RES/DSA/FSCB 2016-03

SPENT FUEL ASSEMBLY HEAT UP CALCULATIONS IN SUPPORT OF TASK 2 OF USER NEED NSIR-2015-001

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April 2016

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LIST OF ACRONYMS

BWR	Boiling Water Reactor
FSTB	Fuel and Source Term Branch (NRC/RES)
KPS	Kewanee Power Station
NRC	U.S. Nuclear Regulatory Commission
NRR	[Office of] Nuclear Reactor Regulation (NRC)
NSIR	[Office of] Nuclear Security and Incident Response (NRC)
PWR	Pressurized Water Reactor
RES	[Office of] Nuclear Regulatory Research (NRC)
SFPS	Spent Fuel Pool Study
SOARCA	State of the Art Reactor Consequence Analysis

1.0 INTRODUCTION

1.1 Background

This report provides the technical basis for Task 2 of the NSIR-2015-001 user need. The analysis is mainly based on the assumption of adiabatic heatup for a generally limiting condition wherein the benefit of radiation and convective heat transfer is not realized. This might be the case when the most recently discharged fuel is surrounded by similar assemblies and the spent fuel pool leak elevation and/or debris blockage prevents natural circulation air cooling.

1.2 Objectives

The main objectives of the present work are to:

1. Provide useful information to NSIR/NRR with regard to onset of a potential zirconium fire and initiation of radioactive release from the fuel following loss of adequate fuel cooling as a function of time since reactor shutdown for both PWR and BWR fuel assemblies. The development of heatup time maps is based on simple calculations similar to what was done in NUREG-1738 [1] and licensee exemption requests. The fuel parameters (e.g., assembly mass, burnup, decay heat) are based on available information used in spent fuel pool study (SFPS) [2], SOARCA, and the most recent analysis for commercial spent nuclear fuel assembly characteristics [3].

2. Provide a qualitative discussion of the degree of benefit that could be achieved by relaxing the adiabatic heatup assumption based on realistic benefits gained from including radiative heat transfer to surrounding colder assemblies and the presence of the racks. The quantitative analysis is based on existing MELCOR results (i.e., SFPS [2]) as well as limited new MELCOR calculations.

This information is provided to NSIR/NRR to inform a discussion on whether additional work in this area is worthwhile.

2.0 LIST OF MAIN ASSUMPTIONS

1. The assembly decay heat is obtained from the information contained in Reference [3] for a 10x10 assembly for BWRs and a 17x17 assembly for PWRs based on calculations using representative average core powers of 38 MW/MTHM for PWRs and 24 MW/MTHM for BWRs. Oak Ridge National Laboratory [3] reviewed discharge data for more than 108,000 PWR assemblies and 135,000 BWR assemblies in the US inventory database (GC-859). The maximum specific assembly powers, averaged over all cycles an assembly resided in the reactor core, can be 45% greater than the values used to calculate decay heat in Reference [3]. Maximum specific powers observed in GC-859 are up to 54 MW/MTHM in PWRs and 35 MW/MTHM for BWRs. Further analysis was performed using historical plant data to assess variations in the assembly specific power during each cycle of operation to identify potentially higher specific powers. This analysis is required to address offload of the entire core for decommissioning or other events. The maximum specific power observed in available PWR data reaches 62 MW/MTHM, 63% larger than the 38 MW/MTHM value used in Reference [3]. Applying this cycle peaking factor to the average BWR specific power of 35 MW/MTHM yields a maximum specific power in any cycle of 40 MW/MTHM. Therefore, the decay heat values in Reference [3] are increased by factors of 1.63 for PWR fuel and 1.67 for BWR fuel immediately after shutdown to be representative of hottest assemblies. For the PWR, the factor decreases to 1.29 and 1.07 after 1 year and 5 years respectively, and for the BWR, the corresponding factors are 1.33 and 1.09.

2. The adiabatic heatup calculations are performed for a range of burnups for both BWR and PWR fuel assemblies. According to Reference [3], the median burnup and enrichment of the spent nuclear fuel has increased steadily over time, although enrichment is limited to less than 5% by NRC regulations, which in turn limits the maximum burnup a fuel assembly can achieve. Among all discharged assemblies, only 0.54% of all BWR and PWR assemblies in the database have burnups above 55 GWd/MTHM. MELCOR calculations are done for a burnup of 60 GWd/MTHM which is consistent with the assumption in NUREG-1738 [1].

