Looking to the future
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ABSTRACT

Rolls-Royce has designed a package to transport and store fresh fuel assemblies and anticipates approval from the regulators for the new package design in the near future. The space between the inner and outer steel shells is filled with shaped blocks of rigid polyurethane foam, of two different densities.

The criticality safety case for the fresh fuel package had to consider single packages and arrays of packages under routine, normal and accident conditions. IAEA regulatory requirements state that the criticality assessment must include investigations on the effect on the neutron multiplication factor (k_{eff}) due to impacts, flooding and fire. Sensitivity studies must also be carried out to determine the effects on the k_{eff} due to any uncertainties in the composition of the fuel and container materials. An important part of the criticality safety case is the treatment of the foam. The approach adopted to model the polyurethane foam is the subject of this paper.

The following were investigated:

- The effect on the k_{eff} of varying the elemental composition of the foam, including the removal of hydrogen.
- The experimental analysis of burnt foam.
- The effect of addition of water to the foam to simulate water absorption.
- A simple representation of crushed foam to simulate knock-back in the package.
- Extreme representations of burnt foam, such as replacing foam with solid carbon or as randomly distributed spheres of carbon to represent soot.
- These investigations were most informative and should be considered in any criticality assessments of transport packages containing large amounts of foam in the future.

INTRODUCTION

Rolls-Royce has designed a package for the transport and storage of fresh fuel assemblies. The general layout of the fresh fuel package is presented in Figure 1.

