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CAN WE CONSIDER THAT WATER IS COMPLETELY ABSENT FOR THE CRITICALITY ANALYSIS FOR PACKAGES EQUIPPED WITH MULTIPLE HIGH STANDARD WATER BARRIERS?

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ABSTRACT

Applicants have to justify the criticality safety of packages loaded with fresh or spent fuel in the conditions of the 9 m drop test where there are high uncertainties about the integrity of fuel geometry.

Due to the lack of knowledge about the behaviour of the fuel elements, the sub-criticality of the single package filled with water was hardly impossible to demonstrate. Therefore, French applicants considered special features in the package design that allow the exclusion of water penetration: in many cases (such as for commercial PWR UO2 fuel) large reactivity margins exist when the quantity of water is limited even if the integrity of fuel assemblies is lost after the tests.

Until 2001, the transitional application of the 1985 edition of the IAEA transport regulations allowed the qualification of a unique watertight barrier in the package; but from then new designs had to integrate two watertight barriers that have to prevent water penetration even as a result of error.

An interpretation of the first part of this requirement is presented in terms of mechanical resistance and water-tightness. Leakage tests performed after simulation of drop tests usually confirm that water penetration would not exceed a fraction of a litre. This quantity has to be added to residual water in the cavity after fuel loading. Then, for different types of commercial nuclear fuel, the increase of reactivity due to the presence of limited quantities of water is given.

A complementary approach consists in analysing implications of operational errors during draining and drying the package cavities. Impact on reactivity of the presence of water in unlimited or limited quantities as a result of the chosen combinations of operational errors with normal and accident conditions of transport (in both cases of the isolated package and packages in arrays) is given.
The implications on the special measures to be taken during package preparation before shipment are presented. These measures aim at guaranteeing full draining and drying of package cavity and compliance of each barrier with leakage test criteria with due account for human factors and materials redundancy.

INTRODUCTION

Since the publication of the 1996 Edition of the IAEA transport regulations, when criticality analysis is performed with the assumption of absence of water, only multiple watertight barriers are accepted for the special features that must be included in the package design. The previous option of other special features subject to multilateral approval has been removed. The unique remaining option is beneficial for the harmonization of the level of safety between different countries. However, divergences in application are possible; for instance, what level of independency is to be provided by the barriers and how should we classify human errors between those that need not be prevented thanks to the design quality and those that should be prevented during operations and with which level of confidence?

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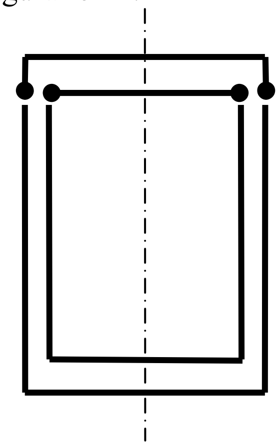
In France, the option of package design with special features has been used for more than ten years, with multilateral approval according to the 1985 edition of the IAEA regulation, for packages equipped with one barrier. Many of the fuel package designs use it. It has become necessary when it was noted that the fuel integrity could not be justified either in normal or in accident conditions of transport. Past tests and recent studies aiming at a better knowledge of fuel behaviour in accident conditions have confirmed that fuels are subject to rod deformation, sliding or rupture and assembly deformation and array pitch modification [ref. 1]. The earlier assumption that the geometry of the LWR fuel elements was not altered even in accident conditions had been found ungrounded and the systematic use of the assessment experience feedback made this issue applicable to most of the spent and fresh fuel package designs [ref. 2, 3].

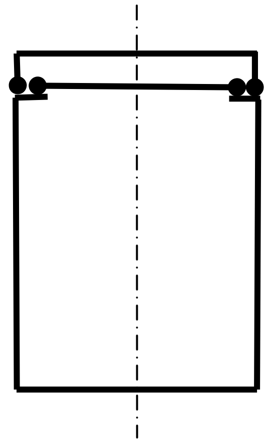
Informal consultations took place in 2004 between Competent Authorities of Germany, UK and France, following an operator request to better define the design and operational requirements associated to such designs. Some general principles were then agreed but more detailed requirements were not prepared. In this communication, the interpretation by IRSN of these principles is detailed.

