# A Study on Effect of Assembly Power History to Gamma Dose Rate in Spent Fuel Pool at a Short Cooling Time


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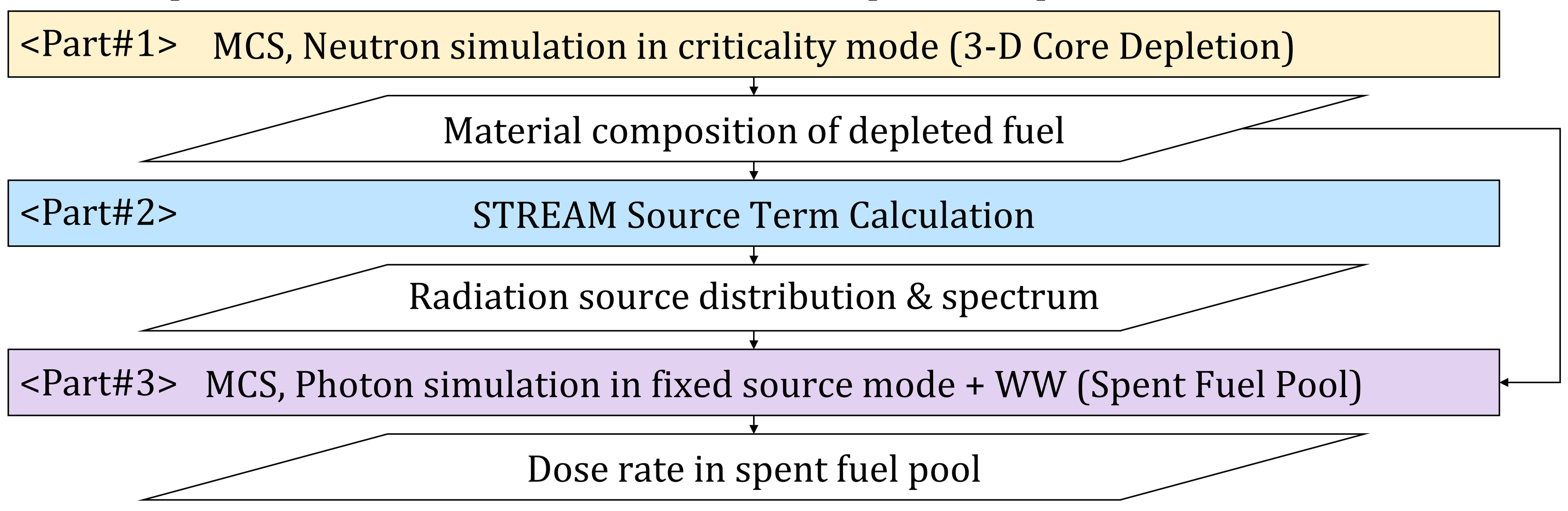
## Introduction

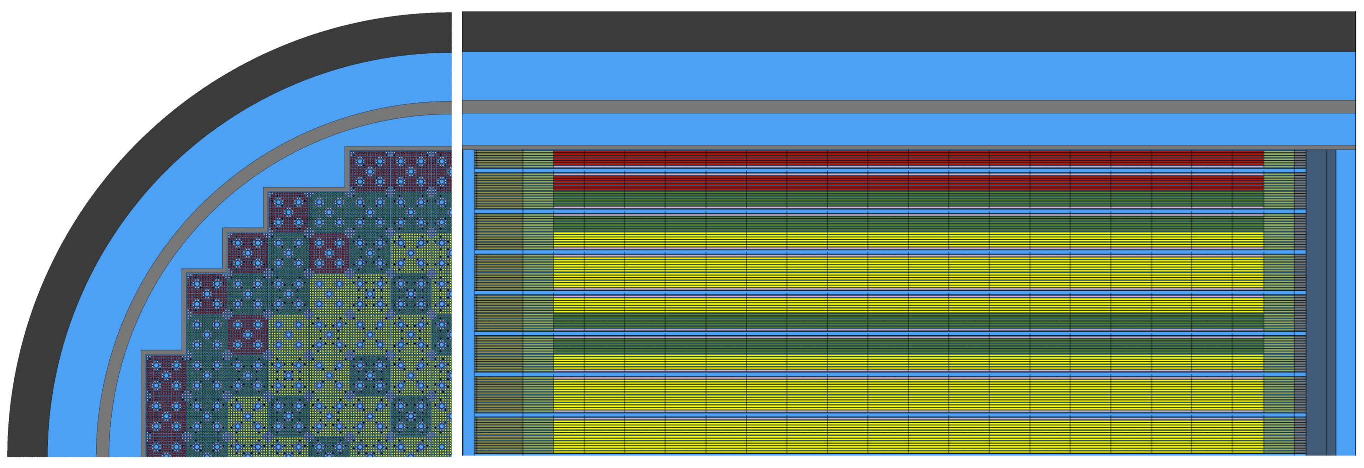
- The radiation dose rate on the water surface of spent fuel pool must be less than 25 $\mu$Sv/hr according to ANSI/ANS 57.1-1992.
- The radiation source terms of spent fuel can be affected by many parameters such as fuel enrichment, assembly burnup, power history, cooling time, etc.
- In this study, tendency of radiation source terms depending on burnup and power history is observed at a short cooling time of 100 hours to consider a refueling situation.