3. In the adiabatic heatup calculations, a single temperature is used to represent the various components including the racks when credited. This is a reasonable assumption since the MELCOR calculations show that various components in the assembly heat up at about the same rate.

4. The initial temperature of the fuel assembly is assumed as 30°C (in SFPS [2], the initial water temperature was 28°C). Small variations in the initial temperature are not expected to be significant since a final temperature of 900°C is used for heatup time calculations.

5. The specific heat[1] of the components is assumed to be a function of temperature based on data provided in Reference [4].

6. In the calculation performed with the racks, the effects of poison materials degradation and melting are not taken into account (e.g., melting temperature of 593-660°C for Boral, 300-500°C for Boraflex – taken from pages EE-8 to EE-9 of Volume 2 of EPRI TR-1025295). Sensitivities are performed to show the importance of the rack poison materials. The specific heat of rack control poison is assumed to be 500 J/kg K based on the material properties in Reference [4].

7. For the MELCOR calculations that show the potential effects of the radiation and convective heat transfer as well as air oxidation, only the BWR model from SFPS [2] is used. Similar trends are expected for PWR assemblies.

8. Cladding is likely to fail by ballooning and burst in the temperature range of 700-850°C, and the creep failure of the cladding at or above 600°C is also possible [1]. NUREG-1738 [1] concludes that to establish the critical decay time for determining availability of 10 hours to evacuate, it is acceptable to use a temperature of 900°C under air oxidation conditions (a higher temperature of 1200°C is recommended if steam oxidation dominates the heatup time). The present results are shown for heatup times of 565°C and 900°C similar to licensee calculations [5].

9. The start time is the time when all cooling is lost to the spent fuel, and conservatively does not consider the initiating event. As such, the time from initiating event to the time when loss of both water and air cooling can occur may range from several hours to days depending on the initiating event and potential damage to the pool walls, spent fuel cooling time, etc., thus providing significant additional time in some cases for licensee to initiate mitigation measures. In SFPS [2], the earliest heatup started at 2.5 hours for moderate leak scenarios post outage compared to about 24 hours for a small leak case.

[1] In the Kewanee calculations [5], the specific heat of fuel is taken to be that of uranium metal, i.e., 146 J/kg K at a temperature of 600 K. The present analysis uses the specific heat of UO2 from Reference [4] and shows that the specific heat can vary between 266-321 J/kg K for a temperature range of 400-1200 K.

3.0 TECHNICAL APPROACH

3.1 Adiabatic Model

The adiabatic heatup of an assembly is calculated as[2]:

$$\sum m_i Cp_i \frac{dT}{dt} = \dot{Q} \qquad \text{(Eq. 1)}$$

Where i represents the assembly component (e.g., UO_2, Zr, or the rack), m is the component mass, Cp is the specific heat as a function of the component temperature T, t is time and $\dot{Q}$ is the assembly heat generation rate. The mass of the components are taken from the latest MELCOR models used in SFPS [2] and SOARCA. The decay heat based on average core powers for the BWR and PWR assemblies is shown in Figure 1. The various curves at different burnups are interpolated from data in Reference [3]. The decay heat factor for the hottest assemblies is shown in Figure 2. This factor represents the ratio of power from the hottest assembly to the average power in Figure 1.

