Appendix N

MINIMUM AND OTHER REFERENCE VALUES

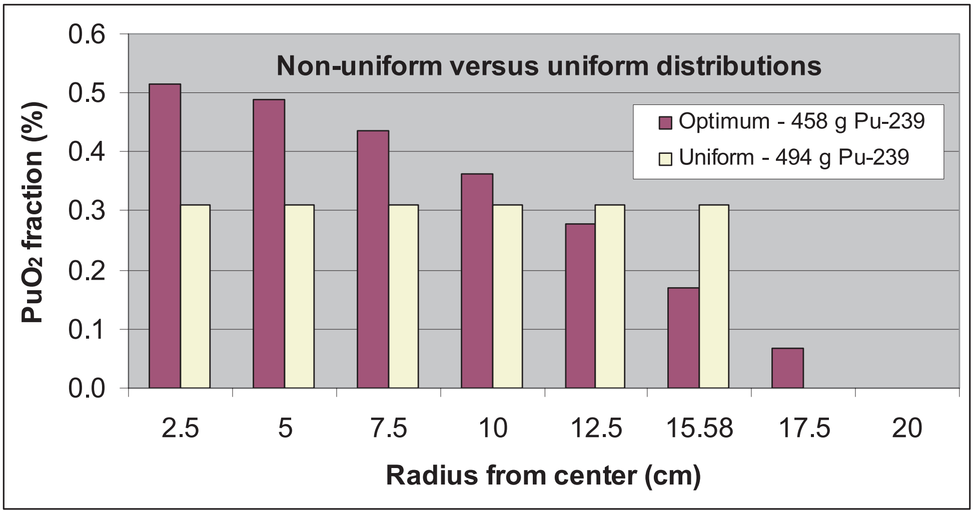
The minimum critical values are not always minimum. As pointed out before, the limiting moderation ratios H/X of interest can be either minimum or maximum, as shown in some IRSN reports. Heterogeneous arrays of fuel rods can reduce the "minimum" critical mass. The SMORES sequence [85] in SCALE 5 can be used to calculate optimum non-uniform distributions. The Japanese Handbook 2 [24] contains such information.

Constraints in geometry and material specifications must be very clear both to the contributor of reference values and to the user of those values. The only geometry constraint for the requested reference systems is that the geometry shape of the fissionable material shall be homogeneous. The purpose of this constraint is to limit the influence of moderation outside the fissionable material. The only material constraint is that the fissionable material shall be uniform. That means that all such material in the system has the same composition and density.

System properties that need to be evaluated are optimum internal water moderation, optimum geometry shape and full water reflection.

The minimum critical mass and volume are requested and used in criticality safety applications without any additional geometry constraints. Reactor physics text books may claim that a sphere gives the minimum critical mass and volume. This may be true but needs to be evaluated or confirmed for each reference value. A cube appears to give the minimum critical volume for $U(100)O_2$. For minimum critical cylinder, the length of the cylinder is not constrained. For minimum critical slab thickness, the other slab dimensions are not constrained. For minimum critical concentration, the size of the system is not constrained.

Figure N1. Minimum critical mass of $Pu(100)O_2$ in uniform and non-uniform distributions



The result of using SMORES on a $Pu(100)O_2$ mixture with water to determine the minimum critical mass is shown in Figure N1. The minimum critical mass for a uniform distribution is 494 g ^{239}Pu and the radius is 15.58 cm. For a non-uniform distribution, SMORES finds a critical mass of 458 g ^{239}Pu and the radius is now increased to 17.5 cm. A slightly smaller mass may be possible with more geometry regions. SMORES is a new tool and it is quite complicated to get convergence. It would be useful to create a few benchmarks for non-uniform distributions. The result was obtained with the 44-group cross-section library. It was confirmed using a direct XSDRNPM/S calculation using the 238-group library.

Comparisons of simple k_∞ calculations can provide important information. Examples are the problem with ^{241}Am in JENDL-3.3 (now revised to solve the problem) and problems with the MONK DICE library. Both of these problems were found (EMS and Serco respectively) during comparisons of k_∞ calculation results for actinide nuclides.

In the determination and use of the concept of "minimum critical concentration", it is very important to understand its meaning. It is not a minimum critical density, even though the units may be identical (e.g. g/cm^3). The concentration is for the fissile material and pure water only and there must not be any voids within the material. A powder particle, with lower than theoretical density, must be completely "flooded" internally with water to fulfil the specifications. To avoid potentially dangerous situations, it may be better to specify the concentration limits as atomic number density ratios (e.g. H/U) or mass ratios (e.g. mass of fissile nuclides per mass of hydrogen).

Another reference value is that which gives criticality for a soluble material at theoretical density. In this study, such reference values for UNH and PuNH crystal density materials would be valuable.

An issue that has been discussed, in particular in the development of transport safety regulations, is the significance of natural and depleted uranium for criticality safety. Addition of natural or depleted uranium to the approved contents of a package can cause criticality if it is not accounted for as a fissile material. Some authorities are aware of this and express it in the certificate to avoid confusion or mistakes. Other authorities are not as aware of the criticality safety significance of natural and depleted uranium. Multilateral approval requirements reduce the remaining risk but it is still there. For packages or materials that don't require criticality safety licensing, the exception criteria are clearly not based on exclusion of fissile nuclides in natural and depleted uranium.

The minimum concentrations (or maximum H/X ratio) that can support criticality were requested for this study and have been evaluated. Very similar values are used to define the exception criteria in the IAEA Transport Regulations. The concentrations are exactly critical in infinite amounts. Will the addition of natural or depleted uranium increase or reduce k_{eff}?

$Pu(100)O_2$ in water at the limiting plutonium concentration was evaluated first. Using MCNP5 and the JENDL-3.3 rev.1 cross-section library, k_∞ for just the plutonium/water mixture was calculated as 0.9991 ± 0.0002. An infinite slab geometry with alternate 4.0 cm thick slabs of the $Pu(100)O_2$ /water mixture and 1.0 cm thick slabs of natural uranium was then calculated using the same method. The resulting k_∞ is 1.1002 ± 0.0003. A similar system with $U(100)O_2$ in water at the limiting uranium concentration, except that the natural uranium slabs were 1.2 cm thick, resulted in a k_∞ of 1.0925 ± 0.0004. A system with $U(3)O_2$ in water at the limiting uranium concentration, with the uranium/water mixture 2.0 cm thick and the natural uranium slabs 0.4 cm thick, resulted in a k_∞ of 1.0441 ± 0.0004.

The systems are not quite optimised but sufficiently clear to demonstrate that natural and even depleted uranium can cause super-criticality in a system that is safe without the natural or depleted uranium. See also [102] concerning the influence of natural uranium on a sub-critical assembly.