## Codes, Methods & Models

- A deterministic neutron transport code using Method of Characteristics, STREAM is used to calculate radiation source term. It is also used in depletion calculation of 2-D fuel assembly.
- It has a capability to compute radioactivity, decay heat, neutron and gamma source spectra for spent nuclear fuel.
- A Monte Carlo particle transport code MCS is used to 3-D whole core depletion calculation and gamma dose rate calculation in spent fuel pool.
- A weight window (WW) variance reduction technique is used in the gamma dose rate calculation.
- Calculation procedure for dose rate calculation in spent fuel pool.

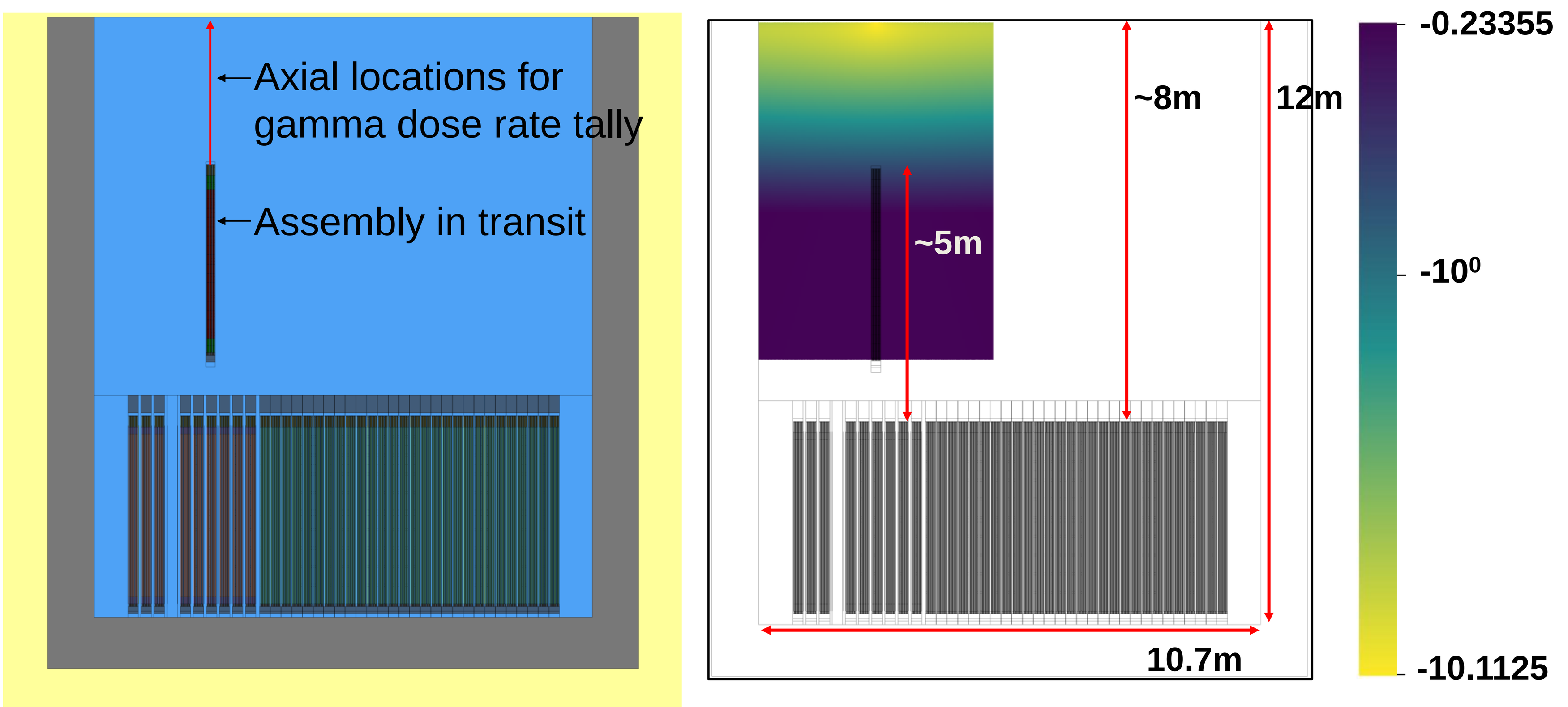



- Hypothetical OPR-1000 whole core model by MCS



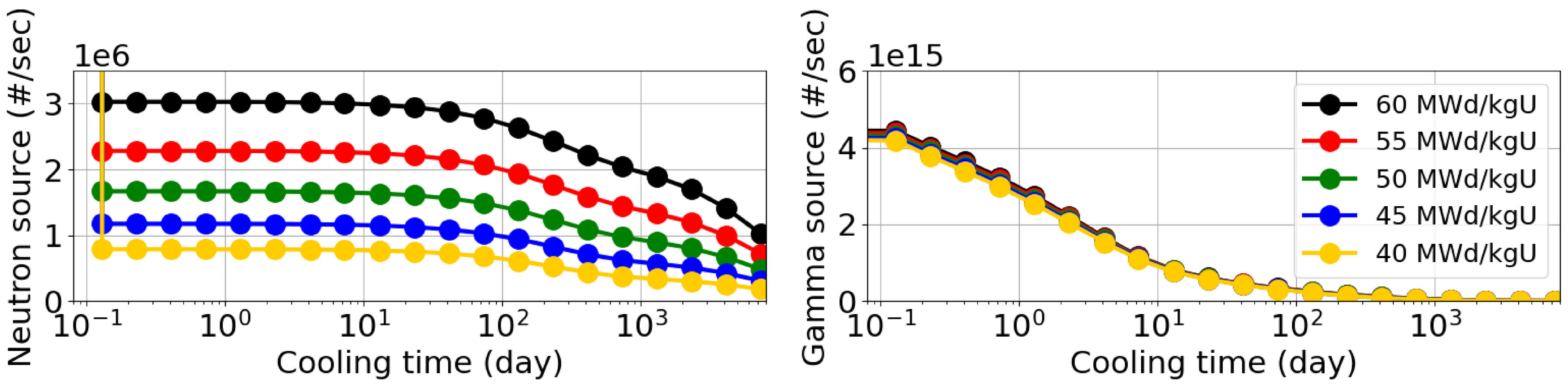
```
if w > w_upper then
  Split the particle
else if w < w_lower then
  Play Russian roulette
end if
```

