Harmonisation of Criticality Assessments of Packages for the Transport of Fissile Nuclear Fuel Cycle Materials

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1. Abstract

The transport of fissile nuclear fuel cycle materials is an international business and for international shipments the regulations require a package to be certified by each country through or into which the consignment is to be transported. This raises a number of harmonisation issues, which have an important bearing on transport activities.

National authorities carry out independent reviews of criticality safety of packages containing fissile materials but the underlying assumptions used in the calculations can differ, and the outcome is that implementation of the regulations is not uniform. A single design may require multiple criticality analyses to obtain base approval and foreign validations. When several Competent Authorities are involved, the approval and validation process of package design can often become time consuming, expensive and an unpredictably lengthy process that can have a significant detrimental effect upon the businesses involved.

The characteristics of the fissile nuclear fuel cycle materials transported by the various countries have much in common and so have the designs of the packages to contain them. A greater degree of standardisation should allow criticality safety to be assessed consistently and efficiently with benefits for the nuclear transport industry and the regulatory bodies.

2. Introduction

Various categories of packages are used to transport fissile nuclear fuel cycle materials, such as enriched uranium hexafluoride, uranium dioxide, fresh fuel and also spent fuel, all of which are capable of sustaining a nuclear chain reaction. Wastes arising from the processing of fissile materials must also be considered.

Depending upon the nature and quantities of materials involved, Industrial, Type A, Type B(U) and Type B(M) packages are used for surface transport and the high duty Type C package for air transport. Packages are classified as fissile packages if they are designed to carry fissile materials and they are then categorised as IF, AF, B(U)F, B(M)F and CF. Appropriate mechanical, thermal and immersion tests are specified in the IAEA Regulations, TS-R-1, which cover any impact, fire or submergence accident which could be realistically envisaged in road, rail, air and sea transport, all of which may be used for nuclear fuel cycle materials.

In order to transport and store nuclear material safely, it is necessary to maintain the material in a subcritical arrangement during routine, normal and under hypothetical accident conditions of transport. Generally, during routine and normal conditions, the geometrical arrangement and state of the material is well characterised, essentially it is assumed to remain in its ‘as-loaded’ arrangement. However, in the event of a serious accident, the integrity and disposition of the nuclear material may not necessarily be maintained and the internal structures of the packaging also may be subjected to re-arrangement, unless this potential is engineered out at the design stage.

Criticality safety assessments have to be carried out on individual packages and also arrays of packages to ensure that a criticality excursion could not occur. Under hypothetical accident conditions the underlying assumptions that are used in the calculations by both Applicants and Competent Authorities can differ widely.

Criticality is a complex (and often counter-intuitive) science. It is hard to explain to carriers, the public or anti-nuclear advocates how criticality evaluations can lead to radically different conclusions depending upon the entity conducting the study or upon the code utilised. This has the ***appearance*** of subjectivity - a more rational approach could help in alleviating this problem.

This paper addresses criticality safety during the transport of LWR fuel assemblies under hypothetical accident conditions and considers the overall strategy for controlling criticality hazards in these circumstances in order to illustrate the issues involved. Some consideration is also given to the criticality safety assessment of fissile wastes. The principles outlined are equally applicable to transport and storage of most nuclear materials.

3. Licensing of Packages for Fissile Materials

3.1 Uniform implementation of regulations

The transport of fissile nuclear fuel cycle materials is an international business and for international shipments the regulations require that packages containing fissile materials require *multilateral approval* in respect of criticality safety. This means not only certification and validation by the competent authority of the country of origin of the design or shipment but also approval by each country through or into which the consignment is to be transported. This raises a number of harmonisation issues, which have an important bearing on transport activities, and some of these are discussed below.

National authorities carry out independent reviews of the criticality safety of packages containing fissile materials and a single design may be subject to multiple criticality analyses to obtain base approval and foreign validations. When several Competent Authorities are involved, the approval/validation process is repeated several times in the different jurisdictions. The resolution of the issues to validate a package can be time consuming and expensive and the outcome may be that the implementation of the Regulations may not be uniform.

