THE FACILITATION OF CRITICALITY SAFETY ASSESSMENTS FOR FUEL ASSEMBLIES

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ABSTRACT

Packages for the international shipment of fissile nuclear fuel cycle materials require multilateral approval in respect of criticality safety. This involves not only certification and validation by the Competent Authority of the country of origin but also approval by each country through, or into which, the consignment is to be transported. Although the regulations in TS-R-1 which govern criticality safety are unambiguous, the interpretation of these regulations and the assumptions which form the basis of the assessment may differ significantly between the applicant and the various Competent Authorities. As a result, gaining a full set of approvals can sometimes be a lengthy and expensive business.

The World Nuclear Transport Institute, WNTI, believes that the approval process can be made more efficient. An improved approach to criticality safety case preparation would be to use consistent methodologies and more realistic assumptions based on reliable data. This could lead to significant reductions in costs and timescales for both applicants and regulators.

WNTI has established a working group of criticality experts from its member companies to explore ways to improve the preparation of criticality safety cases. To begin with the working group has concentrated on fuel cycle materials, with the aim of identifying ways to facilitate consistency, reduce the effort and shorten the time involved in obtaining approvals.

The main features of the WNTI study have been presented elsewhere [1, 2]. The initial focus has been on new and spent fuel assemblies because often criticality safety cases for these materials present technical challenges. Fuel lattice expansion and fuel pin cladding failure under impact accident conditions have been studied and the principal issues and conclusions reported in [1,2]. Recently other criticality methodologies for important topics relevant to the criticality safety case for new and spent fuel elements, namely enrichment mapping, water ingress, burn-up credit, the deformation of internal components of the package and safety margins have been reviewed. The findings are described below.

1. INTRODUCTION

For the criticality assessment of a package, TS-R-1 [3] requires the applicant to demonstrate the nuclear criticality safety of a single package and array of packages under both the normal and accident conditions of transport. TS-R-1 defines specific sequences of package tests to simulate both of these conditions. Section 7 of [3] gives the details. The tests to represent normal and accident conditions are hypothetical in the sense that it would be extremely unlikely that during its life-time, a package would be subjected to conditions as severe as experienced in the tests.

Despite the fact that the requirements in TS-R-1 concerning criticality safety are unambiguous, the application of the Regulations to a criticality safety case may not be straight-forward:

- There can be issues in representing the state of the packages in the normal condition because of data uncertainties (eg the exact composition of structural materials such as steel) or it may not be clear how best to represent certain aspects of the packaging or fissile contents.

- The major issues are usually concerned with modelling the hypothetical accident conditions, that is: representing state of the package (ie packaging + fissile contents) following the sequence of impact, fire and water immersion. The physical consequences of these accidents are usually impossible to predict and model exactly (eg fuel assembly impact damage).

Therefore for both normal and accident conditions, assumptions need to be made in order to model the state of the package and these must bound reality without being unduly conservative. The assessment process is complicated by the following factors:

- Assumptions can differ significantly from package to package for legitimate reasons because of differences in contents and packagings and how these could interact in an accident. Even minor differences can sometimes be significant.

- Criticality safety assessments can be complex, often demanding much high-level and inter-disciplinary effort. The methodologies and underlying assumptions which form the basis of the criticality assessment may require considerable professional expertise and judgement. It has been noticed from the working group discussions that different experts may favour different approaches.

- The transport of fissile nuclear fuel cycle materials is an international business. For international shipments TS-R-1 requires that packages containing fissile materials undergo multilateral approval in respect of criticality safety. This means not only certification and validation by the Competent Authority of the country of origin, but also approval by every country en-route. Each of the national Competent Authorities will carry out an independent review.

Unfortunately, the payload of a package can be sensitive to differences in modelling assumptions. This can be very important when a minimum payload is required in order to enable operations at a plant to proceed efficiently.

Given the number of organisations involved in obtaining a full international approval technical, the complexities of criticality assessment and the inconsistencies in assumptions and methodologies, it is not surprising that obtaining a full set of approvals can be lengthy.

2. WNTI CRITICALITY ASSESSMENT TASK FORCE

With the objective of alleviating some of these difficulties, the WNTI established a working group of criticality experts from its member companies to explore ways to ease the preparation of criticality safety cases. The WNTI has found from past experience that using working groups is an efficient way of identifying potential issues, collating relevant knowledge and experience and formulating solutions.

Specifically the WNTI wishes to identify ways to facilitate consistency, reduce the effort and shorten the time involved in obtaining approvals. Only methodologies which had been accepted by a Competent Authority were reviewed. The study will not lead to advice on the optimum strategy or on design solutions to meet particular regulatory requirements; it is not the intention of the working group to prescribe methodologies and data. These matters will depend on the circumstances relating to a particular application. Rather the study aims to identify the major generic factors which must be addressed in the preparation of safety cases by applicants and the assessment by Competent Authorities.