- XZ view of spent fuel pool & weight window map in log10 scale

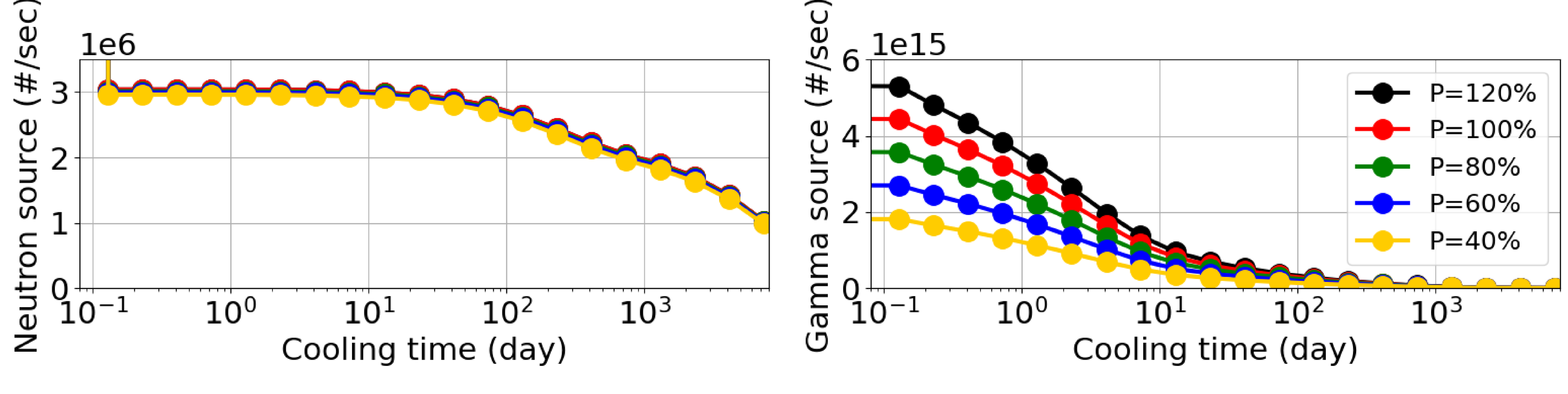



## Radiation Source Term Calculation for 2-D Fuel Assembly

- STREAM is used to depletion & source term calculations for PLUS7 fuel assembly.
- Case 1) Different assembly burnup with the same power density.
  Power density = 36.85 W/g up to each target burnup (60, 55, 50, 45, 40 MWd/kgU).




- Case 2) Same assembly burnup with different power history.
  Power density = 36.85 W/g (0−40 MWd/kgU)
  → 120, 100, 80, 60, 40% of 36.85 W/g (40−60 MWd/kgU)




## Radiation Source Term Calculation for 3-D Core Model

- Assembly-wise burnup and normalized power distribution at end of cycle.

FA-wise Burnup @ EOC (MWd/kgU)

| | H | J | K | L | M | N | P | R |
|---|---|---|---|---|---|---|---|---|
| 1 | 49.1 | 46.5 | 47.7 | | | | | |
| 2 | 20.8 | 20.9 | 20.2 | 15.7 | 47.8 | | | |
| 3 | 43.3 | 40.7 | 23.5 | 52.5 | 17.2 | 49.4 | | |
| 4 | 44.6 | 24.2 | 44.5 | 36.6 | 21.9 | 17.2 | 47.8 | |
| 5 | 23.9 | 44.0 | 38.9 | 42.6 | 36.6 | 52.5 | 15.7 | |
| 6 | 43.4 | 41.8 | 23.7 | 38.9 | 44.5 | 23.5 | 20.2 | 47.7 |
| 7 | 41.0 | 23.0 | 41.8 | 44.0 | 24.2 | 40.7 | 20.9 | 46.5 |
| 8 | 33.8 | 41.0 | 43.4 | 23.9 | 44.6 | 43.3 | 20.8 | 49.1 |

FA-wise Power @ EOC

| | H | J | K | L | M | N | P | R |
|---|---|---|---|---|---|---|---|---|
| 1 | 0.48 | 0.48 | 0.39 | | | | | |
| 2 | 1.21 | 1.21 | 1.14 | 0.90 | 0.39 | | | |
| 3 | 1.07 | 1.14 | 1.30 | 0.88 | 1.02 | 0.44 | | |
| 4 | 1.09 | 1.33 | 1.05 | 1.11 | 1.25 | 1.02 | 0.39 | |
| 5 | 1.32 | 1.08 | 1.12 | 1.05 | 1.11 | 0.88 | 0.90 | |
| 6 | 1.04 | 1.10 | 1.32 | 1.11 | 1.05 | 1.30 | 1.14 | 0.39 |
| 7 | 1.07 | 1.30 | 1.10 | 1.08 | 1.33 | 1.14 | 1.21 | 0.48 |
| 8 | 0.85 | 1.07 | 1.04 | 1.32 | 1.09 | 1.07 | 1.21 | 0.48 |

- Assembly-wise radiation source distribution at cooling time of 100 hours.
- Neutron source highly depends on burnup dist. & Gamma source highly depends on power dist.