3.2 Consequences of unrealistic assumptions

The inclusion of layer upon layer of contingencies and extensive damage scenarios can result in a combination of pessimisms that are in extreme cases unrealistic and unachievable in practice. This can lead to unnecessarily restrictive positions, particularly when several extreme scenarios, some of which can be mutually exclusive, are eventually compounded. Sound pragmatic judgements that reflect reality can be obstructed.

Payload can have a crucial effect on viability; undue pessimism can restrict payload. Avoiding undue conservatism in safety assessments increases payloads and thereby reduces the number of transports necessary. This alone has a beneficial effect on overall safety, including dose minimisation.

Efficient and effective use of resources is a challenge throughout the licensing process. Criticality safety assessments are complex and the number of experienced criticality assessors is limited. Inconsistencies in the initial assessments and during the review/validation process, leading to repetition of work, can result in misuse of the scarce resource. This leads to high costs for both the Competent Authorities as well as the industrial transport organisations involved; generally for very little, if any, real safety benefit. It also results in delays in obtaining approvals.

4. New and Spent Fuel Assemblies

The transport of new and spent fuel assemblies is particularly important and it raises a number of important harmonisation issues, which can be used to illustrate possible ways to rationalise work on criticality assessment.

Criticality safety cases for packages containing new and spent fuel assemblies have to assess reactivity under routine, normal and accident conditions. Depending upon the particular packaging design it may be necessary to consider the fuel assemblies in a variety of states after an accident involving a severe impact. Changes in geometry could cause an increase in the reactivity of the fissile material giving rise to a potential criticality hazard.

Assuming extensive damage scenarios can result in a combination of pessimisms that are in extreme cases unrealistic. For example in a horizontal impact accident involving a LWR fuel flask, the basket, containing the spent (or fresh) fuel, could become compacted increasing reactivity of fuel assemblies due to collapse of the flux gaps and increased interaction of fuel assemblies. This is unlikely to be co-incident with a vertical impact, which could also cause an increase in reactivity by increasing the pin pitch. This combination of conditions is often assumed in the criticality analysis.

Clearly, when judgements are made to create a credible set of assumptions in the criticality safety case, there will always be the opportunity to construct some hypothetical onerous scenarios that would create a higher reactivity for the package arrangement. In these circumstances the issue then becomes one of how credible is the scenario and how the consequential effects are mitigated by the other pessimisms already assumed in the analysis.

It is therefore timely to consider the issue of fuel integrity under impact accident conditions as it relates to fuel assemblies and to seek rational assumptions about configurations possible after accidents which can be realistically envisaged.

To rationalise this aspect of the package safety case, some members of the French and the UK industry [1] have been carrying out a study of fuel integrity. The objective of this project is to develop a common method to assess the response of a LWR fuel assembly when subjected to impacts, which could result from realistic transport accidents. A variety of structural analysis routes will demonstrate the appropriateness of the assumptions used in a package criticality safety case. The work is being undertaken in consultation with the Competent Authorities of the two countries and results are expected to be available by the end of 2004.

5. Accident Damage Scenarios

It is important to remember that due to the nature of transport activities it is more *likely* to have *unexpected* events affect fissile material than *expected* but *unlikely* events as is the case for well defined nuclear plant activities. The criticality assessment of accident conditions during transport is linked to the IAEA tests, which are designed to ensure that potential variations of these accident conditions do not affect reactivity; the criticality assessment, therefore, covers a multitude of accident scenarios in one simple calculation. It is impractical to complete a study of all potential incidents, and, due to the subjective nature of such a study, imaginative assessors could always add to the list. The models adopted need to test the physics of the system rather than a likely scenario.

