Fissile Package Design Basis: Regulations or Analysis?*

D. Mennerdahl
E. Mennerdahl Systems

INTRODUCTION

Designing a package for fissile material and getting it approved for international transport is a difficult and lengthy process. Different interpretations of what is required and credible make the process longer and even unpredictable. *Regulations* refer to the IAEA version (IAEA 1990a). *Fissile material* has a wider meaning than in the Regulations.

Consideration must be given to issues such as functionality, economy, safety, compliance with regulations, manufacturing, quality assurance, maintenance, incident recovery, use of natural resources, public opinion, politics and personal relations. The paper concentrates on nuclear criticality safety.

AN INFINITE NUMBER OF PACKAGES

A criticality safety specialist has a unique quality; looking the public straight in the eye, without blinking or blushing, saying: *An infinite arrangement of packages has been shown to be safe.*

Consider building such a subcritical arrangement of undamaged packages. When the array size grows, the bottom packages are crushed. Growing further, the centre of the earth is moved, leading to climate changes and other nasty consequences. The moon falls down in the Pacific Ocean, just outside San Francisco, and there is a final, spectacular sunset over the array. Eventually, all traces of the growing array are lost, there is just a little black hole where the array used to be. Feeding more packages into the black hole, the process is ended with a big bang. All the time subcriticality is ensured. A criticality specialist validates everything with critical experiments. One of them may have led to the creation of our universe.

Maybe the Regulations and the criticality specialist do not mean what they say. The infinite array is just a single package with periodic or possibly reflective neutronic boundary conditions. No gravity, heat generation, etc. Only six undamaged (one damaged)

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packages have really been shown to be safe. The Transport Index (TI) is only one of the neutron physics parameters. It will not say anything about the integrity of packages in an array. A package design approval does not mean that the allowable number of packages is safe. The shipper must make such an evaluation. Maybe not even a single package is safe!

THE REGULATIONS - A SAFETY GUIDE

Two paragraphs in the Regulations are very important. Para. 562 requires that subcriticality is maintained during transport. Para. 710 requires multilateral approval.

Other paragraphs contain minimum requirements or guidelines. The tests can be used as benchmarks. Complying with the paragraphs will not ensure acceptable safety. The safety level will not be known, emergency response can be dangerous, and information to the public can be disastrous. If the Regulations appear too rigid, the total risk may increase. The credibility of the Regulations may be questioned. This is a potential accident source.

Para. 211 concerns special arrangement. It is used to allow deviations from detailed paragraphs while ensuring the overall safety. Special arrangement shipments are usually safer than other shipments.

THE PACKAGE DESIGN - A PRELIMINARY SAFETY ANALYSIS

A safety analysis for each shipment is an alternative to detailed regulations. However, it requires time and effort that may not be available. A safety analysis should not be rushed.

One purpose of a package design is to allow plenty of time for the safety analysis and for discussions with the authorities. A safety analysis for a package design may not cover each shipment. However, if the analysis is carried out and documented in a way that supports the evaluation of parametric changes, the work of shippers and authorities is simplified.

THE SHIPMENT - A FINAL SAFETY ANALYSIS

Para. 562 of the Regulations requires subcriticality. Compliance with other paragraphs of the Regulations is not sufficient. A good safety report and contacts with the authorities can simplify a final safety analysis. Other measures are to check shipment routes, weather, vehicles, operators, etc. Not relying completely on regulations, designers and authorities is common sense. Driving a car requires similar responsibilities.

A PRIMITIVE DISCIPLINE - RITUALS FOR CRITICALITY SAFETY

Fifty years of criticality safety have led to excellent computer codes and data. However, the methods for safety analysis are primitive. Crude approximations are used without knowing their limitations. There are many specialists (time), but no experts (feeling).