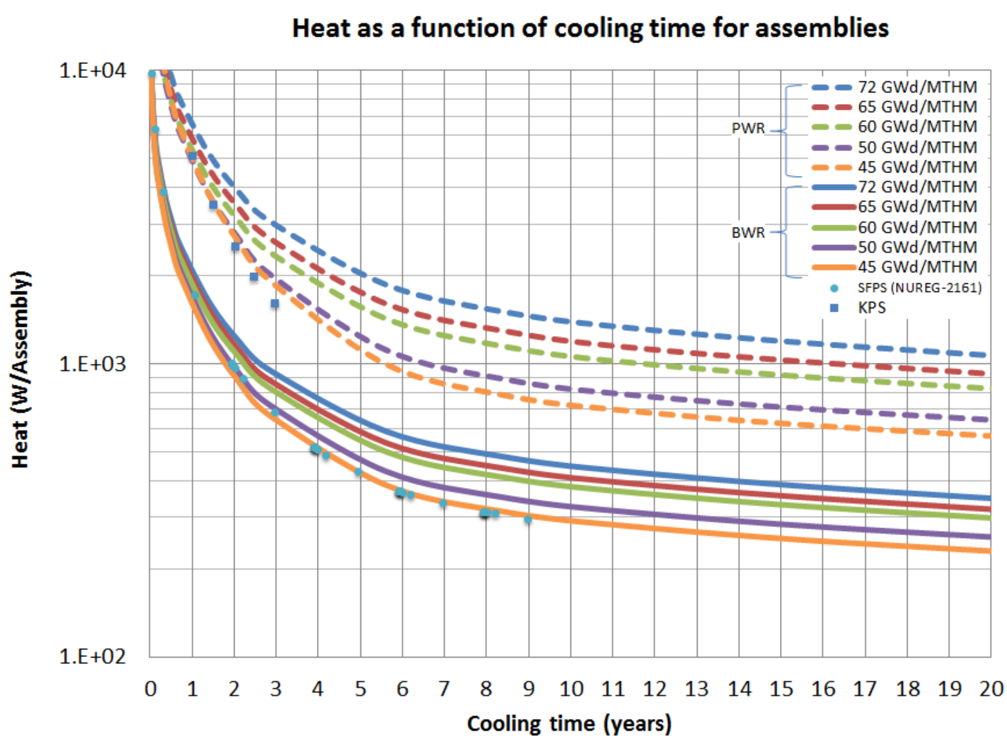

Figure 1: Average decay heat as function of cooling time for BWR and PWR assemblies

[2] In an adiabatic calculation, both the oxidation energy and radiation heat transfer are not taken into account. While the oxidation energy tends to increase the fuel temperature, thermal radiation would limit the fuel heatup. In some scenarios with partial pool draindown, the blocked airflow can limit the more energetic air (as opposed to steam) oxidation reaction, while thermal radiation only depends on the temperature and would play an important role in limiting the fuel heatup rate.

Figure 1 also shows the comparison of the decay heats used in SFPS [2] and Kewanee Power Station (KPS) [5]. In SFPS [2], the older fuel corresponds to lower burnup, and for more recent fuel, the data is more representative of the higher burnup. In the case of KPS, the decay heat reported for the hottest assemblies is consistently lower than the lowest burnup of 45 GWd/MTHM for the PWR curves.

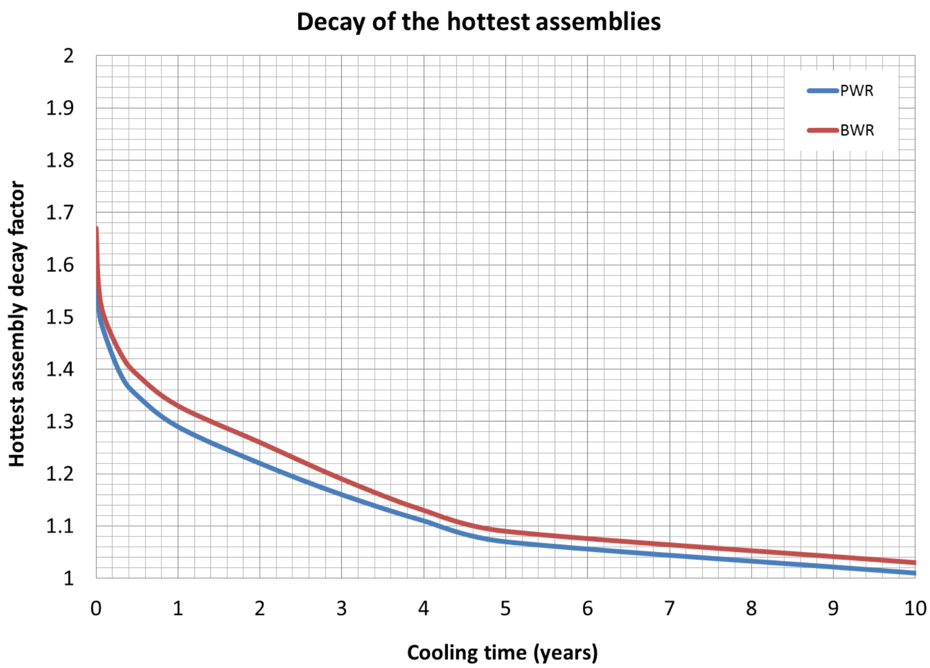

Figure 2: Decay heat factor for the hottest BWR and PWR assemblies

3.2 Fuel Assembly Loading

SFPS [2] showed the potential benefits of radial heat transfer where the recently discharged assembly is surrounded by older assemblies in a variety of configurations. Figure 3 shows three such configurations[3] ,i.e., (1) uniform with assemblies of similar decay heats, (2) checkerboard, and (3) 1x4. In the present analysis, only the effects of radiation heat transfer is considered for these configurations. This is done to compare the results with the adiabatic heatup calculations since it is expected that a uniform configuration (without air flow) can behave adiabatically. For the checkerboard and the 1x4, it is conservatively assumed that the recently discharged fuel is surrounded only by the assemblies from the previous offload thus maximizing the decay heat of the older