Neutron source (1E+08/sec), Tcool = 100 hrs

| | H | J | K | L | M | N | P | R |
|---|---|---|---|---|---|---|---|---|
| 1 | 6.61 | 5.38 | 5.70 | | | | | |
| 2 | 0.36 | 0.37 | 0.33 | 0.15 | 5.84 | | | |
| 3 | 4.78 | 3.85 | 0.53 | 8.42 | 0.20 | 6.71 | | |
| 4 | 5.25 | 0.60 | 5.19 | 2.50 | 0.43 | 0.20 | 5.84 | |
| 5 | 0.57 | 4.97 | 3.16 | 4.38 | 2.50 | 8.41 | 0.15 | |
| 6 | 4.87 | 4.15 | 0.57 | 3.16 | 5.19 | 0.53 | 0.33 | 5.70 |
| 7 | 3.90 | 0.50 | 4.15 | 4.97 | 0.60 | 3.85 | 0.37 | 5.38 |
| 8 | 5.27 | 3.90 | 4.87 | 0.57 | 5.25 | 4.78 | 0.36 | 6.61 |

Gamma source (1E+17/sec), Tcool = 100 hrs

| | H | J | K | L | M | N | P | R |
|---|---|---|---|---|---|---|---|---|
| 1 | 2.98 | 2.95 | 2.46 | | | | | |
| 2 | 6.38 | 6.37 | 5.99 | 4.60 | 2.44 | | | |
| 3 | 6.28 | 6.60 | 6.95 | 5.32 | 5.24 | 2.72 | | |
| 4 | 6.47 | 7.15 | 6.23 | 6.27 | 6.56 | 5.24 | 2.44 | |
| 5 | 7.08 | 6.36 | 6.40 | 6.13 | 6.27 | 5.32 | 4.59 | |
| 6 | 6.12 | 6.38 | 7.04 | 6.40 | 6.23 | 6.95 | 5.98 | 2.46 |
| 7 | 6.17 | 6.92 | 6.38 | 6.36 | 7.15 | 6.60 | 6.38 | 2.95 |
| 8 | 5.16 | 6.17 | 6.12 | 7.08 | 6.47 | 6.28 | 6.38 | 2.98 |

- Assembly-wise radiation source distribution at cooling time of 20 years.
  - Both neutron & gamma sources highly depend on burnup distribution.