Burnup credit - Axial burnup profile

There is a crude approximation, where a realistic axial fuel burnup profile is replaced with an average (flat) axial burnup profile. A topical report (U.S.D.O.E. 1995) claims that this approximation is a valid part of a methodology for burnup credit of PWR fuel without fission products. An OECD/NEA working group is studying the approximation. So far, the working group has concentrated on basic physics; criticality safety may come later.

A study (Mennerdahl 1995b) of axial burnup profiles is summarised in the table. The geometry is a PWR spent fuel cask with borated steel and clean water. Twenty cm of the borated steel at the top of the active fuel are replaced with water. This represents an incident or a modified design (allowing longer fuel assemblies). Of interest is the difference between results (Δk_{eff}) for realistic and flat axial profiles at a certain average burnup (BU, GWd/tU), cooling time (CT, years) and presence of fission products (FP, Yes or No). The uncertainty in Δk_{eff} is about 0.002. The calculations are complicated.

Δk_{eff} Realistic-flat			
BU	CT	FP	Δk_{eff}
10	1	No	0.017
10	1	Yes	0.028
30	5	No	0.052
30	5	Yes	0.074
50	5	No	0.089
50	5	Yes	0.118

The flat profile approximation is not appropriate in a methodology. This is true even for PWR fuel with as little as 10 GWd/tU, 1-year cooling time and no fission products. Higher burnup, longer cooling time or addition of fission products, increases the error. During evaluation of real or postulated incidents, and even if a realistic profile is used, untested calculation methods may not be adequate. Validation is absolutely necessary.

A defence for using the flat profile approximation in the U.S. is that the scenarios are so extreme. The transport cask is shipped without water. At the plants, the water is always borated. These conditions are not a defined part of the methodology, only of some of the designs and scenarios. The double contingency principle (not compatible with the Regulations) may exclude simultaneous addition of unborated water and absence of borated steel. However, the methodology does not preclude other designs or scenarios. In an incident, a question could be: *What is the minimum boron concentration to keep the cask subcritical?* Using a flat profile, the answer is that no boron is required. A realistic profile may require a high boron concentration and a new temperature evaluation.

Boundary conditions - Reflection

Water reflection is the required boundary condition. It is often not the best reflector. In normal transport, it is not even realistic. In accidents it could be. Concrete is normal, at least on one side. Other materials and packages contribute to the boundary conditions.

It is easy to evaluate various boundary conditions to support the safety analysis. During emergency response, it may be important to evaluate a real situation quickly. The lack of experience in considering other boundary conditions than water may prevent this.

Index methods for arrays (comingling)

No packages are identical. An array of packages is considered as mixed, even if the packages belong to the same design. Where is a document that describes how to deal with a mixed array? A recent proposal (Mennerdahl 1995a) for presentation was rejected (ICNC '95 1995). Continuing a previous study (Mennerdahl 1986), the presentation would have shown limitations of mixing rules and proposed new methods. The abstract was clearly not convincing. However, the motivation for the rejection is worth repeating: *The material does not appear new and significant. Because of the low likelihood of arranging units in a mixed array pattern which would increase the effective multiplication factor above that of the uniform array, the practicality and technical significance of this work to the international nuclear criticality safety community cannot be demonstrated.*

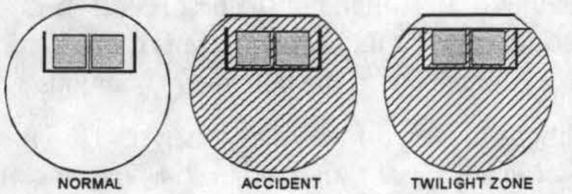
Methods for dealing with arrays are often based on an index such as the TI or on a constant such as k_{eff} or k_{∞}. A few specialists have indicated that they don't trust such methods and restrict array sizes due to this uncertainty. Some specialists express doubts. Section AX.5 (IAEA 1990b) recommends consideration of *unrestricted comingling*.

The TI is probably the most dangerous of the methods. There are at least two reasons related to neutron physics for this conclusion. The neutron interaction in a mixed array is not treated correctly. The boundary conditions are water, even though fissile materials (TI zero) and concrete are present in normal transport conditions. A third reason is related to the lack of gravity and other effects than from neutrons in the determination of the TI.