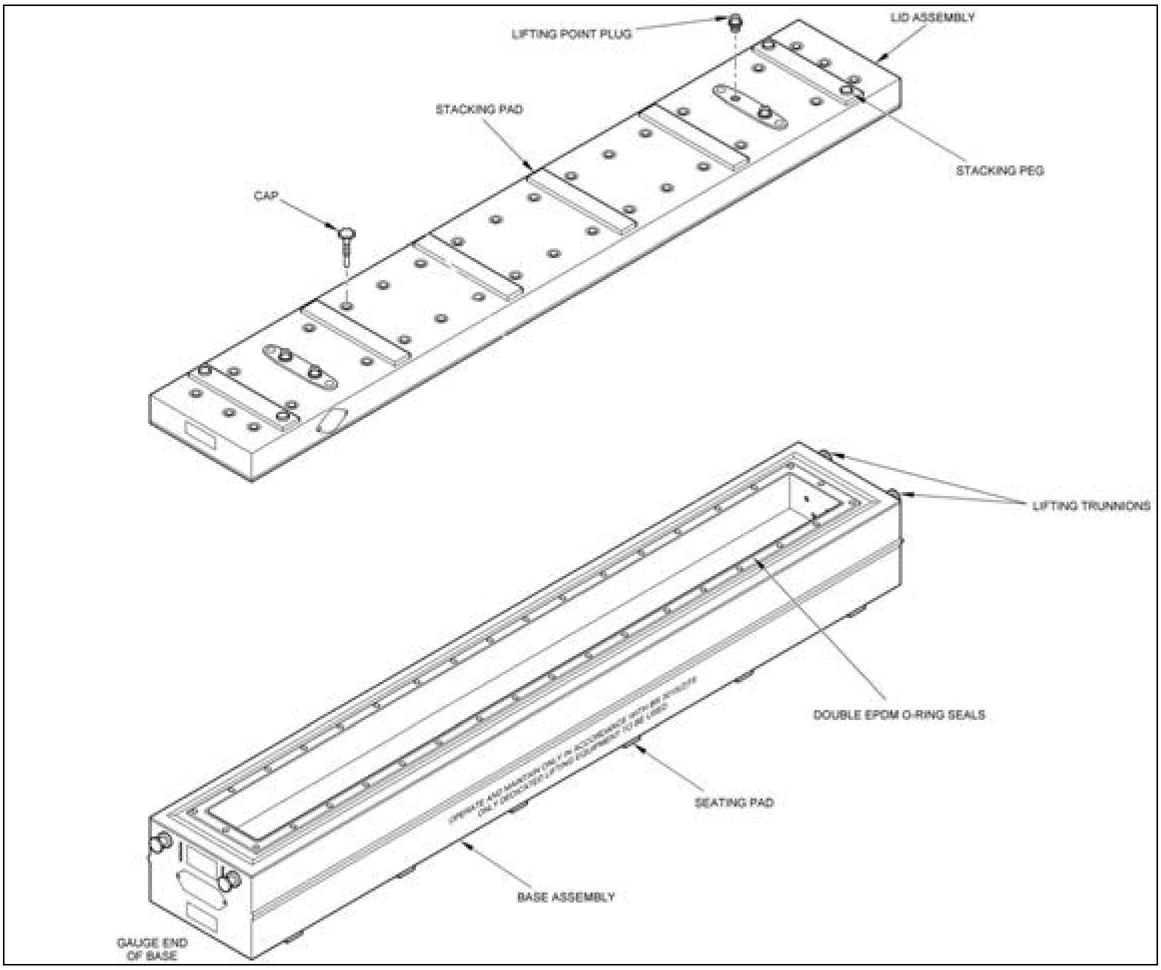

Figure 1. General Layout of the Fresh Fuel Package

The fresh fuel package is a double-skinned stainless steel box. The space between the stainless steel shells contains impact absorbing, flame-retarding foam. The polyurethane foam (PU) used in the package design exhibits almost isotropic properties with compression. The performance variation across all three axes of compression is typically only 10%. This is a significant advantage to the performance of the package, and the cost of manufacture over other designs that use metallic honeycomb and wood shock absorbers. The foam is also an excellent thermal barrier should it be involved in a fire. The foam will progressively intumesce (that is, its surface swells) and degrade from the hot surfaces inwards to leave a charred material that remains as a rigid thermal insulator. In addition, as the foam burns, gases are released, removing much of the heat energy. Finally, there is evidence that the properties of the foam do not degrade over the design lifetime of the package.

The structure and content of the criticality safety case for the transport and storage of the fresh fuel package complies with the requirements of the UK Department for Transport (DfT Guide to

Applicants, 2001) and International Atomic Energy Authority (IAEA, TS-R-1, 2003). The regulations state that the criticality assessment should include investigations on the change in the neutron multiplication factor (k_{eff}) due to impacts, flooding and fire. Sensitivity studies should also be carried out to determine the effects on the k_{eff} of any uncertainties in the composition and physical structure of the fissile material and package materials. Since the package contains a large volume of foam, the material could make significant contributions as a neutron reflector, moderator or absorber and therefore the treatment of foam is an important part of the criticality safety case.

GENERAL METHODOLOGY

The objective of the criticality assessment is to demonstrate that, using calculation and reasoned argument, there will always be sufficient sub-critical margin for packages in isolation and for arrays of packages.

The main method used to support the criticality safety case is the modelling of single and arrays of packages using the criticality code MONK, Version 8B. MONK (ANSWERS(98)6 Serco Assurance, User Guide for Version 8) is a Monte Carlo code widely used in criticality assessments carried out in the United Kingdom. The DICE JEF2.2 nuclear data library was used in the calculations.

Detailed MONK models of the package and fuel were created. Most of the calculations were performed using a finite array of packages. Numerous sensitivity studies were performed to find the most reactive arrangement and demonstrate that this arrangement was still well sub-critical (design target $k_{eff} < 0.85$) for routine, normal and accident conditions.

An important set of sensitivity studies modelled foam in a variety of ways to determine which representation would maximise the k_{eff}.

MODELLING OF UNBURNT FOAM

Sensitivity studies were carried out to determine the elemental composition of the foam that would maximise the k_{eff}. This was done by calculating the k_{eff} where the weight fraction of a chemical element in the foam is set to the maximum and minimum limits allowed by the manufacturing specification of the foam. Each calculation consists of changing only one element in the foam. The unburnt foam composition is given by the combination of the changes in the elements in the foam that increased the k_{eff} (even if the resulting composition was not physically possible).

IMPACT DAMAGE TO THE FOAM

A finite array of packages under impact conditions was modelled. In an accident it is assumed that each package has suffered a severe impact. An impact on one face of each package could result in a permanent compression of each package in that direction, thus bringing the fuel closer together when an array of packages is modelled. This is referred to as knock-back. The amount of knock-back used in an accident came from finite element impact predictions and was confirmed by drop tests. In modelling the accident for an array of packages, the knock-back was applied through-out the length of the package. A simple formula was used to model the crushed foam on the side of the package with the knock-back. The density of the crushed foam was modified so that the mass of the foam was conserved.