REQUIREMENTS APPLICABLE TO BARRIER COMPONENTS

The first issue of multiple high standard water barriers is the level of independency of the components of each barrier. Can two barriers go through the same component? It is tempting to design a package as a one-shell and one-bottom container with two separate lids and to present each barrier as made of the shell, the bottom and one of the lids, as shown in Configuration 2.



Configuration 1: two independent barriers



Configuration 2: single shell, single bottom, double lid

The applicable criteria which are embedded in the regulation are: the barriers should be multiple; each should be of high quality in manufacturing, maintenance and repair and should be designed to remain watertight in accident conditions; in operation water tightness is not strictly required for each barrier but only for their assembly even as a result of [one] error. It should be noted that the requirement in para. 677a to demonstrate the closure of the package before shipment (to avoid water ingress or outlet) cannot be considered identical to the tests required in para. 502e which address the containment of radioactive materials. Consequently the requirements directly mean that:

- each barrier must be designed to sustain accident conditions
- each barrier must be manufactured and maintained to remain watertight, with high quality control
- the package should be tested before shipment to be watertight as a whole
- one error must not affect the water tightness of all the barriers in the same time.

Then it could be imagined that a single-shell package is acceptable since one error (for instance a large scratch or corrosion defect on gasket seat, impairing water tightness) would be detected during the leakage tests if these tests are performed before shipment at appropriate sensitivity. However this is subject to interpretation since a scratch or corrosion defect large enough to affect both barriers can be envisaged and could be considered as not consistent with the requirement that one error must not affect all barriers in the same time. In addition a single error in design (for instance when performing drop tests or concerning brittle fracture analysis), which affects the shell, would raise doubts on the capacity of the package to remain leaktight.
In that respect, IRSN recommends that *configuration 2 with a locally unique barrier should not be taken as a possible design for multiple barriers at least when the existence of comfortable safety margins has not been confirmed.*

IMPACT OF THE DOUBLE CONTINGENCY PRINCIPLE ON SITUATIONS TO BE ASSESSED

The “double contingency” principle is currently used in criticality safety for nuclear facilities: safety should be maintained in the defined operating conditions should one error occur. This principle the application of which results in redundant safety systems is quite similar to the requirement of para. 677 for design of packages loaded with fissile materials. It is understood that a double error which would not have been detected in time would have a sufficiently low probability that do not warrant taking it into consideration. It is now proposed to apply this deduction to package design in considering the different situations of transport, combined or not with human error.

The rationale is based on rough estimates of the range of magnitude of the probability of occurrence of the different situations taken individually or combined.

First, since the requirements of para. 677 refer to high standard of quality, we consider that the probability ($P_{(E)}$) of single errors that may affect water tightness of barriers should be very low. We can also note that this probability should be as low as reasonably achievable; this is an indirect application of the ALARA principle. Let us note:

$P_{(E)} = p$

Then we consider that the situations which are simulated and enveloped by the tests for normal conditions of transport have a probability ($P_{(N)}$) in the same range as the probability of single error.

$P_{(N)} = p$

And we estimate that the situations which are simulated and enveloped by the tests for accident conditions of transport have a probability ($P_{(A)}$), much lower than the probability of single error or normal conditions of transport. Let us assume that $P_{(A)}$ is in the range of magnitude of p^2

For the combined situations it implies that the probability of:

- error combined with normal conditions is $P_{(E+N)} = P_{(E)} \, . \, P_{(N)} = p^2$, which is in the same range as the probability of occurrence of accident conditions of transport; this situation should therefore be considered;
- error combined with accident conditions is $P_{(E+A)} = P_{(E)} \, . \, P_{(A)} = p^3$, which is much less than the probability of occurrence of accident conditions of transport; then it is proposed not to consider this situation for the package design.

On the basis of these considerations we estimate that in addition to normal and accident conditions of transport, *situations where normal conditions of transport are combined with a single error are to be considered in the criticality-safety analysis of the package design. But accident conditions would not need to be associated with an operating error leading to water presence in significant quantity.* Indeed the associated extremely low probability might warrant this situation as a beyond design situation.