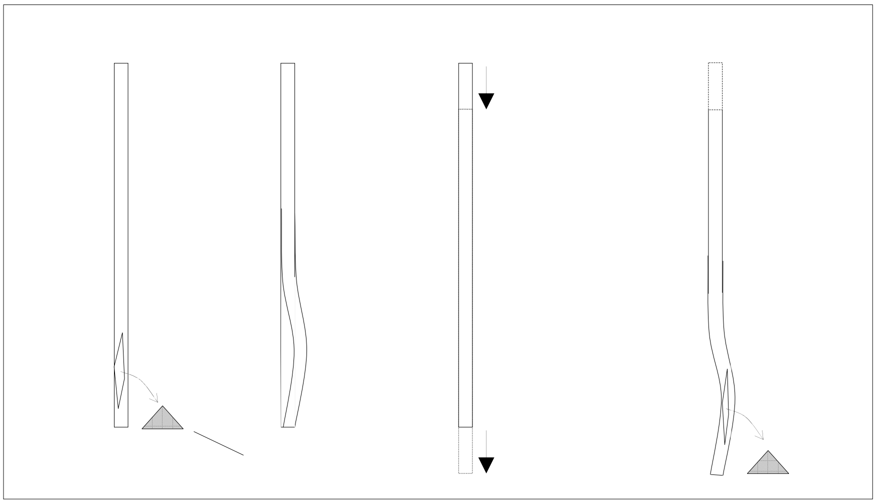
It may prove to be possible to agree on the realistic worst cases, i.e. those which would have most effect on approach to criticality, based on sound engineering principles and analysis, coupled with experimental evidence following the IAEA tests relevant to accident conditions of transport.

A set of potential faults could be developed without necessarily identifying the fault-initiating event. Qualified mechanical and criticality experts from BNFL and Cogema Logistics carried out a review of hypothetical impact accidents and damage that is potentially significant from a criticality perspective.

The scenarios identified fall into three categories. Fuel pins can bend, they can rupture and they can be displaced with respect to their original location. These three effects can act in combination. Deformation of other fuel assembly components such as end fittings could also occur. Such damage could potentially cause pins to rupture and this would allow fissile material to escape from the pins and accumulate elsewhere. Damage of the inner components of the packaging, such as would cause changes to the position of neutron poisoning plates and increase interaction, could also occur. In the extreme, these conditions could potentially move fissile material into an arrangement that could present a criticality hazard.

From this review it was apparent that the three principle types of damage that are important in criticality safety can be summarised as, deformation, slippage/displacement and rupture. The figure below illustrates the concepts.

Figure 1 – Potential Damaged States



By way of example, some of these damaged states are considered below and possible worst case modelling assumptions are proposed.

5.1 Fuel Pin Deformation - BWR Fuel assemblies - Preliminary Conclusion

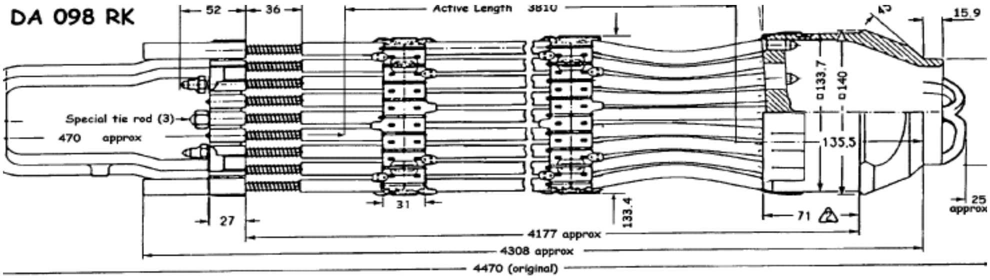
Fuel pin deformation has been observed in both irradiated and unirradiated BWR fuel assemblies. In both cases, the deformation leads to a localised reduction in the cross section of the fuel assembly and, as LWR fuel is slightly under-moderated, any lattice pitch compression would reduce $k_{effective}$. Hence the fuel assemblies, damaged in this way, are significantly less reactive than the undamaged assemblies. Current assessment philosophy does not allow credit to be taken for such a positive occurrence.

The mechanism that leads to this reduction in the fuel assembly cross section is well understood and logical. The basis is that the deformation of the end fittings, on most BWR fuel assembly designs, would tend to cause the pins to bend inwards rather than outwards as the fuel pins are connected to the end fittings. Two examples of this behaviour are provided below. This is not the case for PWR fuels where lattice expansion could be expected in an impact accident.

Example 1 Uncontrolled Lowering of a BWR Fuel Assembly in a Spent Fuel Storage Pond

On 11th June 1989, an event occurred at a German Nuclear Power Plant (NPP). A fuel assembly was lowered 5m in an uncontrolled manner and collided with the base of the spent fuel pool floor.