No claim is made that the confinement system will be watertight under normal and accident conditions. Sensitivity studies were performed to determine the most reactive differential flooding scenario. The k_{eff} for this accident was 0.7375 (one standard deviation is 0.0008). This accident corresponds to flooding of only the fuel. The rest of the package was dry.

Rolls-Royce has used this calculation as a baseline to carry out several sensitivity studies to take account of variations in the as-built parameters of the fuel and package. Finally, the worst case was defined as the combination of all the variations that can increase the reactivity. The criticality safety case demonstrated that, even with this extremely unlikely combination, the array of packages was still well sub-critical.

GENERAL BEHAVIOUR OF FOAM IN A FIRE

Most of the variations in the parameters are usually well defined, for example as-built variation of the fuel composition. However, the behavior of PU foam under fire is complex. The composition and structure of the burnt foam can have a significant effect on the k_{eff}.. A number of investigations were performed to find a means to represent burnt foam that Rolls-Royce is confident is conservative, that is that would bound all changes in the foam that could lead to an increase in the k_{eff}.

Rolls-Royce has commissioned fire tests on boxes containing the foam. One such test exposed one side of the box to 800ºC for thirty minutes. After the test, the test box was cut open (see Figure 2). It was discovered that, although there was charring, the foam maintained its shape. Gases were observed to emanate from the box during the fire test.

Figure 2. Effect on the Foam Following a Fire on the Other Side of the Test Box

Derek Putley (Putley, 2006) gave a presentation at an ANSWERS Seminar on the assessment of packages damaged by fire. Putley described the “traditional” approach where a package with damage by fire would be modelled by a reduction in the thickness of the organic material e.g. foam and cork. The new approach (which has been reviewed by the UK’s Department for Transport (DfT)) is to consider the change in the chemical composition of the organic material. An important issue would be hydrogen depletion as a precursor to combustion. In the absence of oxygen, heat from a fire could lead to gaseous hydrogen and carbon monoxide being driven off the burnt foam.

An accurate, physical representation of the burnt foam would be difficult to produce. In addition the actual composition of the burnt foam is dependent on the fire conditions. Rolls-Royce has carried out sensitivity studies using relatively simple changes to the foam to represent extreme damage under fire. From these sensitivity studies, a pessimistic representation for burnt foam was identified.

The results presented in this paper illustrate the kind of investigations Rolls-Royce believes should be considered in any analysis of packages containing large amounts of foam material.

MODELLING BURNT FOAM AS SOOT

Soot was modelled as small carbon spheres randomly distributed in void (very low density water). Rolls-Royce used MONK’s RANDOM HOLE feature to carry out this investigation. Two sensitivity studies were performed. The first study was to determine the effect on the k_{eff} due to variation of the volume fraction of the spheres in the space that was occupied by foam. A constraint on sphere size was used (actually, a uniform distribution of radii between 0.001cm and 0.0005cm was modelled). The second study considered the effect of carbon sphere size on the k_{eff} (with a fixed volume fraction so that, the larger the spheres, the fewer there are of them). It should be noted that, in contrast, the first study does not conserve the total amount of carbon. The results are presented in Figures 3 and 4. It should be noted that the error bars correspond to three standard deviations, that is, 0.0024.

In the variation of volume fraction study, two different densities of carbon were used (this refers to the density of the material inside the sphere). The first set of results were produced by assuming that the carbon spheres had the same number density as the foam. The second set of results was produced by using a higher density of carbon. The reason for increasing the carbon density was to observe more clearly any trends that may be masked by small changes in the k_{eff}. The density employed was that of amorphous carbon (Perry’s Chemical Engineer’s Handbook). Amorphous carbon was used simply to produce an upper limit on the density of carbon. Comparing the results in Figures 3 and 4, it can be seen that the amount of carbon in the space occupied by the foam has a greater influence on the k_{eff} than the size of the spheres. It should be noted that, when amorphous carbon is used in the study (Figure 3), a volume fraction of carbon in the soot of about 2% preserves the total carbon content of the unburnt foam (implying $k_{eff} < 0.77$).