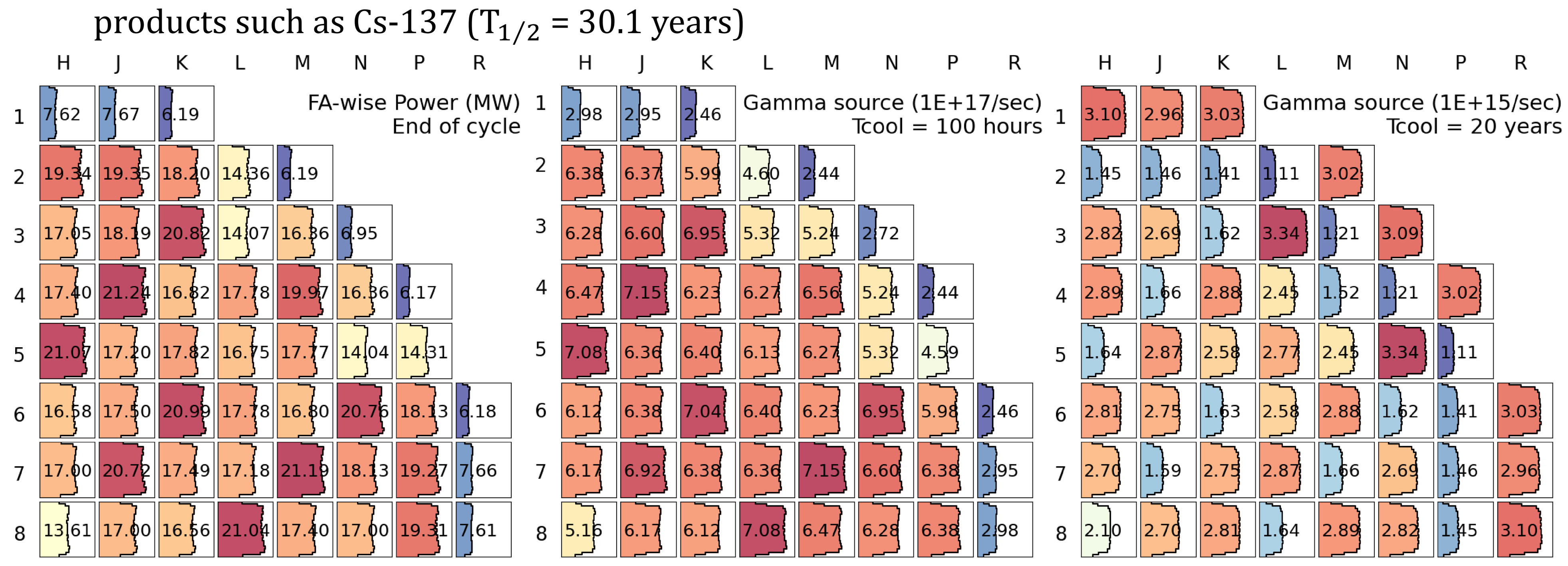
Neutron source (1E+08/sec), Tcool = 20 years

| | H | J | K | L | M | N | P | R |
|---|---|---|---|---|---|---|---|---|
| 1 | 2.16 | 1.67 | 1.88 | | | | | |
| 2 | 0.06 | 0.06 | 0.05 | 0.02 | 1.93 | | | |
| 3 | 1.35 | 1.04 | 0.10 | 2.70 | 0.03 | 2.23 | | |
| 4 | 1.53 | 0.11 | 1.51 | 0.60 | 0.07 | 0.03 | 1.93 | |
| 5 | 0.11 | 1.43 | 0.82 | 1.23 | 0.60 | 2.70 | 0.02 | |
| 6 | 1.38 | 1.14 | 0.11 | 0.82 | 1.51 | 0.10 | 0.05 | 1.88 |
| 7 | 1.04 | 0.09 | 1.14 | 1.43 | 0.11 | 1.04 | 0.06 | 1.67 |
| 8 | 1.60 | 1.04 | 1.38 | 0.11 | 1.53 | 1.35 | 0.06 | 2.16 |

