# Criticality Assessments Of Polyurethane Foam

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# Introduction

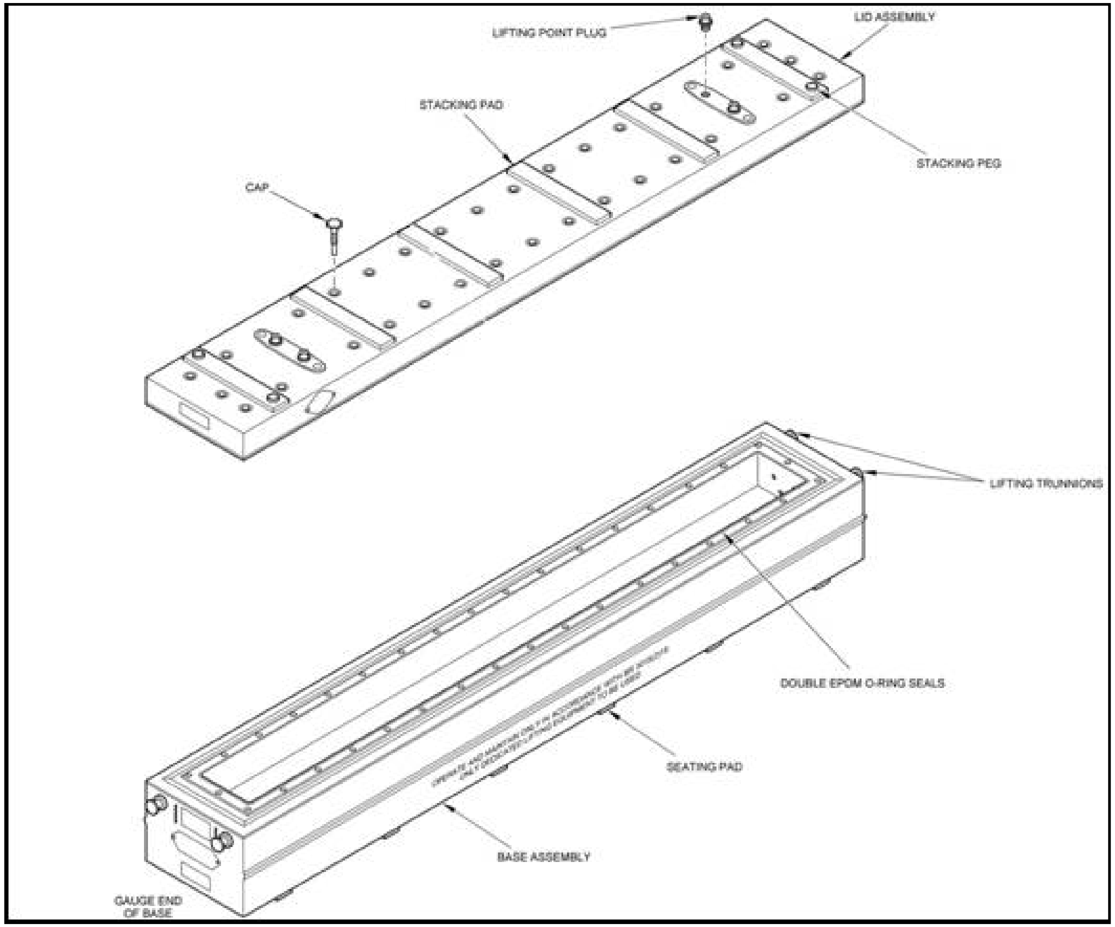
- Rolls-Royce has designed a fresh fuel package.
- The design incorporates large amounts of polyurethane foam.
- A criticality assessment must consider the effect on the neutron multiplication factor of foam especially when burnt.

# Introduction (continued)

- **Rolls-Royce has adopted the following approach to find a conservative yet reasonably realistic representation of burnt foam.**

- The following were investigated
  - The effect of varying the elemental composition of the foam in particular hydrogen and carbon.
  - The experimental analysis of burnt foam.
  - Extreme physical representation of burnt foam.
  - The effect on the $k_{eff}$ of adding water to burnt foam.