[3] In SFPS [2], for low density configuration, the older fuel was placed in a checkerboard pattern surrounded by empty rack cells, and assumed that a licensee places more recent discharged assemblies in a 1x4 with empty cells. This would be more limiting than the 1x4 or checkerboard surrounded by older assemblies but less limiting than the uniform pattern. In addition, a 1x8 situation was also considered in SFPS [2], but is not further discussed since a full core offload cannot be placed in a 1x8.

assemblies (in SFPS [2], the assemblies surrounding the recently discharged represented an average of all the older assemblies)

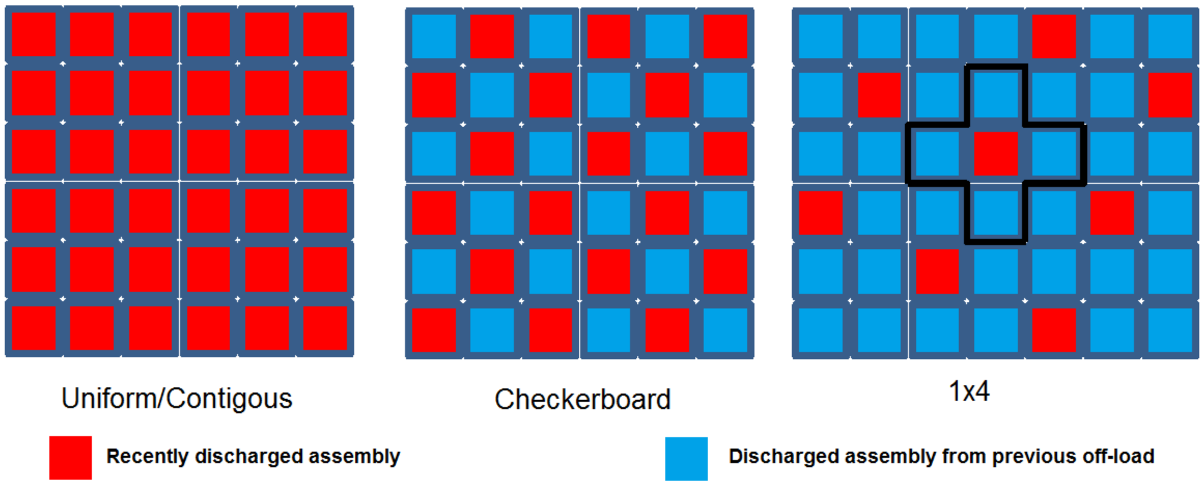

Figure 3: Fuel loading configuration in a spent fuel pool

3.3 MELCOR BWR Model

The MELCOR model from SFPS [2] is used to estimate the effects of radial heat transfer and air cooling and oxidation during the assembly heatup. It is also used to compare the results to the adiabatic heatup calculations. The two ring model is shown in Figure 4. In the uniform configuration, only ring 1 is used, and for the checkerboard and 1x4 configurations, ring 2 represents the discharged assemblies from the previous offload. An adiabatic boundary condition is assumed for ring 2. For the case with air cooling enabled, the results are only calculated for the uniform configuration. Because of heatup sensitivity to the inlet air temperature, two cases were considered. For minimum air cooling, the model from SFPS [2] was used by filling the entire spent fuel pool with assemblies of recently discharged fuel that tends to maximize the inlet air temperature and reduce the heatup time. This is considered a conservative assumption. For the maximum air cooling, only ring 1 assemblies from SFPS [2] are filled.