Gamma source (1E+15/sec), Tcool = 20 years

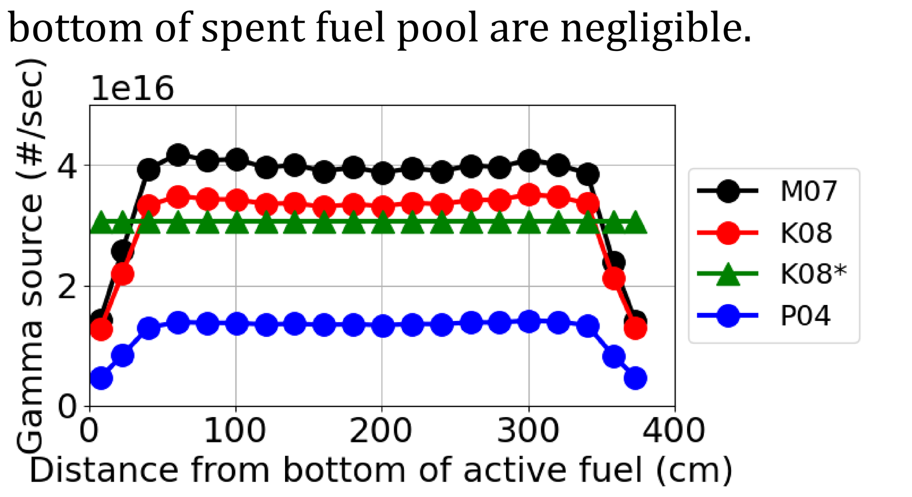
| | H | J | K | L | M | N | P | R |
|---|---|---|---|---|---|---|---|---|
| 1 | 3.10 | 2.96 | 3.03 | | | | | |
| 2 | 1.45 | 1.46 | 1.41 | 1.11 | 3.02 | | | |
| 3 | 2.82 | 2.69 | 1.62 | 3.34 | 1.21 | 3.09 | | |
| 4 | 2.89 | 1.66 | 2.88 | 2.45 | 1.52 | 1.21 | 3.02 | |
| 5 | 1.64 | 2.87 | 2.58 | 2.77 | 2.45 | 3.34 | 1.11 | |
| 6 | 2.81 | 2.75 | 1.63 | 2.58 | 2.88 | 1.62 | 1.41 | 3.03 |
| 7 | 2.70 | 1.59 | 2.75 | 2.87 | 1.66 | 2.69 | 1.46 | 2.96 |
| 8 | 2.10 | 2.70 | 2.81 | 1.64 | 2.89 | 2.82 | 1.45 | 3.10 |