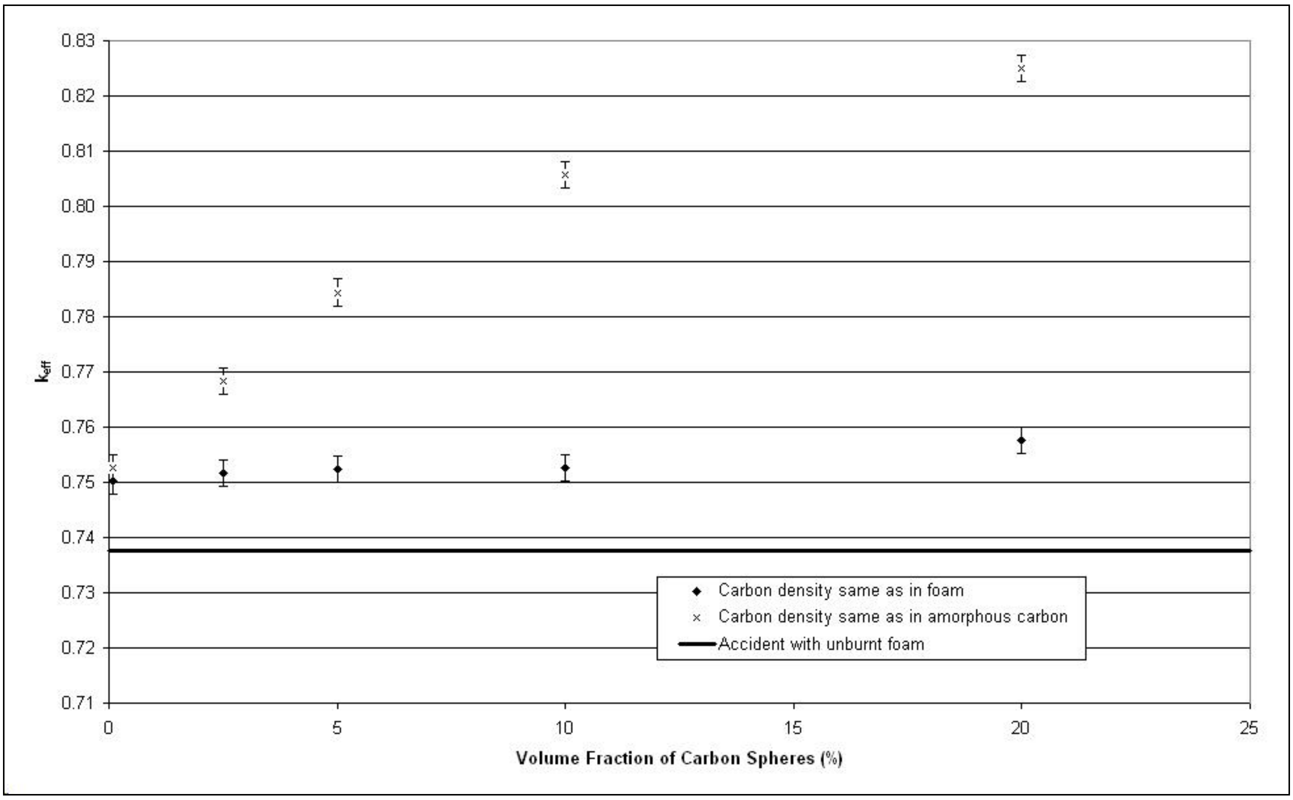

Figure 3. Variation of the k_{eff} With Volume Fraction – Maximum Radius of the Spheres is 0.001cm