The fuel pins did not leak, there was no damage to the end plugs of the fuel pins. In addition, none of the fuel pins were released from their positions in the end nozzle and, therefore, there was no opportunity for the pins to slide and arrange into more optimised geometry. The BWR fuel pins buckled under the impact load, as did the lower fuel assembly nozzle. The combined effect was that the pins bent inwards, which produced a local reduction in the cross section of the fuel assembly, see the figure below, provided by the NPP.



Example 2 FS-74 Drop Test

During the testing of the FS-74 package, dummy BWR fuel assemblies were included in the package as part of the test programme. The results of the axially orientated drop tests were similar to those seen for the incident described above. The BWR fuel pins buckled under the impact loads, as did the lower fuel assembly nozzle, which produced a local reduction in the cross section of the fuel assembly. In this instance, however, some of the fuel pins were ruptured near the lower end plug weld. There are no reports of fuel pellets being released despite one pin being sheared completely in two.

It is therefore concluded that modelling the undamaged pin pitch adequately (and pessimistically) bound damage to BWR fuel assemblies in an axial impact accident. The undamaged pin pitch is a conservative representation of the pin pitch in the region of the assembly with reduced cross section.

The above does not preclude the requirement to consider fuel pin rupture or other forms of damage for BWR fuels.

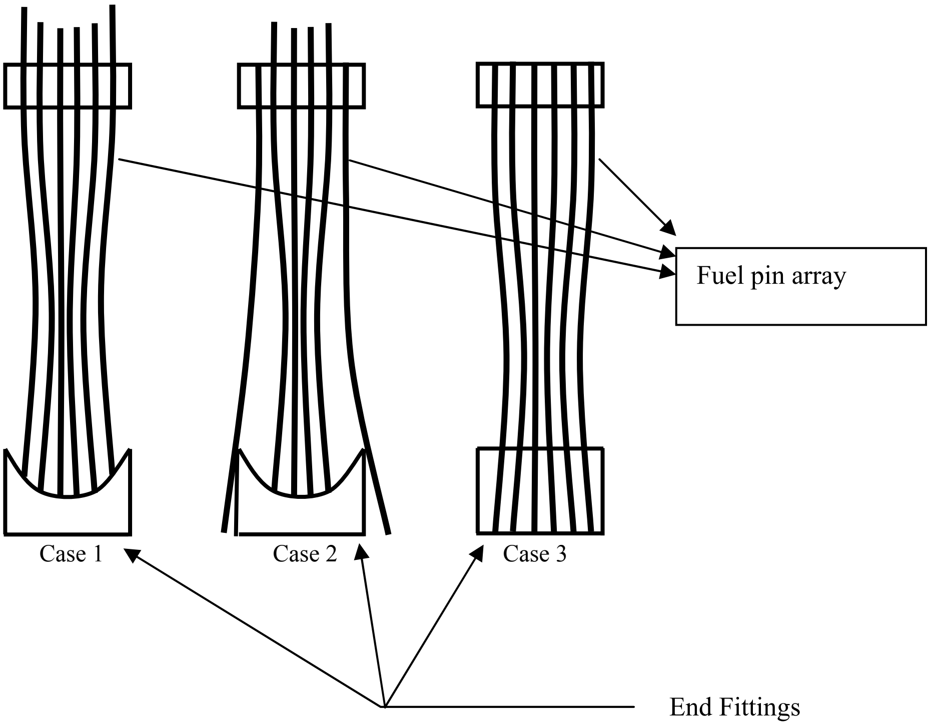
5.2 Fuel Pin Displacement - PWR Fuel assemblies - Preliminary conclusions

Many accident conditions could be postulated which would lead to displacement/dislocation of the fuel pins from their original location. Essentially, all these scenarios reduce to the following cases.