# Fresh fuel package design



# Polyurethane foam

- The polyurethane foam used in the package:
  - Impact absorbing.
  - Flame retarding.
  - Performance across across all three axes of compression is almost isotropic.
  - There is evidence that the properties of the foam do not degrade through the design-life of the package.

# Polyurethane foam under fire

- **Under fire the foam will intumesce (its surface swells) and degrade from the hot surface inwards to leave a charred material that continues to act as a rigid thermal barrier.**
- **In addition gases are released removing much of the heat energy.**

# Thermal test

# Earlier work on combustion of organic materials.

- Derek Putley (ANSWERS Seminar, UK, 2006).
- Examined what can happen to organic material under combustion especially in the absence of oxygen.
- Combustion of organic material is complex.
- In the absence of oxygen hydrogen and carbon monoxide gases released leaving lower density carbon compounds.
- Work reviewed by the UK Department for Transport (DfT).

# Recommendations following DfT Review

- **Need to consider changes in the composition of the material in particular hydrogen depletion.**

# Calculational methods

- Used MONK8B using the DICE JEF2.2 nuclear data library.
- Created detailed MONK models of the fuel and fresh fuel package.
- Sensitivity studies were ran on finite arrays of the packages.
- Note sensitivity studies carried to values that are no physically possible to demonstrate trends.
- One standard deviation is 0.0008.
- Number densities of nuclides in the foam derived from the manufacturing specifications.

# Modelling of unburnt foam

- **Sensitivity studies were carried out to determine the elemental composition of the foam that would maximise the keff.**
- **Calculations were carried out where one of the chemical elements was at the maximum or minimum limits of the weight fraction allowed by the manufacturing specification.**
- **Unburnt foam composition given by the combination of the changes that increased the keff (even if the composition is not physically possible).**

# Modelling of impact damage to foam (1)

- **In normal operation and accident conditions the package can undergo impacts on a package face.**
- **An impact on one face of each package could result in permanent compression of that package in that direction. In a finite array of packages the fuel could become closer together (knockback).**
- **Amount from knockback used in an accident came from finite element impact predictions and confirmed by drop tests.**

# Modelling of impact damage to foam (2)

- **Knock-back applied throughout one side of the package.**
- **Compressed foam modelled by increasing its density to conserve the amount of foam in the package.**