- Axial power distribution at end of cycle (left) and Gamma source distribution at cooling time of 100 hours (center) & 20 years (right).
  - At a short cooling time, the gamma source emission is largely affected by short-lived nuclides in fission products. After few years cooling period, it is mostly affected by long-lived fission products such as Cs-137 ($T_{1/2}$ = 30.1 years)

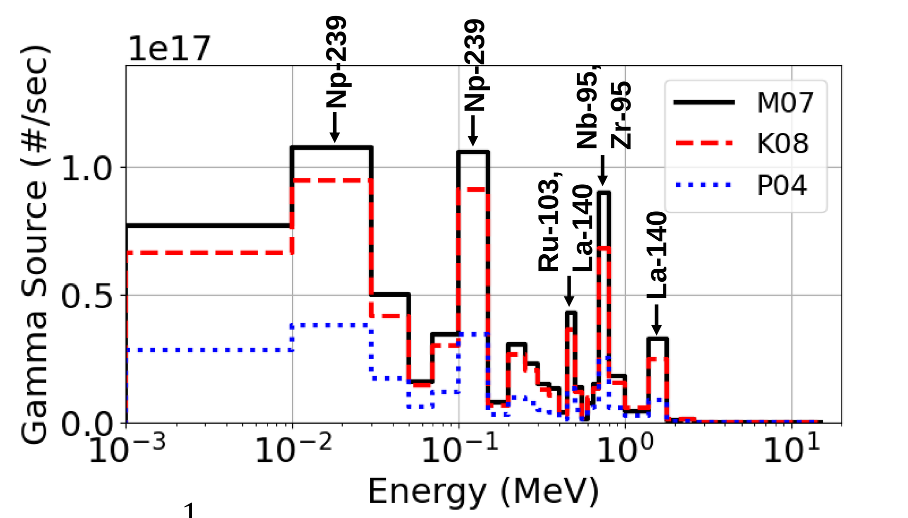



## Dose Rate Calculation in Spent Fuel Pool

- Gamma source only from the assembly in transit is considered in dose rate calculation. The contribution by gamma from FAs stored at bottom of spent fuel pool are negligible.
- Axial gamma source distribution of selected FAs at cooling time of 100 hours.




- Gamma source spectrum of selected FAs at cooling time of 100 hours.
  - About 68% of gamma sources are emitted below 450 keV.
  - Most of low energy photons are caused by Np-239 ($T_{1/2}$ = 2.36 d), which is produced in a transmutation process from U-238 to Pu-239
  - Spectrum peak at 450-500 keV: Ru-103 ($T_{1/2}$ = 39.2 d) and La-140 ($T_{1/2}$ = 1.68 d)
  - Spectrum peak at 700-800 keV: Nb-95 ($T_{1/2}$ = 35 d) and Zr-95 ($T_{1/2}$ = 64 d)