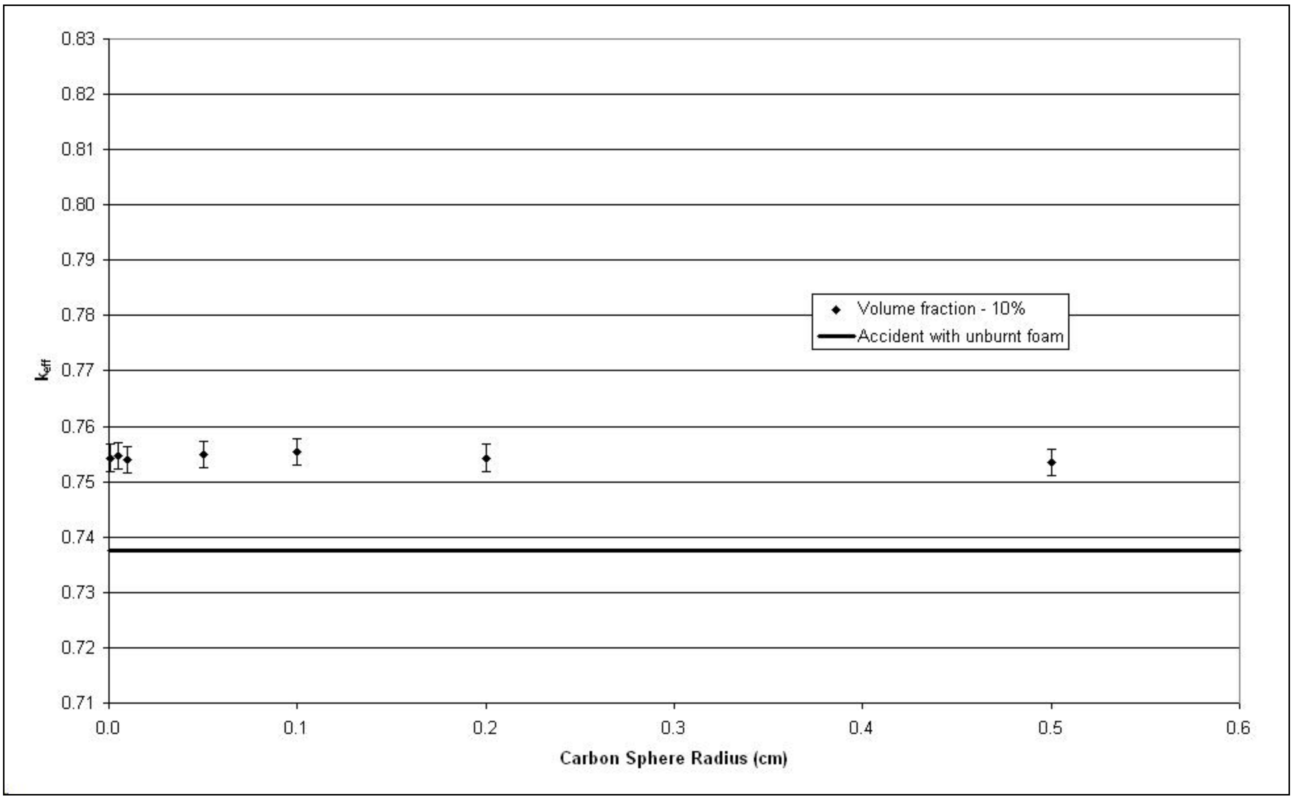

Figure 4. Variation of the k_{eff} with Size of the Carbon Spheres - Volume Fraction is 10%

MODELLING OF THE BURNT FOAM AS A CHARRED LAYER

Under the thermal tests commissioned by Rolls-Royce, the foam was shown to progressively intumesce (that is, its surface swells) and degrade from the surface inwards, leaving a rigid charred layer. In these tests the charred foam maintains its shape. An extreme representation of burnt foam would be that the structure of the foam completely breaks down leaving a carbon layer on the surface of the inner steel shell.

Sensitivity studies were carried out by modelling the burnt foam as a carbon layer of varying thickness. It was assumed that other chemical elements have been completely removed. In one sensitivity study, the layer consisted of carbon of the same number density as in the unburnt foam. In another study the layer of carbon number density corresponded to amorphous carbon. The use of amorphous carbon considerably increases the amount of carbon in the layer (for the same thickness). The results are presented in Figure 5.