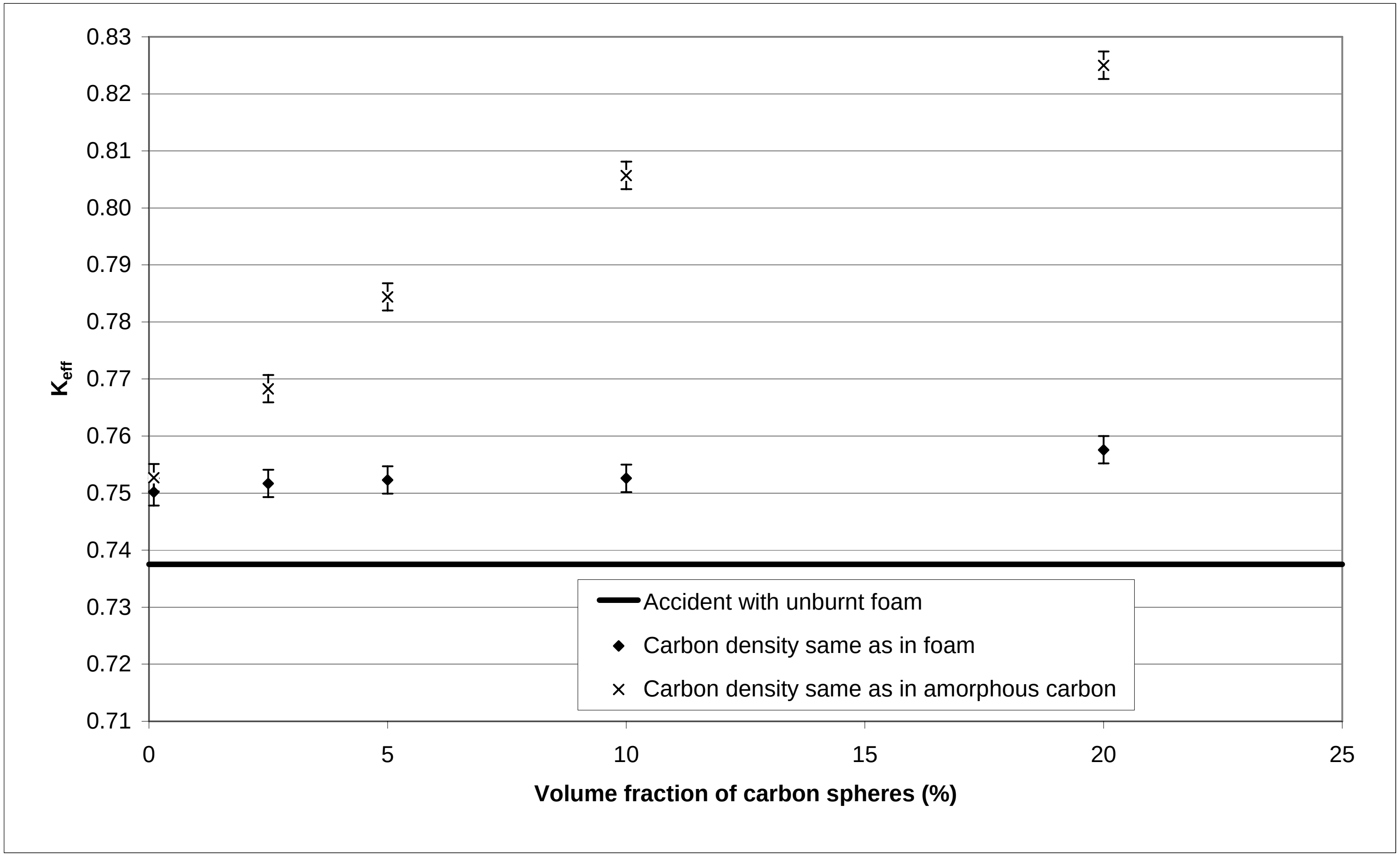
# Baseline accident case.

- No claim made that the package is watertight in an accident.
- Ran a set of calculations to determine the most reactive differential flooding case using a finite array. These cases include the knockback and unburnt foam.
- The worst differential flooding case is flooding of the fuel with the rest of the package dry.
- For this presentation this case will be used as a baseline to compare different representations of burnt foam (keff=0.7375).