The study of arrays, planned for presentation at ICNC '95, has been modified somewhat (Mennerdahl 1996). The arrays are divided into two categories, each including a pair of different fissile unit types complementing each other. One category involves an excessive amount of hydrogen in F-units (Female), while the M-units (Male) contain less hydrogen. In a mixed array, the excessive hydrogen in the F-units is balanced by the lack of hydrogen in the M-units. K_{eff} increases. The other category involves unit types with different neutron leakage and production capabilities. The E-unit (Extrovert) has high neutron leakage and production, while the I-unit (Introvert) has lower neutron leakage and production. Again, a mixed array increases k_{eff}. The categorisation simplifies early identification (before a criticality accident) of potentially dangerous arrays.

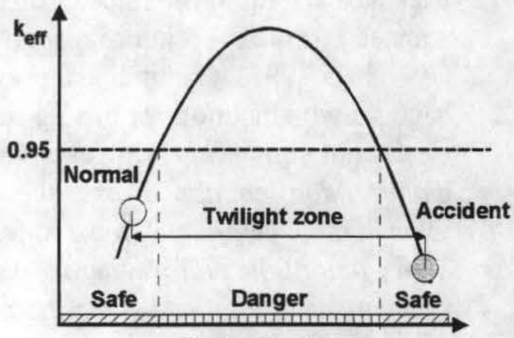
The twilight zone - Between normal and maximum accident conditions

The overall intention may be lost by detailed requirements. The safety analysis becomes a paragraph analysis. An example is the assumption that the maximum damage (mechanical, thermal, inleakage of water, etc.) to a package defines a damaged package. The range of conditions between normal and maximum damage is here referred to as the *twilight zone*.



Transport packages, normally dry, are often flooded in the maximum damage condition. The range of conditions, between empty and full, defines the twilight zone. Some people even question the credibility of partial (sometimes called preferential) water filling.

A package design contains ashes with UO_2 and 5 wt% ^{235}U in the uranium. The maximum uranium density is 0.2 g/cm^3. Under normal conditions, the dry ashes are undermoderated. With maximum damage, the flooded ashes are overmoderated. The safety report confused density and concentration in a saturated mixture with water. Carbon, oxygen, voids and other materials were replaced by water. A very serious and alarming mistake. A certificate for the package design was issued. The contents were specified as ashes with a concentration of not more than 0.2 gU/cm^3 (dry and very wet at the same time).



Validation - Unsuitable critical experiments

There are many excellent critical experiments. However, some are not suitable for Monte Carlo code validation. The problem occurs if the reactivity value of an experimental parameter is very small, compared with the corresponding reactivity value in a transport package. Many safety reports still validate codes using such experiments.

Optimum moderation

Usually, the effects of moderation and reduced neutron leakage due to scattering from nuclides are not separated. This often leads to incorrect conclusions. Especially when the fissile material is diluted and contains nuclides that are not considered in handbooks. The safety of an array is even more complicated; the fissile material is never homogeneous.

Conservative methods - Something good?

Specialists often exclude other issues than criticality safety. Using a conservative method is normally considered very good. However, conservatism causes economical and other problems; a reason for separating the useful part of the TI (radiation) from the suspect part (criticality). During incidents, conservatism may lead to evacuation, panic as well as damage to property and the environment, when there is really no need for concern.

MISSION IMPOSSIBLE - REVISION OF THE REGULATIONS

During many IAEA meetings, the author has informally proposed changes of the regulations. The first response is: *Don't fix it - it ain't broken!* However, everything is broken. We can often live with it - if we think we know and accept the consequences.

Often, the author disagreed with the majority. Reservations to majority decisions are often not documented. Looking back at minutes from meetings, it is embarrassing to appear as a supporter of some of the decisions. Reports to the sponsor of this paper clearly show the opposite. Some of the proposals and other comments are briefly discussed here.

