containment system. However, if the packaging design incorporates special features to prevent such leakage, these regulations permit the absence of water to be assumed.

This paper describes the special features listed in the regulations, discusses differences between subcriticality and other regulatory performance requirements, and presents additional considerations that should be addressed to justify that water leakage may be neglected in the criticality analysis of individual packages.

The assumption of no water leakage should be considered as an exception that is appropriate only in those instances in which its benefits clearly outweigh the additional risk. Justification of this assumption will generally necessitate an increase in design margin and a substantial effort in package evaluation, operating procedures, acceptance testing, maintenance, and quality assurance programs.

INTRODUCTION

Regulations for the Safe Transport of Radioactive Material (No. ST-1) address three general radiological performance requirements for an individual Type B fissile material package under accident conditions of transport:

- Containment—restrict the loss of radioactive contents in a period of one week to not more than 10 A_2 for krypton-85 and not more than A_2 for all other radionuclides
- Shielding—retain sufficient shielding to ensure that the radiation level at 1 m from the surface of the package does not exceed 10 mSv/h
- Subcriticality—remain subcritical when reflected by at least 20 cm of water, with package conditions that result in the maximum neutron multiplication consistent with the tests for both normal and accident conditions of transport.

These regulations further specify that the criticality analysis of an individual package shall assume that water can leak into or out of all void spaces in the package, including those within the containment system. However, if the packaging design incorporates special features to prevent such leakage of water, even as the result of human error, absence of leakage may be assumed. Special features are defined to include:

- Multiple high standard water barriers, each of which would remain watertight under the accident-condition tests

- A high degree of quality control in the manufacture, maintenance, and repair of packagings

- Tests that demonstrate the closure of each package before shipment.

Additional examples of special features are provided for uranium-hexafluoride packages, which are not addressed in this paper.

CONSEQUENCES OF CRITICALITY

The consequences of not satisfying the requirements for subcriticality differ significantly from those for containment and shielding. Subcriticality is an "either-or" condition—the package (or shipment) is either subcritical or it is not. A multiplication factor of 0.95 results in no criticality consequences; a multiplication factor of 1.05 has potentially severe consequences. In addition to possible direct radiation exposure to members of the public and response personnel, an accidental criticality may also compromise package integrity and release radioactive material in excess of the containment limits described above. Even if the health consequences of a particular accident are minor, the complicated recovery effort and the adverse publicity of such an accident would no doubt be significant.

For containment or shielding, however, the difference between just meeting or just exceeding the regulatory limits is small, and, in fact, the uncertainty in measuring this difference under accident conditions could exceed the difference itself. For example, considerable attention has focused recently in the United States on the accidental release of ^{238}Pu from radioisotope thermoelectric generators. The A_2 value for this isotope of plutonium is 2×10^{-4} TBq, or approximately 0.3 mg. Consequently, the mass difference between a release of 0.95 A_2 and 1.05 A_2 is only 3×10^{-5} g.

Because subcriticality differs from other radiological requirements, the absence of water leakage should not be assumed without a thorough evaluation of the basis and the risk/benefit of such an assumption. In addition to the special features listed above, several other considerations should be addressed in justifying that water leakage may be neglected. For convenience of discussion, these considerations can be grouped according to: (1) thoroughness of the testing or analysis to demonstrate that water leakage does not occur, (2) comparison of test specimens with actual packages, (3) common-mode failure of multiple barriers, (4) human error, (5) margin of safety, (6) allowed leakage rate and closure verification, (7) leakage conditions necessary for criticality, and (8) risk/benefit of neglecting water leakage. Although these considerations could also be applicable to containment and shielding analysis, the "either-or" nature of criticality significantly their importance in the evaluation of water leakage.