TYPICAL ERRORS FOR PREPARATION OF LWR OR MTR FUEL PACKAGES

Paragraph 677 is the only place in the IAEA transport regulation, where human error is mentioned: "if the design incorporates special features to prevent such leakage of water into or out of certain void spaces, **even as a result of error**, absence of leakage may be assumed in respect of those void spaces." This statement raises two issues: what kind of error should be considered and are *multiple barriers with a high degree of quality control in the manufacture, maintenance, and repair of packagings and test to demonstrate the closure of each package before each shipment* sufficient to avoid presence of water in the package cavity for any single error?

Such errors should be either those leading to the failure of barrier watertightness in the different transport conditions, or those leading to the inadvertent presence of water in the cavity. While the former may be solved by multiple barriers, subject to actual independence of barriers, the latter are not.

Following examples of such errors and similar ones have been collected from the French transport incident record data base. The collected events concern the effective closure of the package, the leaktightness, the drying process and the pressure adjustment process.

<u>Incident 1</u> –June 2000: consignee notes a low tightening torque of the lid bolts of a spent fuel cask. No full explanation provided. Actions were taken to improve quality of process and equipment used for bolt torquing.
<u>Incident 2</u> - April 2004: consignee notes a low tightening torque of some of the lid bolts of a spent fuel cask.
<u>Incident 3</u> – March 2003: consignee notes that cavity of a spent fuel cask is at ambient pressure instead of approx. 500 mbar abs. However bolt torques were satisfactory. Further investigation revealed that the cavity pressure adjustment loop was connected to the package cavity through a valve that remained closed.
<u>Incident 4</u> –July 2005: consignee notes a pressure of 800 mbar abs. in cavity of a fresh MOX fuel cask instead of approx. 500 mbar abs. No satisfactory explanation was produced. It was suspected that an orifice plug was not correctly installed by remote operation.
<u>Incident 5</u> – October 2005: during the preparation of a packaging before shipment of spent fuel, the operator is slightly contaminated by release of water when opening the lower orifice; the origin of the water is an incomplete draining of a can remaining in the cavity after the preceding shipment.
<u>Incident 6</u> – January 2006: the consignee discovers 30 kg of water in a package approved for the transport of a few spent MOX fuel pins in dry condition.
After investigation, it was concluded to a double error linked to the use of a new procedure and a new loop; first, the draining of the internal bottle had not been performed completely due to the inappropriate draining procedure and second, the check of the drying of the cavity was impaired by an inappropriate equipment.

These examples confirm that the error probability is significant; furthermore, configurations with multiple barriers and a high degree of quality control in manufacturing, maintenance and closure cannot prevent, alone, the presence of some quantity of water inside a presumed dry cavity. For packages loaded under water, the operations of assembling any closure component, bolt torquing, leaktightness testing, draining, drying and drying testing all could lead - when improperly performed - to inadvertent presence of water and thus all deserve a high degree in quality control.

APPLICATION TO CRITICALITY ANALYSIS FOR LWR FUEL PACKAGE DESIGN

For each transport situation to be studied assumptions have to be selected for the package and contents geometries and for water quantities. Considering the regulations and the advisory material, it is required to assume the following quantities (table 1).

WATER QUANTITIES TO BE CONSIDERED (in package cavity)	Without multiple water barriers	With multiple water barriers
Individual package in isolation	Water quantity that leads to greatest reactivity	No water leakage (watertight package)
Package arrays	Quantity of water able to penetrate in the package in normal (during spray test 721) or accident (during immersion test 733) conditions of transport	

Let us note that for individual package with multiple barriers, the absence of leakage does not mean that the package cavity is exempt of water. For packages transported with dry cavity, some quantities of water may still remain in the cavity due to imperfect draining or drying of cavity inner structures, guide tubes and ruptured or suspicious fuel rods or to presence of hydrated materials such as boron precipitates. Likewise, for the assessment of package arrays, the water that penetrates the package is to be cumulated to the water residues present in the cavity prior to shipment.