***Environment temperature*:** The Regulations are not clear on the temperature range -40°C to +38°C for criticality safety. Three IAEA meetings with criticality specialists rejected a proposal from the author to make the Regulations clear. In 1995, a change was finally approved; after being formally proposed by a member state (not Sweden).

***A confinement system specialist - Something to be*:** The 1996 Revision will contain this new concept. It is defined as *The assembly of fissile material and packaging components specified by the designer and agreed to by the competent authority as intended to preserve criticality safety.* This is also referred to as the *free lunch paragraph.* With that definition there is hardly any need for other paragraphs (only restaurants). There is a lot that has to be agreed upon. A series of international conferences may simplify multilateral approval. The author was against this concept. The real purpose of the confinement system is not clear. If there is one, it should be expressed.

***Boundary conditions*:** Consideration of other boundary conditions than water, in particular concrete, has been proposed several times. No proposal was complete with arguments, calculations and examples. Due to the limited time, it is understandable that extensive discussions were rejected. There seems to be, however, some interest.

***Transport Index*:** The author does not consider the TI for criticality safety a serious control. It is definitely not a *criticality safety index*. Proposals have been made to change the Regulations. They have understandably been rejected (same motivation as for the boundary conditions). The methodology for determining the TI for criticality safety is wrong, but it is not easy to find existing packages that are dangerous in a certain shipment. Accidents seem unlikely and the packages are more conservatively designed than required.

***Fissile material*:** The Regulations define fissile material as one or more fissile nuclides. Everything could contain a fissile nuclide. It is confusing to have *fissile nuclides* and *fissile material* meaning the same thing. A proof of that is para. 568 with requirements for *irradiated fissile material* and *unspecified fissile material that has a moderation ratio*. Is this intended to mean an irradiated fissile nuclide?

***Package with fissile material*:** The 15 g exception level per package is dangerous. Large freight containers are shipped with such packages. In a fuel fabrication plant, there are thousands of 1-litre polyethylene bottles with uranium compounds. A few boxes with bottles are enough for criticality without any previous damage. A single damaged box may be enough for criticality. Another potential use of this option is the shipment of ADU that is recovered from scrap materials. ADU is quite well moderated, even when dry. Finally, it is not too extreme to consider large freight containers, filled with excepted packages of UO_2 powder or pellets. The economical advantages may be great. Excepted packages can contain more uranium than licensed packages in the same volume. After 20 years of debate, the 1996 Revision will limit the mass of fissile nuclides per consignment.

***Crush test*:** IAEA (1981) rejected the addition of a crush test for criticality safety. The motivation was: *for a reduction in the volume of packages in an array of no more than 50%, analysis has shown that a criticality hazard could not arise*. This is not correct. The author pointed this out in 1981 and during recent IAEA meetings. An additional reason was the discussion in 1994 of new air mode requirements. This time, the idea was not rejected. In 1995, a member state prepared a formal proposal that was accepted. The potential effect of crush forces on criticality safety is recognised. It should be considered for all package designs, irrespective of the total mass or average density.

***Air transport*:** In 1994, the majority of an IAEA working group decided that criticality safety must be ensured, combining new air mode tests (Type C) and existing array requirements. The "trigger" for air mode tests was based on A_2 values. An infinite array would fly and then be damaged. The trigger was changed to plutonium and the majority decision was cancelled. Then the trigger was changed back to A_2 values. Fortunately, the specialists now agree on less extreme requirements. The author was against (surprise!) the previous majority decision. Criticality should be very unlikely, even after a major plane accident, but it should not be mandatory to comply with the array requirements of the Regulations for packages damaged in the air mode tests.