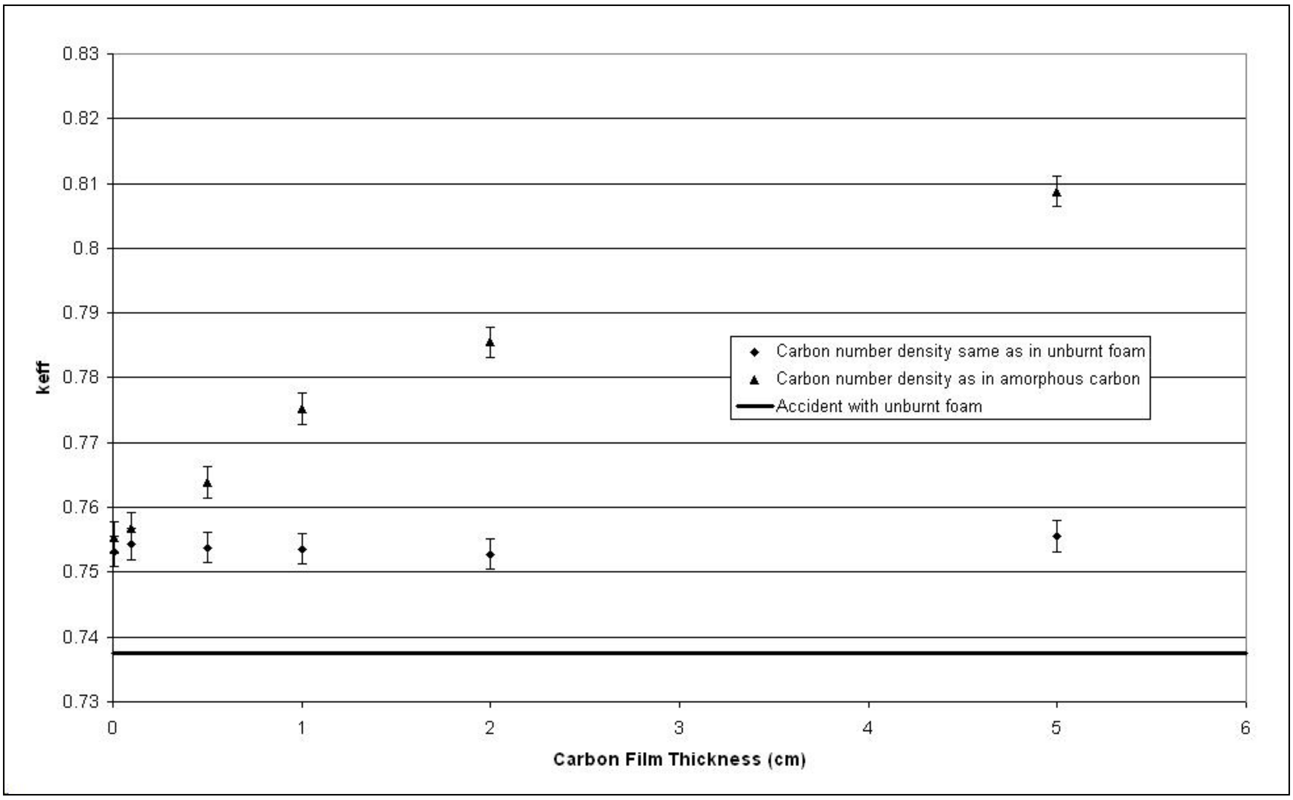

Figure 5. Variation of the k_{eff} with the Thickness of the Carbon Layer

The results presented in Figure 5 show that, once again, the k_{eff} is influenced by the amount of carbon in the space occupied by the foam. It should be noted that preserving the amount of carbon in unburnt foam would lead to a maximum carbon layer thickness of about 0.3cm if burning the foam leaves a layer made from amorphous carbon. The k_{eff} for an amorphous carbon layer is about 0.76.

The results of the previous sensitivity studies suggest that it is the amount of material, in particular carbon that has a large influence on the k_{eff}. For example, in the cases where the amount of carbon is that in unburnt foam (Figure 3, volume fraction is 2% and Figure 5, amorphous carbon layer thickness is 0.3cm) the values for the k_{eff} are very similar (0.77 to 0.76 respectively).

The results presented in Figures 3 to 5 are from investigations where the foam has completely disintegrated. The findings from the thermal tests show that, although there was charring throughout the foam, the burnt foam did not disintegrate. The next section examines the change on the k_{eff} by changing the chemical composition of the foam (without changing its geometric foam or volume).

VARYING THE CHEMICAL COMPOSITION OF FOAM

A study was carried out to determine the effect on the k_{eff} of removing each chemical element from the foam. There were no changes to the number density of the remaining elements in the foam. There are a number of orders in which elements can be removed. In one study hydrogen was first removed from the foam. In another study, carbon was first removed, followed by hydrogen. The results are presented in Figure 6. Removing hydrogen significantly increased the k_{eff} whilst removing the carbon reduced the k_{eff}.