The main features of the WNTI study have been presented elsewhere, where fuel lattice expansion and fuel pin cladding failure under impact accident conditions have been considered in detail [1, 2]. Recent work by the WNTI working group has considered other topics which can be important to a criticality safety case for new and spent fuel elements, namely:

- Enrichment mapping
- Water ingress
- Burn-up credit
- Deformation of Internal Components
- Safety Margins

and the findings from the review are summarised below.

3. ENRICHMENT MAPPING

In order to optimise reactor performance, or to compensate for the lower neutron output of instrumentation pins, the fissile (235U or Pu) content of a fuel assembly may vary radially or axially. For these types of fuel assembly, discussions with member organisations showed that three approaches to criticality modelling have commonly been employed and accepted by Competent Authorities: using the actual arrangement of fuel pins within the fuel assembly, using a value based on the average fissile enrichment or using the maximum value of the U235 or Pu content. All three methods should be acceptable as the assumed basis and the most appropriate one can be chosen by the designer for a particular case, on the bases of a cost/benefit analysis.

- **Actual mapping** In this approach, the actual configurations and fuel distributions are modelled. Modelling complexity can be increased over the other approaches, though most criticality codes have special features to simplify the effort needed to represent the pin map. However, consideration needs to be given in representing a damaged fuel assembly; often a bounding enrichment is used to represent displaced fuel pins and fuel debris. Because there is no excess conservatism in this approach, a reduction of the manufacturing cost for the packaging and its basket and/or an increase in payload may be obtained over the other methods. No justification is required for this option because there are no potentially optimistic approximations.

- **Average value** Approaches in which all of the fuel pins in the assembly are assumed to have enrichment based on a average value – usually the arithmetic mean - have been used to model fuel assemblies. Note that, in general, averaging over the fuel assembly will not be a conservative process because the fission rate in regions of high flux can be under-represented. However, this difficulty can easily be remedied by adding an “offset” to the average; that is using a value a little larger than the mean. Clearly, preliminary work will be needed to establish a suitable enrichment value. The advantage of this approach is that the criticality modelling work can be simplified. The disadvantage is that the conservatism introduced may result in a reduced payload. Also consideration needs to be given to the means of representing a damaged fuel assembly.

- **Maximum enrichment** Using the maximum enrichment to model all of the fuel pins in an assembly is the simplest approach. There would be no decisions to be made about how to model fuel debris or pin displacement because these accident conditions would be modelled at the maximum enrichment. No justification is required because this is clearly a conservative assumption. However, there could be significant penalty in terms of package payload.

4.WATER INGRESS

Except for packages which incorporate special features to prevent water ingress, the leakage of water into the void space of the individual package needs to be explicitly considered in a criticality assessment. Member companies were canvassed for the issues that Competent Authorities had shown concerns about:

- **Assuming no water ingress** into the package In order to make a claim for this, multiple water barriers of a high standard must be present in the package. (Residual water, for example from wet fuel assemblies, would need consideration). This is not a commonly used assessment route, but package approvals have been given on this basis; these required a high degree of quality control on the production and maintenance of the packagings.

- **Differential flooding or leakage** The packaging configuration with the greatest neutron multiplication factor does not necessarily occur with complete flooding. Intermediates states, such as can occur with partial or differential flooding, or where void spaces are filled with water mists, can prove more reactive. The review showed a variety of approaches with some applications assessing all void spaces and others just the main ones. In general spaces in the packaging that need consideration include the: Flask cavity, Fuel assembly compartments (including the spaces within the fuel assembly) and Neutron flux traps. There may be other spaces that need to be assessed.

5. BURN-UP CREDIT

During irradiation in a reactor, the fissile material in the fuel is “burnt”, causing a decrease in its reactivity. The decrease may be taken into account to justify the criticality safety of packages. Because enrichment and burn-up are increasing in modern reactors, and are likely to increase even further in the next generation, the assumption of fresh or unirradiated fuel is likely to become penalizing. The use of a burn-up credit methodology may minimize the use of expensive neutron poisons in the baskets and increase the payload of the packages.

In taking account of irradiation in a fuel assembly, assumptions must be made about the axial and radial irradiation profiles of the fuel and its radioactive inventory because it is not practicable to precisely model either. Methodologies that have been successfully used by WNTI member organizations in applications to Competent Authorities for uranium LWR packages include:

- **No burn up**. This is the conventional approach and assumes that the package contains fresh fuel. The advantages include: ease of assessment and no need for burn-up monitoring. The disadvantage is in overestimating the neutron multiplication factor of the package and possibly reducing the payload.

- **Flat burn-up profile.** The irradiation profile is assumed to be constant along the entire length of the fuel assembly. A uniform radial profile is assumed. The irradiation is based on a level which can be guaranteed for irradiation over one cycle in core or at a level which can be guaranteed by a measurement 50 cm from the ends of the fissile part. The advantage of this approach is that it is comparatively simple to carry out.