***Leakage from arrays*:** Several times, the author has proposed that leakage of fissile material from more than one package must be clearly restricted. One interpretation of the Regulations is that a single package can lose all its contents if it is turned upside down and there is less than a critical mass. Turning two or more packages upside down could lead to criticality. However, the Regulations can be interpreted in another way. A package design includes the packaging and its radioactive contents according to the specifications. If some of the fissile material leaks during tests, it is still a part of the package design. The same is true for an array of packages; all the leaked material must be subcritical. The 1996 Revision will clearly restrict the leakage from a package array. For a package design with a TI of 0, the leakage requirement is tough: not a single fissile atom is allowed to escape.

Probability of a criticality accident in transport

The major conclusion of a 1981 Technical Committee (IAEA 1981) was that criticality during transport is *incredible (very, very low probability)*. A surprising attitude. Unexpected human errors have caused many criticality accidents. Serious errors are often made by criticality safety specialists. The complications, primitive methods and lack of experts make it extremely difficult to predict probabilities. The probability is so incredible that it is unbelievable (the author does not believe it).

Requirement or option?

The Regulations contain requirements, options, definitions and other specifications. It is important that the specifications correctly correspond to the intentions. A few times, the author has pointed out that the text, in the Regulations or in approved changes, does not seem to correspond to the intentions. Usually, obvious mistakes are corrected directly. Some minor corrections required extensive discussion. Other questions were not settled at all. Examples are the discussions on the difference between requirement and option.

Para. 567.(a) of the Regulations requires that 5 times 'N' undamaged packages *without anything between the packages* are subcritical. The marked text is clearly intended as an option. An optimum water layer is not required. If a shipper considers rain or snow to be normal conditions of transport (the Regulations do not), a study of water between the packages would be useful. The approved 1996 Revision will change the option to a clear requirement: *There shall not be anything between the packages*. Not very encouraging.

The Regulations refer to the exception paragraph 560 as a provision. It is an option. Other options use the word *may*. The exception paragraph of the first drafts of the 1996 Revision was referred to as a requirement. This was questioned by the author. However, the word *may* was not accepted in paragraphs related to criticality safety. The text of the 1996 Revision was finally changed; the exception paragraph will remain an option.

INHERENTLY SAFE FEATURES OF PACKAGES

An example is a balloon package. It will easily survive the drop test (the future crush test will not be so easy, but other features can handle that) and can be designed to stop a fire, etc. The author has many other bright ideas (air bags, etc.) on how to comply with the Regulations, but to keep the paper length restriction this section is shortened.

Bright ideas can be amusing, but the intent is to demonstrate that compliance with the test requirements of the Regulations is not sufficient. The lack of crush forces after the thermal test is one area of concern. A sequence of drop, thermal and submersion tests is realistic for individual packages or for small arrays of packages handled together. A sequence of thermal, crush and submersion tests may be more realistic and restrictive for large arrays.

A package or vehicle falling, being involved in a fire and submerged in water is realistic. A sequence of such processes, leading to a large array of damaged packages is not realistic.

A large, but realistic, array of packages with wooden impact limiters can be involved in a fire, damaged by crush forces and submerged. The crush forces can be caused by the packages themselves, by other cargo or by the collapse of a building (transit storage).

The familiar RA type of packagings for fresh BWR fuel assemblies is an example. It is much stronger after a fire test than what is required by the Regulations. Other packages may not be designed so well. Some integrity should be required after the thermal test.

CONCLUSIONS

A general analysis of all issues, leading to a reasonable balance of goals, gives the shipper a solid basis for precautions, instructions and information to the public. The ALARA (As Low As Reasonably Achievable) principle can be applied with credible results.

The Regulations are important but not sufficient for safety. Some requirements are still confusing, even in the 1996 Revision. The Transport Index cannot be trusted for criticality control. Too much responsibility is required of the shipper at the time of shipment.

Criticality safety assessment methods are primitive. They are often based on traditional rituals, with little scientific support. No criticality safety assessment should be trusted.

Criticality during transport is a realistic possibility. It may be avoided if the Regulations, certificates, safety analyses and shipping operations are questioned, repeatedly.

The universe was created as a critical experiment or as a shipment of fissile material.

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