Burn-up Credit in Criticality Safety of PWR Spent Fuel

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Objectives

- To Model the spent fuel pool for a typical pressurized water nuclear power plant (Sizewell-B);
- To analyze the criticality events for different accident scenarios using WIMS-5D and MCNP5 neutronic codes;
- Studying the spent nuclear fuel inventory and activity.
Background

- Spent nuclear fuel is transferred from the reactor core after each cycle of operation. These spent fuel assemblies require safe management.
- Spent fuel assemblies are cooled down for a suitably period of time to cope with the decay heat produced by the fission products.
- Therefore, to remove the decay heat and radiation, the spent fuel assemblies are transferred to pool storage.
• The Spent fuel storage pool should provide safe storage conditions systems, and components to accomplish the following:
  ✓ Cooling System to remove the decay heat from the spent fuel providing a forced cooling;
  ✓ Water Chemistry Control System to prevent fuel degradation
  ✓ Criticality safety conditions, i.e., the spent fuel should be sub-criticality all the time;
  ✓ Radiation shielding conditions to protect the workers;
  ✓ The water gap between assemblies in the pool should be considerable to have enough cooling flow, and;
  ✓ Protect the fuel from mechanical damage.
There are two approaches for spent fuel assemblies after its removal from the core:

- Spent Fuel Pools
- Dry Cask Storage
Spent Fuel Pools

- Spent fuel assemblies are safely stored at pools to cool down by circulation through heat exchangers and provide shielding from radiation.
Dry Cask Storage

- Spent fuel assemblies are encapsulate at dry cask after storing at pool.
- Current practice is to move spent fuel to dry storage when reactor pools become filled or not processing.
Description of Sizewell-B NPP

- Sizewell B power station is the first PWR built in UK, Suffolk coast on the East Anglian coast.
- It is 4 loop PWR of Westinghouse type with 193 fuel assemblies and thermal capacity is $3411 \text{ MW}_{\text{th}}$ and the fuel enrichment for reloading is $3.1\%$ with average burn-up $33\text{GWd/MtU}$. 
• Size well B reactor operates under normal conditions for one-year cycle operation with average enrichment $= 3\%$ to reach average discharge burnup about $33\text{GWd/MtU}$.

• By performing depletion calculations by MCNPX, we can get the effective multiplication factor ($K_{\text{eff}}$) and the burnup behavior through the reactor operation cycle. Also, the activity of the spent fuel as will be presented in the next slides.
Sizewell-B core criticality through one cycle.
Burn Up vs time of one cycle
Sizewell-B Pool Description

The proposed design of the spent fuel pool are based on the following assumptions:

- Pool is rectangular in cross-section and approximately 40ft deep;
- Spent fuel pool can accommodate three reactor cores;
- Pool is filled with treated light water;
- Spent fuel racks made of stainless-steel plates sandwiched with \( \text{B}_4\text{C}/\text{Ag-In-Cd} \) of approximately \( 1/4 " \) thickness to insure a leak tight system and assembly pitch in the range (4.0-8.0) cm;
- Decay heat is removed by a special cooling system.
Simulation and Modelling of Spent Nuclear Fuel Pool

The proposed wet storage were simulated using WIMS-5D and MCNP5 neutronic codes to perform criticality safety analysis.

The basic conditions and assumptions which were applied are:-

• Use of Winfrith Improved Multi-group Scheme (WIMS-5D code) to get precise values of burned fuel concentrations at different burn-up and using Mont Carlo (MCNP5) for modeling and calculation of the multiplication factor (K_{eff}).

• Assuming the fuel is at its highest enrichment and maximum burn-up or fresh as a conservative case, also, the pool water is without boron.
Simulated Spent Fuel Assembly
by visedX_24E
Events related to criticality conditions

Based on Fukushima learnt lessons, a parametric study was investigated for four cases with the utilizations of different types of fixed absorbers through analyzing the criticality of the pool.