- **More realistic burn-up profile**. The irradiation profile is approximated as a piece-wise continuous function (ie a histogram), with a small number of “divisions” and with a uniform radial profile. The assumed profile would need to be verified against measured axial profiles for the fuels. The advantage of this approach is that it would be more accurate (ie less inherently conservate) than the flat profile.

- **Actinides only** The post-irradiation inventory of the fuel is represented by a limited number of actinides – principally 234U, 235U, 238U, 238Pu, 239Pu, 240Pu, 241Pu and 242Pu.

- **Actinides and fission products**. Here the criticality models of the fuel include the actinides above, with the addition of 241Am and certain non-volatile, long lived fission products.

Reference [5] gives a good account of these approaches.

6. EFFECTS OF CHANGES IN INTERNAL ARRANGEMENTS

The criticality safety of a package depends on the arrangement of the fuels, moderator, structural absorbers and neutron poisons relative to one another. Maintaining this arrangement within safe limits often depends on the integrity of the structures within the package, chiefly flux gaps, tie-rods, spacer plates, stools, fuel holders and shrouds. The behavior in an accident of water channels, water pins and instrumentation pins may also need to be considered. Collectively the WNTI membership has a great deal of experience in assessing the effects of damage to these structures. A number of methodologies have been developed which have proved acceptable to Competent Authorities.

However, the review revealed inconsistencies of approach, with some applications assessing damage to some structures but not others. For example in the assessment of flux gaps, the following approaches have all been used:

- **Optimised reduction in flux gaps** Calculations are undertaken to establish the most reactive width of (ie optimise) the flux gap. No justification is needed for this modelling assumption because it is the most conservative and results in the greatest ΔK. This has sometimes been applied to a number of the flux gaps and at other times to all of these structures.

- **No or partial loss of flux gaps** Validated data from impact tests (or a validated methodology such as Finite Element Analysis) has been used in a model in which the width of some or all flux gaps is reduced.

- **Loss of neutron absorbing materials.** Usually, there is no need for this assessment because standard absorbing materials (eg boronated steels or aluminium) in spent fuel packages can be confidently assumed to remain in place during an accident. Nevertheless, it sometimes been used as an assessment technique. The loss of novel types of neutron absorber may require consideration.

7. SAFETY CRITERIA

In assessing the criticality safety of a package, a criticality safety criterion is always required. For assessments based on the results of modeling with Monte-Carlo criticality codes (nowadays the norm), the general form of the criticality safety criterion is [4]:

$$K + n.\sigma \leq 1 - \Delta K_m - \Delta K_u$$

where: K is the estimate of the neutron multiplication factor produced by the criticality computer code, σ represents the associated standard error associated with the estimate of K and n is a number chosen to give the required statistical confidence. Of the remaining factors: ΔK_m is the required margin of sub-criticality and ΔK_u is an allowance for calculational biases and uncertainties.

Discussions within the WNTI group revealed some small, but potentially significant, differences. In particular it was found that:

- **ΔK_m** - is a value set by agreement between the applicant and the Competent Authority and is subjective, effectively representing an attitude to criticality risk. For the same fissile materials, some package approvals are based on a value of 0.05 some on 0.02 and others in between. Some approvals use one value for normal conditions and another for accident conditions; whilst others use the same value throughout.

- **n** – This is also a subjective value. Sometimes n = 3 is used; more often the value used is = 2. (Note that using a "$K+3\sigma$" value means that there is about a 0.1% chance of repeating the calculation and getting a higher value, whereas this probability increases to about 2.5% for n=2.So there is quite a difference in risk terms.) Using a value of n=3 rather than n= 2, effectively increases the value of K by a $\Delta K = \sigma$.

- **ΔK_u.** The treatment of biases and uncertainties is also governed by judgment and showed the largest range of approaches. In some applications, statistical errors were simply added together, in others all of the errors (including σ) were added in quadrature. Some assessments were not statistically consistent. Some applications used professional judgment for setting nuclear data error terms, whereas others used sophisticated techniques based on sensitivity analysis.

These differences seem quite small, but they can have a significant effect on K, and therefore on payload, particularly in systems which are close to the safety criterion.

8. CONCLUDING REMARKS

Criticality safety assessments for transport packages frequently rely on complex inter-disciplinary safety justifications. It is perhaps not surprising that often they need a lot of high level-effort from both applicants and regulators. It’s also not surprising that there may be inconsistencies in the approaches preferred by the applicants and the various Competent Authorities involved in the approval process. Protracted discussions and rework are not uncommon, resulting in high costs for all and delays in the transport.

The World Nuclear Transport Institute considers that these difficulties could be alleviated by a more efficient approach to criticality safety case preparation; that is by encouraging the use of internationally consistent methodologies, data and assumptions.

A first step in this process is to understand the range of differences in the approach to transport criticality assessments. A working group, established by the WNTI, has been busy reviewing the various approaches that have been successfully employed by the member organizations in gaining package approvals. This paper summarises recent findings by the group in this respect, in the assessment of new and spent fuel.

9. REFERENCES

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