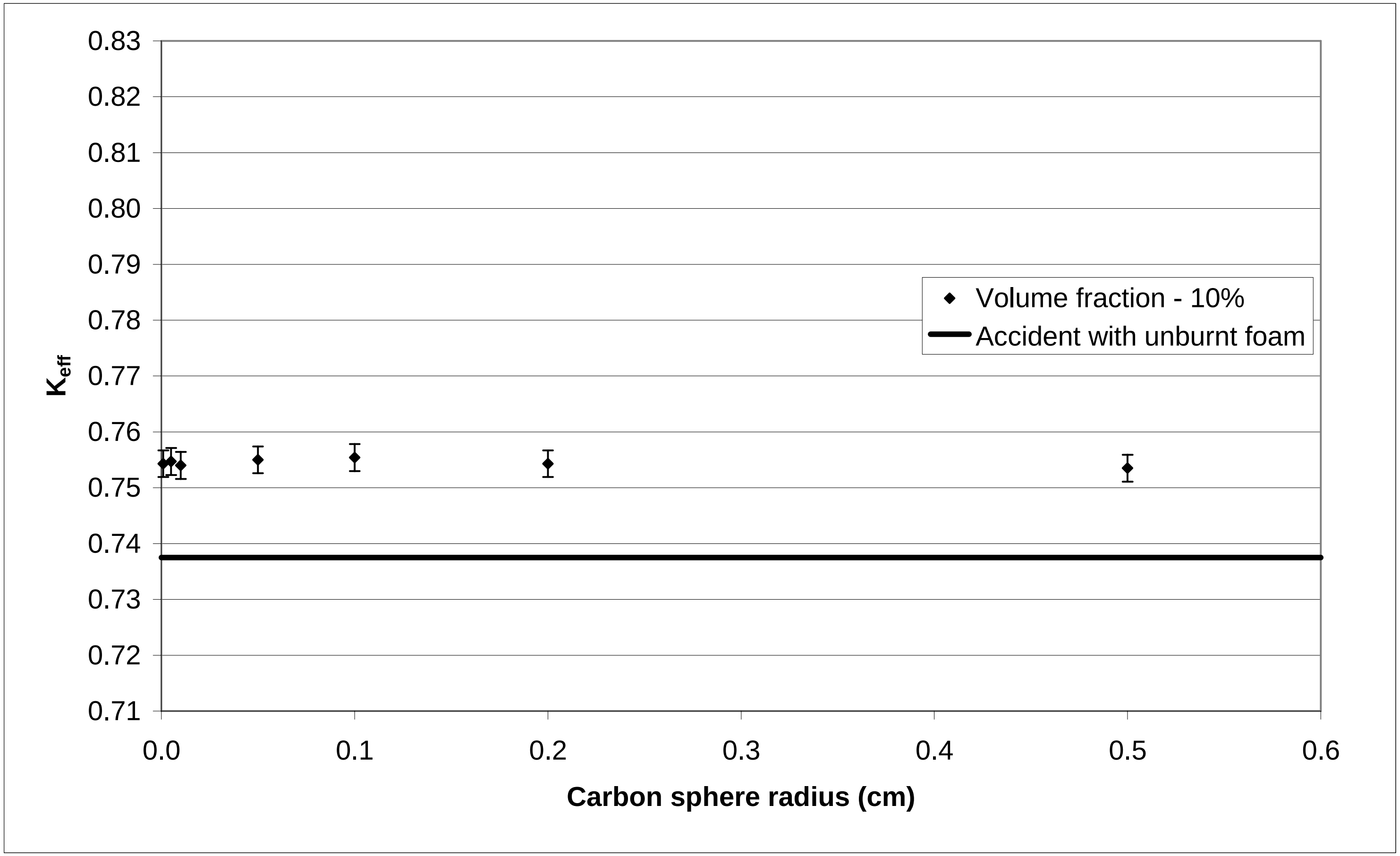
# Extreme physical representations of burnt foam (1)

- **Soot**
  - **Modelled as spheres of carbon randomly distributed in void.**
  - **Void represented as very low density water.**
  - **Vary volume fraction of the spheres in foam but keep radii of the spheres within 0.0005 to 0.001cm**
    - **Spheres made of carbon of the same number density as in unburnt foam.**
    - **Spheres made from carbon of higher density than in the foam (Used amorphous carbon).**
  - **Vary radii of the spheres but keep the volume fraction fixed.**