THOROUGHNESS OF TESTING OR ANALYSIS

The testing or analysis should clearly identify and evaluate the scenario most likely to result in water leakage during normal and accident conditions of transport, including the initial test conditions, the package orientations for drop/crush and puncture tests, the package orientation for fire test, and the water conditions and package orientation for the water immersion tests. The evaluation of water leakage must be based on the cumulative effect of all tests, rather than most damaging effect of any single test. For example, for drum packagings with a ring-secured lid, the most damaging orientation for the drop/crush test may actually hinder the removal of the lid during the puncture test and hence lessen the subsequent damage to the packaging containment seals during the fire test.

Because of the large number of different package conditions that must be considered, an absolute determination of most unfavorable sequence of these conditions may be difficult to identify with certainty. The number of test packages available or the complexity of the required analysis generally limits the number of variations that can be examined in detail, and considerable judgment on the part of the evaluator is often necessary. An inappropriate choice of test conditions or package orientations may result in an invalid conclusion regarding the possibility of water leakage.

COMPARISON OF TEST SPECIMENS WITH ACTUAL PACKAGES

If packages are evaluated by test, the evaluation should demonstrate that the test specimens are no better in performance than any actual package that will be fabricated. Verification that the material properties and fabrication processes of the test packages met only the minimum specifications of the approved design is difficult, if not impractical, for most packages.

Regardless of whether the packages are evaluated by test or analysis, the evaluation should also justify that all packagings will be fabricated, tested, inspected, and maintained to ensure that their performance at any time during their service life will be in accordance with the design specifications. This will generally necessitate that all components related to criticality control (e.g., support and containment structures) comply with a nuclear-grade structural code, such as Section III of the American Society of Mechanical Engineers Boiler and Pressure Vessel Code (ASME Code). Other criticality-control components (e.g., neutron poisons) may not be adequately addressed by codes or standards, and detailed specifications for their design, fabrication, testing, inspection, and maintenance may need to be separately developed, justified, and implemented.

COMMON-MODE FAILURE OF MULTIPLE BARRIERS

The transport regulations specify that special design features such as multiple barriers may be considered in the assumption to neglect water leakage. In addition to the general effectiveness of these barriers, the evaluation should address in detail the possibility of common-mode failures that could result in the loss of multiple barriers by a single accident effect.

For example, because national regulations (10 CFR Part 71) require double containment for certain plutonium contents, packages for U.S. shipment of plutonium often consist of an inner and outer containment system, surrounded by an insulating and impact-absorbing material enclosed by a metal drum. Loss of the drum lid during the regulatory drop tests, a degraded performance of the insulating material, and perhaps other single events could result in failure of the seals of both containment systems during the regulatory fire test.

HUMAN ERROR

Although the regulations include quality assurance as a special feature, they do not address quality assurance in the loading of packages, except for tests to demonstrate closure. Many other loading operations are subject to human error, and quality assurance requirements for these operations may need to be more stringent if water leakage is neglected. Examples of loading operations in which an error could significantly affect the assumption of no water leakage include weighing the mass of the fissile contents, measuring the moisture content, limiting the presence of plastic bags or other moderating materials, venting of gases to reduce pressure stresses, selection of proper seals, and positioning of the contents, spacers, or poisons.

Actual package loading errors have been detected after the packages were opened at their destination, even though existing quality assurance programs should have discovered these errors prior to shipment. Other errors have no doubt remained undetected because the package did not experience accident conditions. Although these errors have generally been of minor safety importance, an assumption of no water leakage introduces a risk in which human errors could be very significant.

MARGIN OF SAFETY

The accident conditions of transport represent regulatory conditions, not the absolute upper bound of all conditions that might be encountered during transportation. One probabilistic analysis (Fischer et al.) has estimated that approximately 0.6% of transportation accidents could exceed the regulatory conditions. For example, a 1991 accident involving the shipment of unirradiated reactor fuel assemblies in the United States resulted in a fire that significantly exceeded the regulatory 30-minute duration because no attempt was made to extinguish the fire (Carlson and Fischer).

The possibility of very severe accidents, in addition to the uncertainties in the evaluation and potential human errors discussed above, necessitate a very large margin of safety if the package design relies on no water leakage to maintain subcriticality.