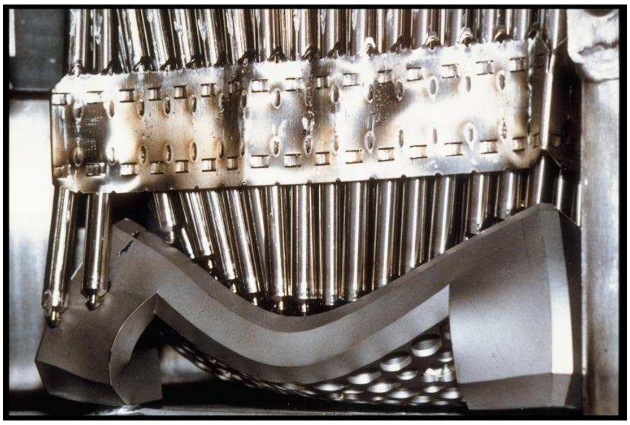
Then, considering the proposals from previous section on situations to be assessed, the individual package with multiple barriers should be assessed first in normal conditions of transport with the quantity of water which leads to the maximum reactivity and second in accident conditions of transport with the water residues present in the cavity prior to shipment, cumulated with the water that can penetrate during the immersion test.

Taking into account the damages to LWR fuel that are deemed possible in normal and in accident conditions of transport, the configurations to be analysed can be defined as shown in Table 2.

	IN NORMAL CONDITIONS OF TRANSPORT	IN ACCIDENT CONDITIONS OF TRANSPORT
TYPICAL FUEL DAMAGE	Pin or assembly longitudinal slipping, assembly side shifting	In addition: assembly birdcaging, some pin ruptures (+ damages to inner structures, when appropriate)
WATER QUANTITIES PROPOSED TO BE CONSIDERED IN CAVITY OF PACKAGE WITH MULTIPLE BARRIERS	Water quantity that leads to greatest reactivity	Quantity of water able to penetrate in the package during immersion test 733 + quantity of residual water present prior to shipment

Table 2: Selection of geometrical and water assumptions

Figure 1:
Example of fuel assembly damage with bending and sliding of fuel pins



It can be noted that the configurations with important fuel damage such as birdcaging combined with large quantities of water in the cavity are not covered. Such configurations would not be consistent with the probability estimations presented in the paper. But if these estimations were to be reviewed, the consequence on package designs should be considerable and there would be no longer any benefit provided by multiple barriers concept since the reactivity of these configuration is generally not acceptable.

The practical experience collected shows that the accident configuration is not a limiting one for current maximum water quantities in the range of 1 liter. That value generally preserves a large reactivity margin for uranium oxide fuel enriched by less than 6 % in ^{235}U. But reactivity with mixed oxide fuel increases more quickly with water content.

RECOMMENDATIONS FOR OPERATIONAL MEASURES

As required in the AIEA transport regulation, *"a high degree of quality control in the manufacture, maintenance, and repair of packagings and test to demonstrate the closure of each package before each shipment"* must be implemented. This is applicable to each component of each watertight barrier, including welds, seals, bolts and all orifice components.

It also concerns bolt torquing and leaktesting. Furthermore it should be paid attention to the risk of common cause failure. For instance using the same procedure for leak testing each of the barriers would not guarantee the watertightness in case of occurrence of an error in the procedure.

The applicable quality assurance or management system should be fully applied to these operations. If the performance of the barriers in accident conditions has been demonstrated by testing with a specimen, it also applies to the specimen the representativity of which should be carefully checked.

To prevent common cause errors, we recommend the implementation of independent operations on each barrier and that the drying and the closure of the multiple barriers should be checked twice by independent operators and if possible by different methods. All operations and test criteria are to be qualified as appropriate, in particular for drying and leak testing.

DISCUSSION AND RECOMMENDATIONS FOR REGULATORY PROVISIONS

The incidents reported in this paper show that the probability of errors leading to the presence of large quantities of water in packages where it must be prevented for criticality safety is not negligible. The presented approach to still assure criticality-safety is supported by the assumption that the probability is low. It is therefore essential that it is kept as low as reasonably possible. To achieve this, it is needed to extend the requirement for high degree of quality control to draining and drying operations on packages loaded under water. In addition incidents must be subject to a permanent survey to assure that situations combining cavity flooding occurrences with an accident are kept at negligible probability.

It is also needed to eliminate common cause errors that could affect all the watertight barriers of a package or several packages. Since the case of arrays of packages full of water has not been assessed with water in cavities, the probability for the repetition of an error in different packages that are likely to be grouped during transport should also be negligible.

Finally we recommend more concise requirements or guidance concerning the concepts of independency of barriers and of safety for single error.

REFERENCES

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[3]: Patram 2007, IRSN’s experience feedback list for the transport package design safety appraisals, S. Le Mao, M. Moutarde, MT. Lizot, G. Sert