1. Pins move axially until they strike the end fitting, the end fitting bows and the fuel continues to move downwards (See Figure 2, case 1), this is discussed above for BWR fuel.
2. Pins move axially until they strike the end fitting. The end fitting bows and the fuel continues to move downwards, some fuel pins move around the outside of the end fitting and continue until they meet the end of the multi element bottle (MEB) or open frame (this scenario is sometimes referred to as "elephant footing").
3. Pins move axially and pass through water circulation holes built into the end fittings. It is acknowledged that pin pitch *may* not be reduced over the central region as indicated from the schematic.
4. A combination of cases 2 and 3.

The following discussion is limited to case 2, illustrated in Figure 2 below.

Figure 2 – Axial Dislocation of Fuel Pins in a LWR fuel assembly



The following scenarios were investigated [6]:

- Axial slippage downward or upward of the outer ring of fuel pins.
- Axial slippage downward or upward of the outermost two layers of pins on two adjacent sides only of the fuel assembly.
- Axial slippage downward or upward of the fuel as described above, with alternate pins slipping or remaining in place to produce a ‘chequerboard’ array.

Each scenario produces a different array of pins around the appropriate nozzle and creates a region at the opposite end of the assembly in which the outside layer(s) of pins are displaced.

The conclusion from this analysis is that the reactivity of a UO_2 fuel assembly that has undergone axial pin slippage is unchanged ($k_{effective}$ is actually reduced) from that of an undamaged fuel assembly, as the most reactive part of the assembly continues to be the unchanged part of the fuel. This is the case for both a single assembly and for any array of assemblies, and is generic to all PWR UO_2 fuel assemblies and MEB configurations. Thus, provided that axial displacement towards an unpoisoned region of the flask is limited, no additional criticality hazard arises from this mode of axial pin slippage and modelling the undamaged fuel assembly bounds this damage scenario.

The above does not preclude the requirement to consider fuel pin rupture or other forms of damage for PWR fuels.

6. Fissile Wastes

Waste arising from the processing of fissile materials and also from the decommissioning of nuclear facilities is becoming a very large component of the nuclear transport business. The concern is that often the waste form is viewed and assessed as a highly reactive unpoisoned process material, i.e. similar to plutonium powder, rather than the waste that it actually is. The challenge is to provide 100% proof of the waste form or assume worst case.

The models used in the analysis may bear no resemblance to the waste, even under the worst credible accident conditions, e.g.

- spheres
- uniform fissile/moderator mixtures AND mass limits on the amount of moderating material
- all forms of reflectors: concrete, graphite, steel, Be, BeO

This can lead to pessimism being compounded with pessimism.

There are examples where the mass limits for PuO_2/UO_2 transports are less restrictive than the mass limits for transport of fissile contaminated materials; this is clearly inappropriate.

6.1 Fissile and Fissile Excepted Waste Forms

In the UK, and elsewhere, there is a growing requirement to transport waste material containing low concentrations of low enrichment uranium (or U+ Pu). In many cases the material also has average uranium enrichment below 1w/o, which complies with current Fissile Exception Regulations. However, in some of these waste streams there are small quantities above 1w/o U235 enrichment, and, although most criticality assessors acknowledge that these are low-risk, (for criticality), waste materials this material does not automatically qualify for exemption.

It is generally recognised that full criticality safety assessment for the transport of these types of materials is onerous and not commensurate with the risk of criticality. It is therefore timely to consider the issue of fissile content of low level waste and to provide solutions to issues arising from the fissile exception clauses within the Transport Regulations. A fundamental component of such a study is the determination of rational assumptions about configurations possible after accidents, which can be realistically envisaged.

The key aims of this initiative would be:

- To avoid unnecessary repackaging or sorting operations on waste with attendant dose uptake by operators
- To avoid unnecessary transport journeys
- To establish an approach which is commensurate with the risk
- To make best use of finite safety assessment resources, both within the industry and the regulatory bodies

To achieve this would require co-ordinated efforts to create a characterisation process for waste streams that will be adopted by all parties involved in the processing, transport and disposal facilities of fissile material (excepted or otherwise).

This will involve a comprehensive review of:

1. the waste streams being managed now and in the future and what forms they will take given current retrieval practices i.e. powder, rubble, metallic, non-metallic, crates, drums, etc;
2. sampling strategies;
3. the assay/monitoring techniques to determine the radioactive composition of the waste, recognising the accuracy and pessimism involved in each technique;
4. the types of packaging currently available and the future requirements;
5. the criticality analysis techniques (pessimism, assumptions, etc).