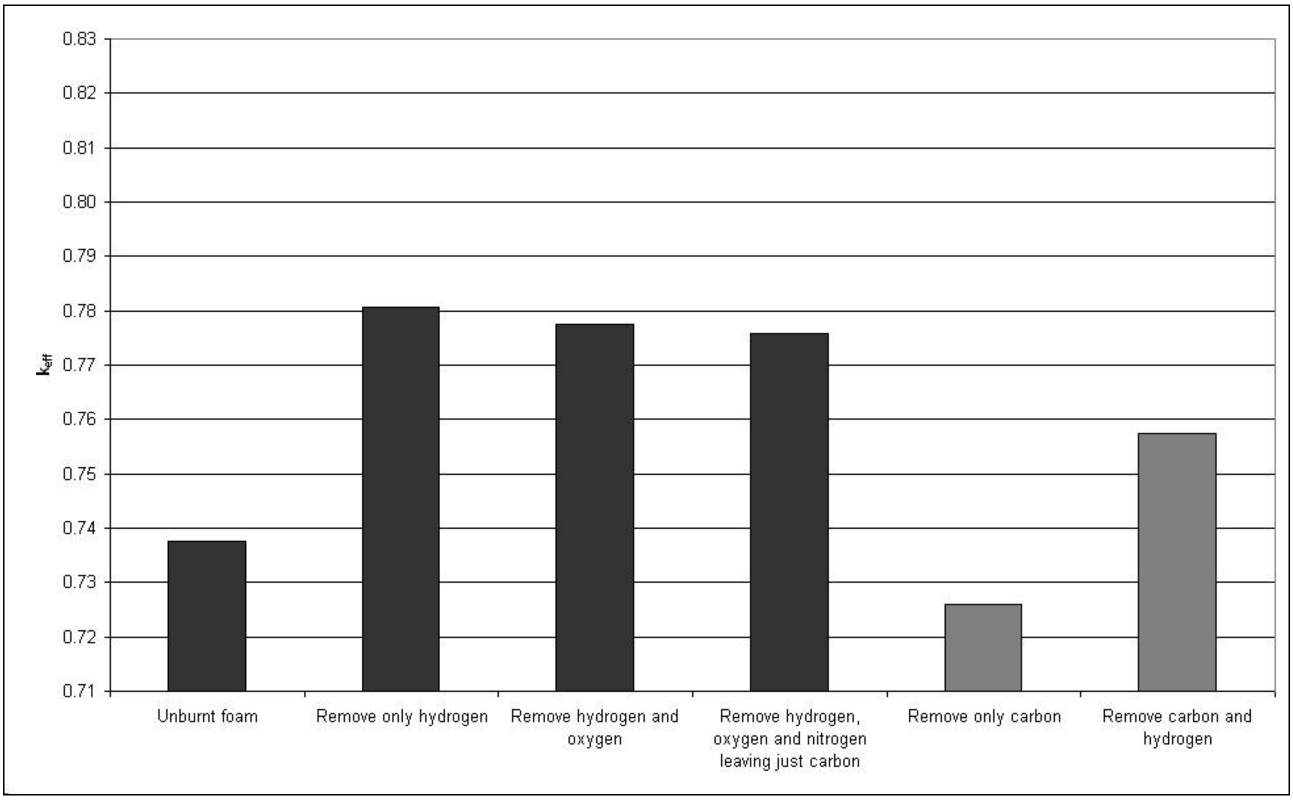

Figure 6 Effect on the k_{eff} of Removing Elements from the Foam

REPRESENTATION OF BURNT FOAM ADOPTED IN THE ROLLS-ROYCE CRITICALITY ASSESSMENT

Rolls-Royce believes that the removal of only hydrogen from the foam best represents burnt foam. The findings from the fire tests (see Figure 2) showed that the foam kept its shape and that gases (probably removing the hydrogen in the foam) were observed to be driven off from the foam. Extreme approximations such as soot (that is, void containing a low density distribution of small carbon particles) or the formation on surfaces of a dense carbon layer (void elsewhere) were considered highly unlikely to represent burnt foam. Furthermore, the sensitivity studies showed that, to achieve the increase in the k_{eff} due to hydrogen removal would require more carbon than is actually present in unburnt foam.

ADDITION OF WATER TO BURNT FOAM

A sensitivity study was carried out to determine the effect on the k_{eff} of the addition of water to burnt foam. In the study water in burnt foam was represented as a homogeneous mush. MONK calculations were carried out for different number densities of the hydrogen and oxygen in water. The results are presented in Figure 7 and clearly show that adding water to burnt foam would significantly decrease the k_{eff}.