# Volume fraction varying, maximum sphere radius is 0.001cm.



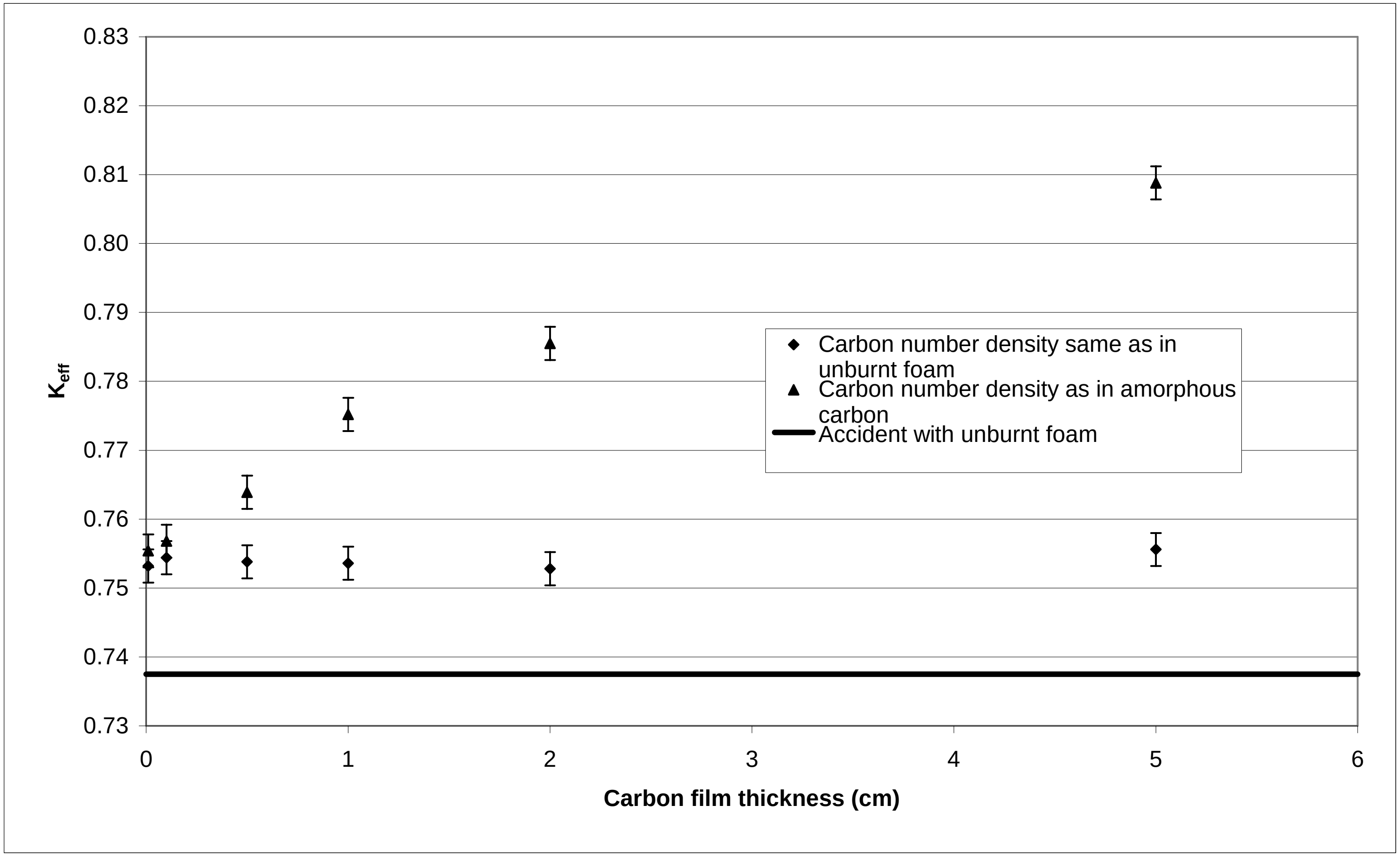
# Sphere radii varying up to 0.6cm, volume fraction = 10%.



# Extreme physical representations of burnt foam (2)

- Assume foam completely breaks down to leave a carbon layer on the surface of the steel shell of the inner cavity.
- Vary thickness of carbon.
  - Carbon layer made of carbon of the same number density as in unburnt foam.
  - Carbon layer made of carbon of higher density than in unburnt foam (amorphous carbon).