Ultimately, this would lead to the development of a Waste Characterisation Guide (Fissile and Fissile Excepted), which could be sufficiently generic to be valid worldwide, and a Characterised Waste Directory (Fissile and Fissile Excepted), which may be more site specific. These could include issues of averaging across consignments and recommendations for maximum single item limits.

To effect the Guides and Directories the supporting criticality analysis would need to consider:

- the properties of the waste, which help to prevent criticality (materials, concentration, stability, etc.);
- the way in which these properties are controlled;
- credible arrangement and re-arrangement of the waste material during loading and transport, based on the output from the waste characterisation exercise and any physical measures of control;
- ease of separation of fissile species (both isotopic separation and separation from the waste matrix) based on the output from the waste characterisation exercise;
- amounts of materials in the various enrichment bands, where appropriate;
- bulk concentration of fissile material, based on the output from the waste characterisation exercise;
- presence of (non-flammable) neutron absorbers, based on the output from the waste characterisation exercise

In summary, the concentration of fissile material in wastes is normally low but its distribution is not very well defined. As in the case of fuel assemblies, it is important in criticality assessments that whereas the assumed scenarios should be conservative they should also be realistic. One way to achieve this is to provide the criticality assessor with rigorous evidence of the low risk nature of the waste. This will enable several firm conclusions to be drawn with regard to the neutron moderating and reflecting abilities of the waste constituents, which can be confidently reflected in the criticality model.

7. Computer Codes for Criticality Assessment

The designers of fissile fuel cycle packages and also the Competent Authorities in the various countries generally use their own country codes where possible for criticality assessment. For example, in the USA the code MCNP [2] is used, in the UK the code is MONK [3], in France APPOLLO/MORET and CRISTAL [4] are used, and SCALE [5] is used in Germany and the USA. These codes are all very comprehensive, very similar in capability and achieve the virtually same result. Although the use of different codes provides verification, and applicants have the option of using any of them, there may be scope for some benefit in rationalisation which requires further investigation.

8. A Possible Way Forward

Possibly the way forward is to produce a "Criticality Assessment Guide" which would be helpful to both Industry and Competent Authorities. The guide could specify a format to present information, which ***would always be acceptable,*** but which would be sufficiently flexible to allow essential information to be presented. The guide would be a tool for criticality safety specialists to build on.

It may be possible to set a basic standard as the foundation for a safety case and thereby establish the rules, which must be followed, or deviations justified.

It may also prove possible to agree on the realistic worst cases, i.e. those which would have most effect on approach to criticality, based on sound engineering principles and analysis, coupled with experimental evidence following the IAEA tests relevant to accident conditions of transport.

9. Conclusions

The characteristics of the fissile nuclear fuel cycle materials transported by the various countries have much in common and so have the design of the packages to contain them. In this case there may be opportunities to rationalise the methodology used for criticality safety assessment in order to increase efficiency by reducing the resources needed for assessments and at the same time reducing delays in the licensing process. A greater degree of standardisation should allow criticality safety to be assessed consistently and to a better standard with benefits for the nuclear transport industry and the regulatory bodies.

Some encouraging progress has already been made in seeking a common approach to one important topic in this field; the extent of damage to fuel pins under accident conditions of transport which could have a significant effect on criticality. Fissile wastes are another important category, where co-ordinated efforts to characterise waste streams could provide the necessary evidence to support more realistic limits in the criticality safety case. A comparison of the codes and data banks used in criticality assessments has also been helpful.

A number of specific examples of other fissile nuclear material transports, such as enriched uranium dioxide powder and pellets, and also enriched uranium hexafluoride could also be considered to determine how the criticality assessments for these could be rationalised.

The objective would be to agree, as far as possible a standardised methodology for each class of material which Competent Authorities might be prepared to adopt and thereby benefit and simplify the licensing process.

A way forward would be to develop further co-operation and co-ordination of this work between package designers, including criticality specialists, Competent Authorities and the IAEA.

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