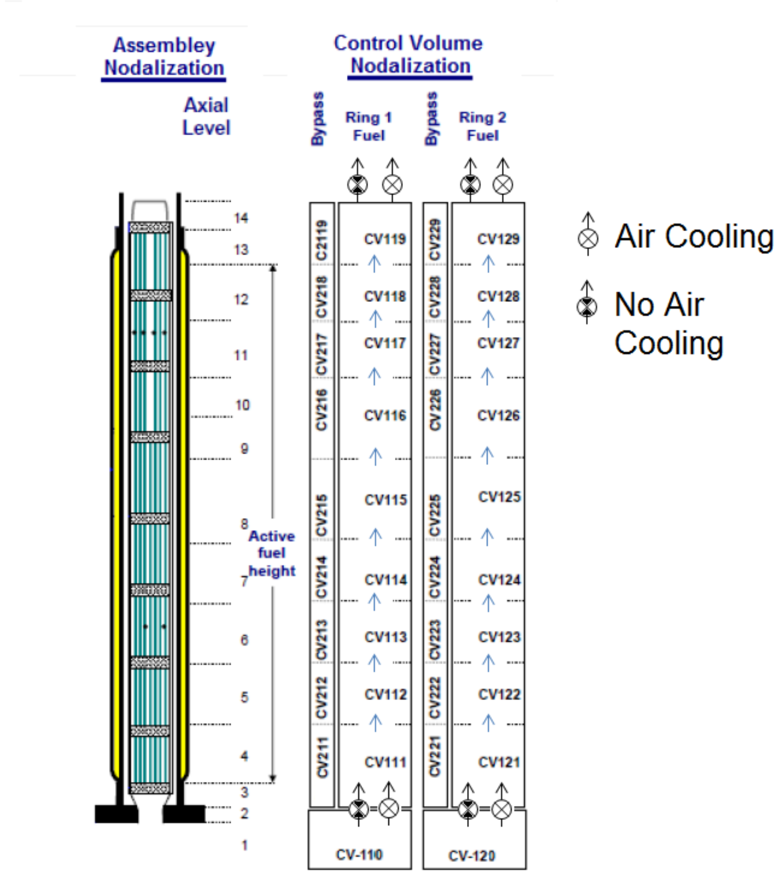

Figure 4: MELCOR nodalization of the BWR fuel assembly [SFPS]

4.0 RESULTS

The BWR assembly heatup calculations for the burnup of 60 GWD/MTHM and the average decay heat from Figure 1 are shown in Figures 5 and 6. The solid lines in these figures are based on the adiabatic calculations using Equation (1), and the symbols represent MELCOR calculations assuming adiabatic boundary conditions. The heatup profile is not exactly linear because of the dependence of specific heat on temperature. Comparing Figures 5 and 6 indicates that the racks can significantly delay the heatup time (i.e., by 38%), and this is a reasonable assumption since in a realistic MELCOR calculation, the cladding, channel boxes and the racks heat up at nearly the same rate. In these calculations, the effect of rack control poison is taken into account. Depending on the source of information, the material properties of control poison can be significantly different; however, its mass is relatively small compared to other components. If only the stainless steel component of the racks is included, the heatup time is reduced by less than 5%. Therefore, the inclusion of the control poison does not significantly affect the overall results.