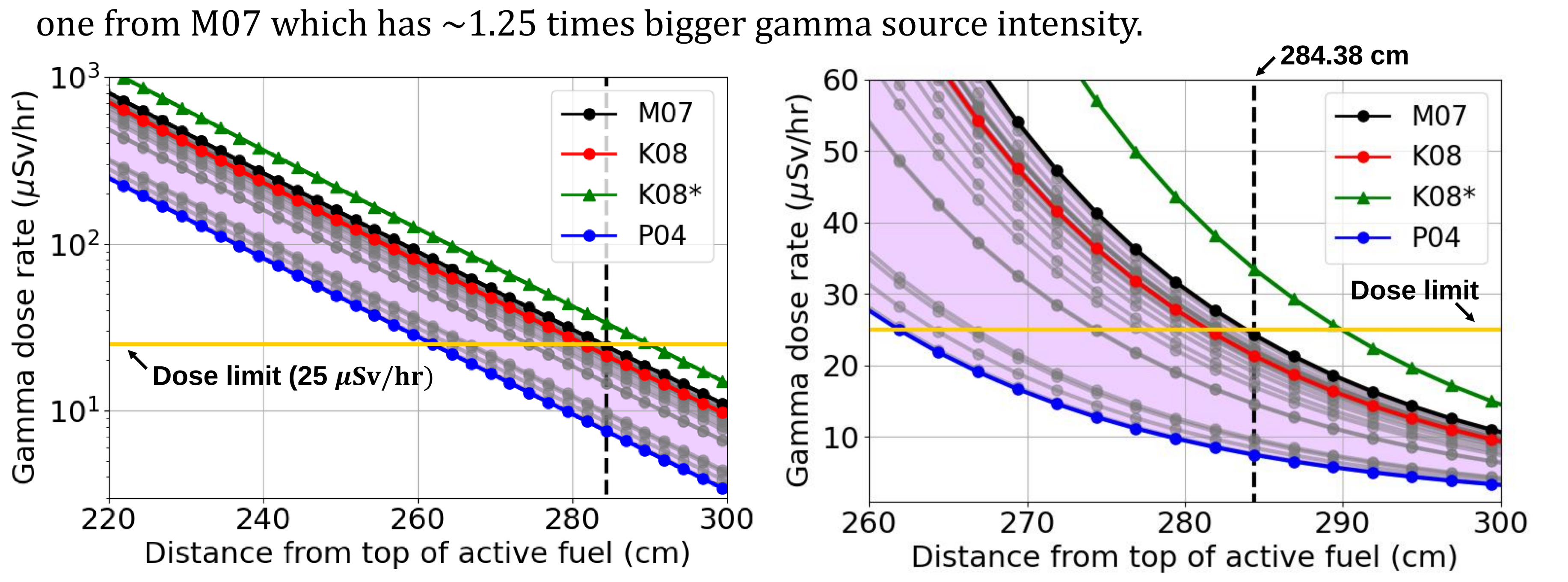



↓ Table: Effect of weight window method in dose rate calculation

| Loc.(cm) | Analog (16.3 hours) | | WW (6.89 hours) | | FOM ratio |
|---|---|---|---|---|---|
| 84.38 | 4.6E-9 ±0.5% | 74026 | 4.5E-9 ±0.09% | 1.6E+7 | 75 |
| 134.38 | 1.7E-10 ±3% | 2533 | 1.7E-10 ±0.1% | 7.1E+6 | 802 |
| 184.38 | 8.9E-12 ±13% | 119 | 8.7E-12 ±0.2% | 4.1E+6 | 7083 |
| 209.38 | 1.9E-12 ±33% | 19 | 2.1E-12 ±0.3% | 3.3E+6 | 31207 |

$$\rightarrow \text{FOM} = \frac{1}{T\sigma^2}$$

- Dose rate of selected FAs (ICRP-116 is used as a photon flux-to-dose conversion factor)
  - The light purple region between M07 & P04 represents available gamma dose rates.
  - Dose rate from K08* is ~1.6 times higher than the one from K08. It is much higher than the one from M07 which has ~1.25 times bigger gamma source intensity.




## Conclusion

- At a short cooling period, it is observed that neutron source intensity highly depends on burnup and gamma source intensity highly depends on power history.
- Therefore, not only assembly burnup, but also assembly power history should be carefully considered for the source term and dose rate calculations at a short cooling time such as a refueling period.