# Variation of the carbon layer thickness (up to 6cm)



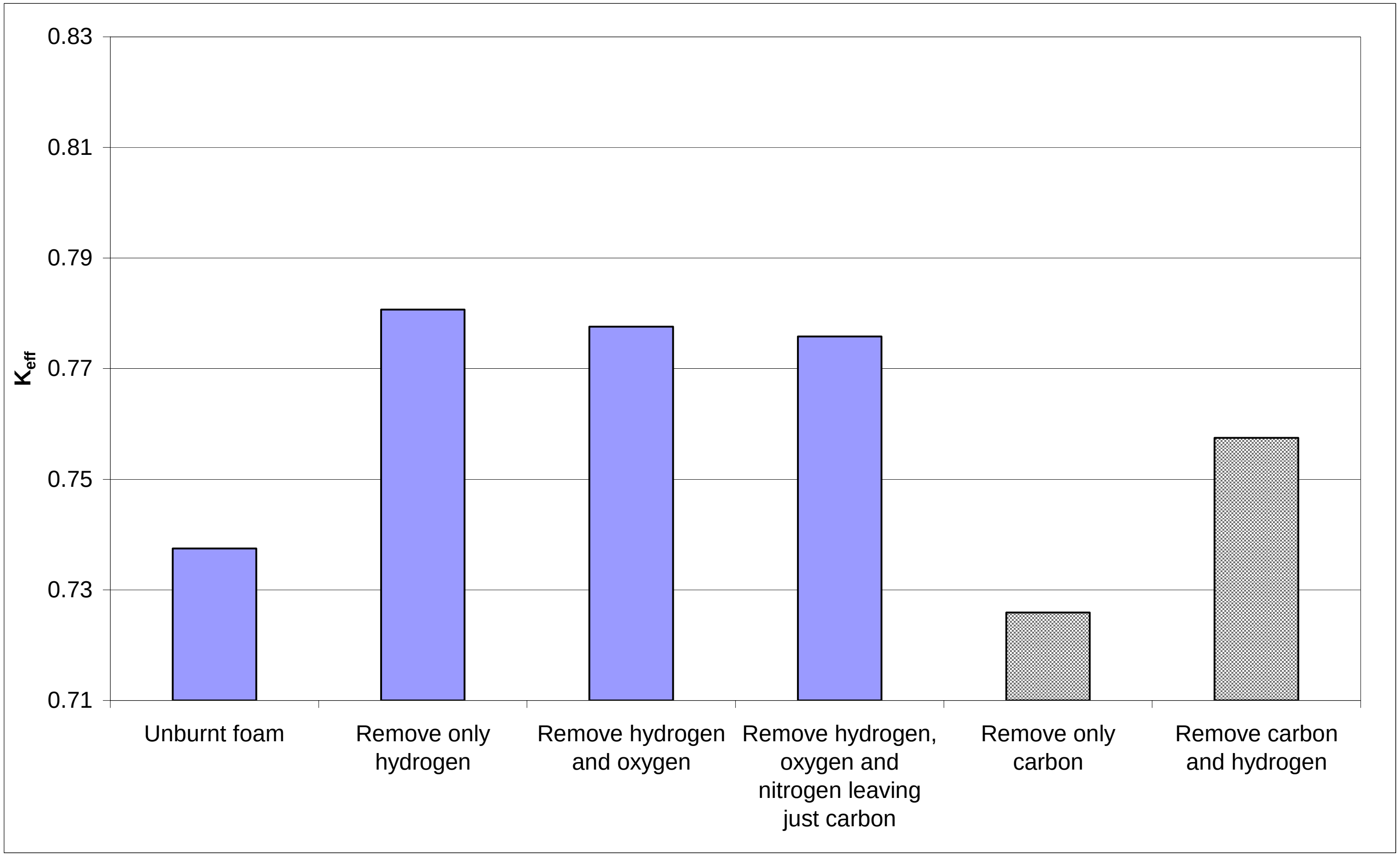
# Extreme physical representations of burnt foam (3)

- **Sensitivity studies such as varying the volume fraction of the carbon spheres in soot and the thickness of the carbon layer do not conserve the amount of carbon.**
- **Amorphous carbon results but the amount of carbon is the same as in unburnt foam:**
  - **Soot – keff ~0.76**
  - **Carbon layer ~ 0.77.**
- **Suggest that the keff is determined more by the amount of carbon rather than the physical representation of burnt foam.**

# Chemical composition of foam

- Burnt foam assumed to maintain its shape.
- Sensitivity studies carried out to remove one element at a time from the foam.
  - Two orders investigated.
  - Remove hydrogen first and then other elements to leave carbon.
  - Remove carbon first and then hydrogen.
  - Number density of the remaining elements unchanged.