- Water loss accident
- Change of distance between assemblies
- Change of water density
- Different Burn Ups values
Change of $k_{eff}$ with Water loss accident
Water loss Accident

The causes of water loss in the spent fuel pool can be summarized as follows;

• Leak through the pool structure;
• Inadequate spent fuel pool level monitoring;
• Loss of coolant through pump circulation;
For spent fuel with different BUs with $\text{B}_4\text{C}$ half volume absorber, enrichment=5%, water density= 0.7g/cc and distance between assemblies=0cm
• As the water level decreases, $k_{\text{eff}}$ decrease due to the lack of moderation.
• We can notice that the behavior of criticality decrease at higher burn-ups due to the build up of Fission Products and the massive reduction of fissile material (U235)
Change of $k_{eff}$ with change of distance between assemblies
For fresh fuel enriched with 5% and water density= 0.7g/cc.
For spent fuel with different BUs, enrichment=5% and water density= 0.7 g/cc
• The previous Figures show that as the pitch increases the effective multiplication factor \( k_{\text{eff}} \) decreases as a result of Dancoff factor (i.e. self shielding).

• The first-flight escape probability must be corrected by the probability that a neutron escaping a fuel lump will enter another fuel lump, which referred to as the “shadowing effect”. This probability is called the Dancoff factor.
Change of $k_{\text{eff}}$ with different Burn Ups (BU)
For spent fuel in different BUs, enrichment=5% and water density= 0.7g/cc in two different spent fuel racks lined with $\text{B}_4\text{C}$ and Ag-In-Cd.
• From the previous Figures, we found that for the same $B_4C$ absorber total volume and for the same BU, as pitch increases, $k_{eff}$ decreases.

• Also for the same pitch, with half absorber volume, as BU level increases $k_{eff}$ decreases, and all cases of the spent fuel are subcritical.

• For the same pitch and different absorber like ($B_4C$ and Ag-In-Cd) $k_{eff}$ is more sub critical, for $B_4C$ and for more safety we can use $B_4C$ as an absorber between the spent fuel assemblies and can be lined in the fuel casts.
Change of $k_{\text{eff}}$ with change of water density
Causes of Water Density Change

The causes of water density change in the spent fuel pool can be summarized as follows:

• High temperature i.e.; decay heat increase;
• Deficiency of cooling system.
Fresh fuel with B₄C absorber total volume, distance between assemblies=0cm; and, enrichment = 5%.
The Spent fuel with two different burn ups and the distance between assemblies is 0cm and B₄C absorber total volume
• As water density decrease, $k_{\text{eff}}$ decreases, this is due to the high temperature which causes reduction in the reactivity (Doppler Broadening).
Studying the spent nuclear fuel inventory and activity.
• From the activity of the actinides radionuclides of spent fuel after cooling down for 1 month (30 Days), we can see that, the highest activity of plutonium (Pu241) is 3.03E+17Bq, which has a half life of 14 years and decays to Am241.
• For U235 has an activity 6.83E+10Bq with a half life of about 700 millions years and decays to Th231.
• Also, the knowledge of radionuclides composition are crucial for the interface between nuclear security and safeguard.
Conclusion

• Criticality accidents for nuclear fuel can be simulated and modeled using WIMS5D and MCNP5 Codes;
• Effective multiplication factor ($k_{eff}$) in the spent fuel pool increases as the spacing between the fuel racks deceases, the safe spacing should be more than 4cm;
• For fresh fuel, the effective multiplication factor ($k_{eff}$) increases as water density increases, as for burned fuel $k_{eff}$ decreases as water density increases due to the buildup of fission products and high temperature which causes reduction in reactivity as moderation decreases(Doppler Broadening).
- Water loss accident in the spent fuel pool can increase the possibility of fuel degradation due to the decrease in the decay heat removal;
- As the burn up value increases, the lower $k_{eff}$. This reduction is due to the accumulation of fission products and minor actinides as burn up increases.
- As the spent fuel has high activity, then it require special arrangements for handling, reprocessing and storage.
- The proposed design for spent fuel storage satisfy the criticality safety conditions through all the analysis and pool remains subcritical.
Thank you for your attention
Any questions?