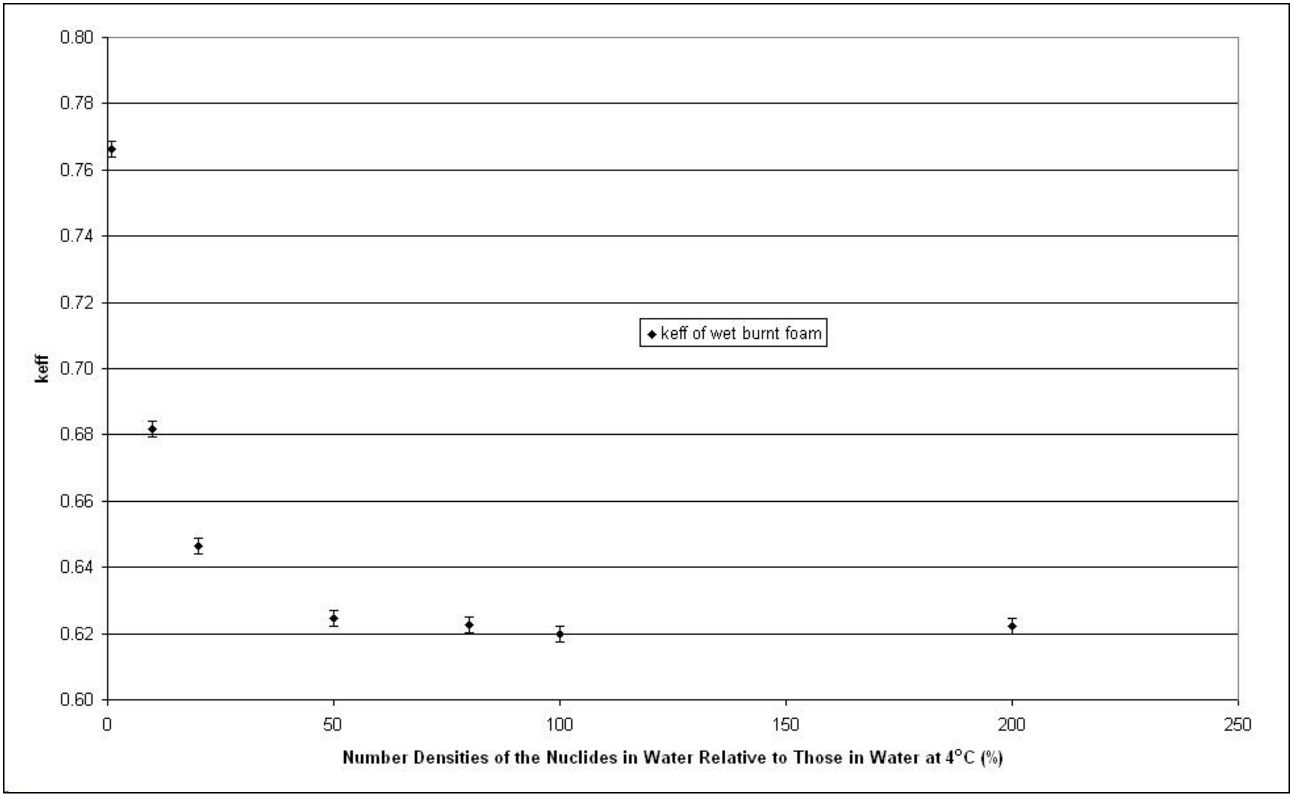

Figure 7. Effect on the k_{eff} on the Addition of Water to Burnt Foam

SUMMARY AND CONCLUSIONS

The Rolls-Royce designed fresh fuel package contains large amounts of impact-resistant foam. In a criticality assessment of packages containing large amounts of foam, the treatment of this material under accident conditions such as impact and fire needs to the considered. The accurate representation of burnt foam is difficult. However a number of sensitivity studies with different representations of the foam damaged by fire enabled the production of a pessimistic but still reasonably realistic representation of burnt foam. Removing hydrogen whilst leaving oxygen, carbon and nitrogen number densities (and the volume of the foam) unchanged was considered conservative.

ACKNOWLEDGMENTS

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