ALLOWABLE LEAKAGE RATE AND CLOSURE VERIFICATION

Packages are designed to ensure that the allowable leakage rate satisfies the containment requirements during both normal and accident conditions of transport. The regulations and standards (ANSI N14.5) further specify that each package be tested prior to first use, periodically during service life, and before each shipment to ensure that satisfactory performance is achieved. Depending on the specific contents intended for a package, however, the allowable leakage rate may be comparable to that which would allow leakage of water. If leakage of water is neglected, the design leakage rate may need to be more stringent than that based on containment considerations only, and more comprehensive testing may be necessary to verify package closure.

The design leakage rate of a package is typically specified and measured in standard cubic centimeters of air (or helium) leaking from the containment system to the environment. Relating this gas leakage rate to a water leakage rate raises several issues. First, the water leakage rate can depend significantly on surface-tension effects, which depend on the cleanliness of the water. Converting a gas leakage rate to a water leakage with surface-tension effects results in uncertainties. Second, the leakage of water is into the package, opposite in direction to that demonstrated for containment. Considerable justification and demonstration may be necessary to account for this difference in the direction of flow.

LEAKAGE CONDITIONS NECESSARY FOR CRITICALITY

A criticality analysis based on no water leakage should demonstrate the sensitivity of the analysis to this assumption. This sensitivity may include the amount of water leakage needed to achieve criticality, the accuracy needed for determination of the initial moisture content, the configuration of the contents, and the presence/absence of product cans, spacers, plastic wrapping, or other material in the containment system. Depending on the design, a small amount of water leakage or a minor human error in packaging loading could significantly affect the results of the criticality analysis. In these cases a substantial effort to ensure proper loading and closure of the package could significantly increase the complexity of package operating procedures.

Although this paper deals primarily with the criticality analysis of an individual package, the regulations also require that arrays of packages be demonstrated to be subcritical. Consequently, the criticality analysis should also address the sensitivity of the package arrays to water leakage. Although an individual package might be subcritical even with water leakage, the interaction of a leaking package with adjacent packages, even those that do not leak, may result in different conclusions on the sensitivity of the package to water leakage.

RISK/BENEFIT OF NEGLECTING WATER LEAKAGE

Reliance on the packaging to prevent water leakage is clearly not a conservative assumption and introduces additional risk into the shipment of such packages. In many situations the concern about water leakage for an individual package can be completely eliminated by the choice of a geometry design (e.g., diameter or volume of the containment system) or other package restrictions (e.g., limitation on void space) without incurring a significant penalty or cost for the shipment.

U.S. regulations state that the approving authority "*may* approve exceptions to the requirements" to assume water leakage. This wording emphasizes that neglecting water leakage is an exception to the regulations, and it does not provide unconditional approval of this assumption even if the package incorporates special features and can be shown not to leak. Each case should be considered on its own merits, including any additional restrictions that might be placed on a shipment to reduce the risk of water leakage. Consequently, even if the approval for a particular shipment is based on the absence of leakage, this assumption might not be appropriate for the use of the package in general.

As an aside, the concern for neglecting water leakage may not be limited to the transport of the material. Storage requirements may also be significantly increased in order to alleviate a criticality concern. These requirements may include the need to repackage the material or the necessity to maintain moderation control in the storage facility before and after transport. Both of these procedures can be very costly to implement, and in the case of moderation control, introduce a long-term operational requirement that is undesirable if alternative solutions are practical.

CONCLUSION

The consequences of not maintaining subcriticality can be significantly different from those of not meeting the other regulatory requirements for the radiological performance of a package. The assumption of no water leakage in the criticality analysis of an individual package necessitates a thorough evaluation of the basis, risk, and benefit of such an assumption.

Neglecting water leakage should be considered as an exception that is appropriate only in those instances in which its benefits clearly outweigh the additional risk. Justification of this assumption will generally necessitate an increase in design margin and a substantial effort in package evaluation, operating procedures, acceptance testing, maintenance, and quality assurance programs.

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