# Removing elements from foam - results



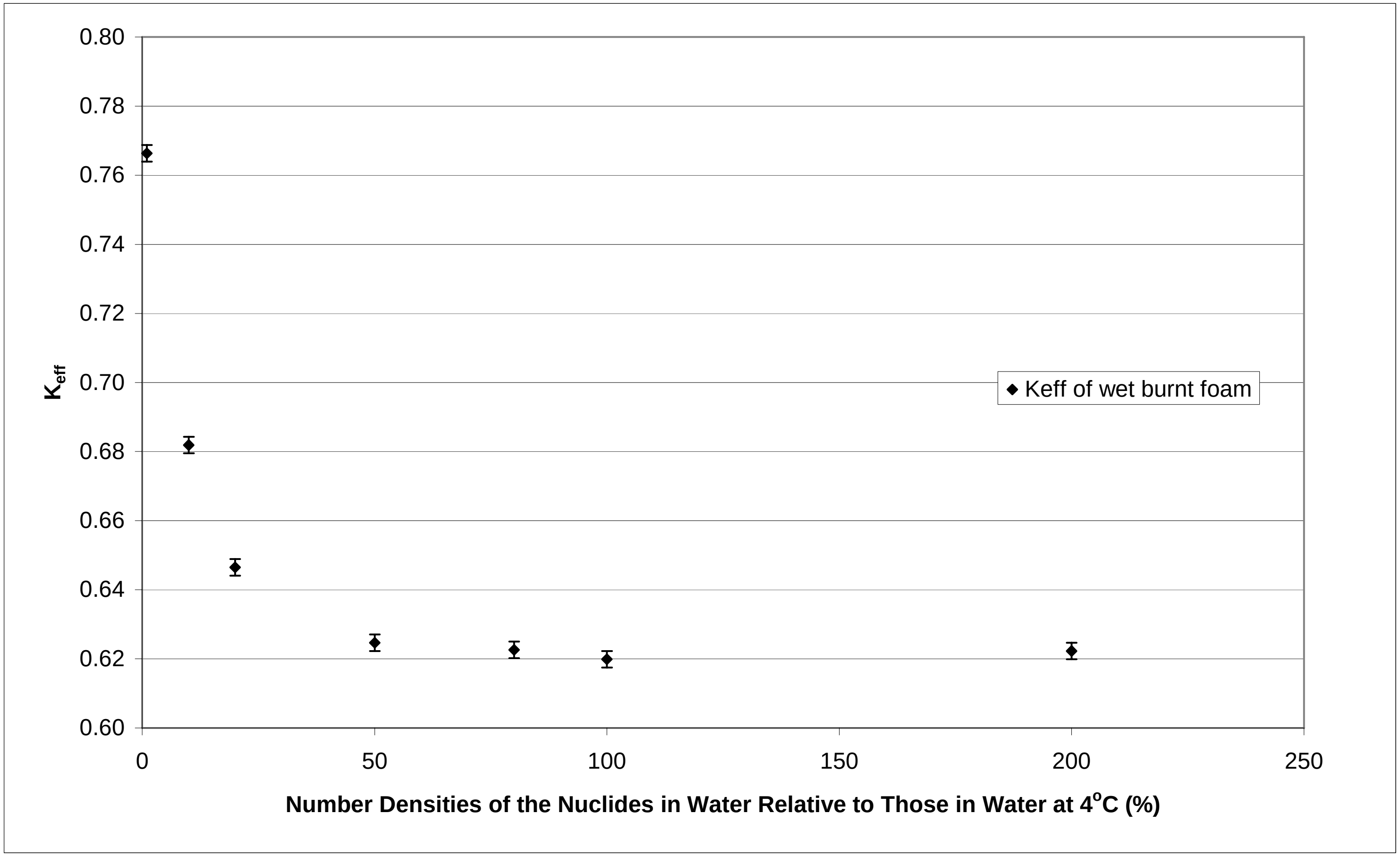
# Representation of burnt foam Rolls-Royce used in the criticality assessment

- Hydrogen removed from the foam, and not changing the number densities of the remaining elements.
- Conservative
  - Unlikely that all hydrogen will be depleted in a fire.
  - Some carbon will also be removed.
- Reasonably realistic
  - Thermal tests show that although there is charring throughout the burnt foam, the burnt foam kept its shape.

# Adding water to burnt foam

- Water in burnt foam represented by a mush in MONK.
- Sensitivity study carried out where the number densities of the hydrogen and water were varied.
- Results show that adding water to burnt foam decreases the keff so more conservative to model the foam dry.

# Adding water to burnt foam - results



# Conclusions

- A number of sensitivity studies were performed to determine a conservative but realistic representation of burnt foam.

- We believe that these studies should be considered in criticality assessments of packages containing large amounts of foam.