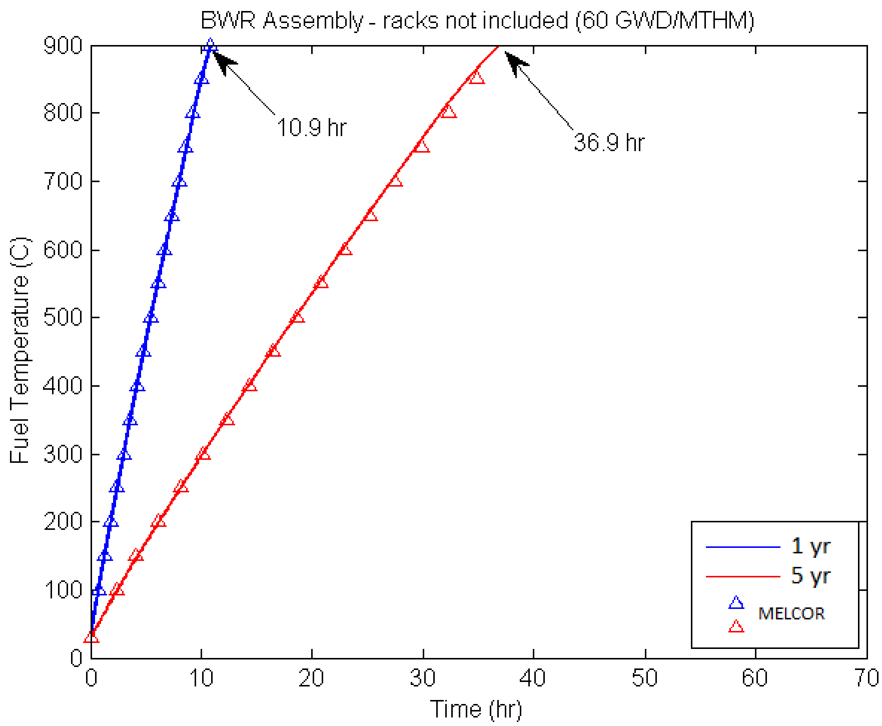

Figure 5: BWR fuel assembly adiabatic heatup without the effect of the racks

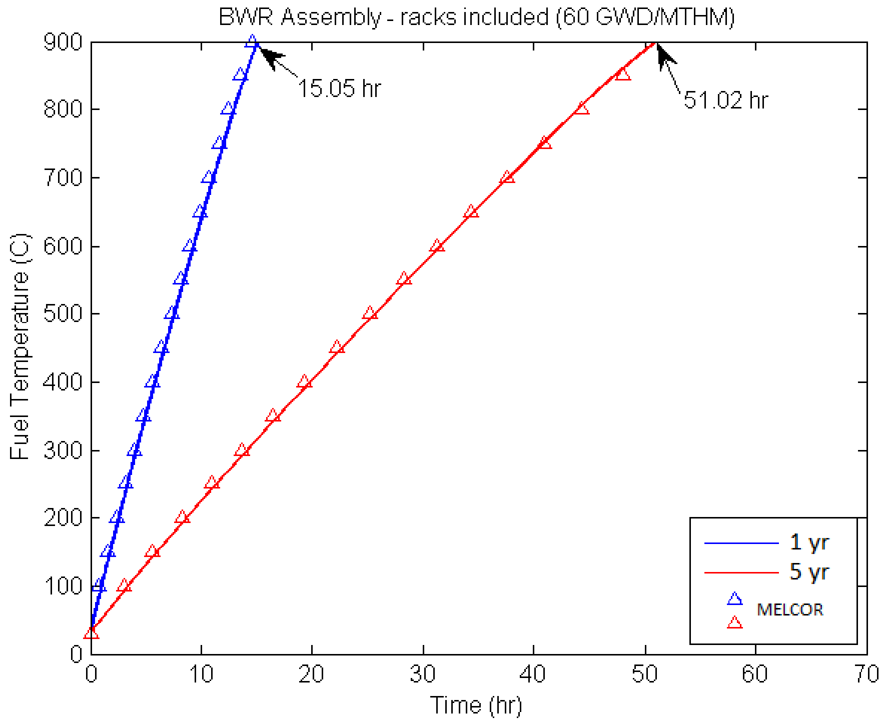

Figure 6: BWR fuel assembly adiabatic heatup with the effect of the racks

The results of the adiabatic heatup calculations for both average and hottest assemblies are shown in Figures 7 and 8. These figures do not include the effect of the racks. The heatup time is significantly affected by the assembly decay heat. The cooling time corresponding to the 10-hour heatup time can vary by as much as 28% for the hottest assembly compared to the average assembly for the BWR with a burnup of 60 GWd/MTHM, and the corresponding number for the PWR is 24%. For the 10-hour heatup time to 900°C, the BWR cooling time required can vary between 0.73-1.03 years using the average assembly decay power compared to 1.06-1.39 years for the hottest assembly. In the case of the PWR assemblies for the 10-hour heatup time to 900°C, the cooling time required varies between 1.17-1.65 years using the average assembly decay power compared to 1.48-2.12 years for the hottest assembly. Comparing the BWR and PWR hottest assemblies with a burnup of 60 GWd/MTHM, the cooling times required for the 10-hour heatup time are 1.21 and 1.64 years, respectively. The cooling time required for PWR assembly is 36% higher than the BWR even though the decay heat could be a factor of 2-3 higher for PWR assemblies (PWR assemblies are heavier than BWRs). Figure 8 also shows the comparison of the present heatup times with NUREG-1738 [1] and KPS [5]. The differences between NUREG-1738 can be attributed to different decay powers and the axial peaking factor[4]. For the KPS, the differences are due to different decay heats (Figure 1) as well as assumptions regarding material properties for the adiabatic heatup calculation.

[4] In NUREG-1738, the decay heat for 60 GWD/MTHM was extrapolated from the values reported in NUREG/CR-5625 for a limiting burnup of 50 GWD/MTHM.

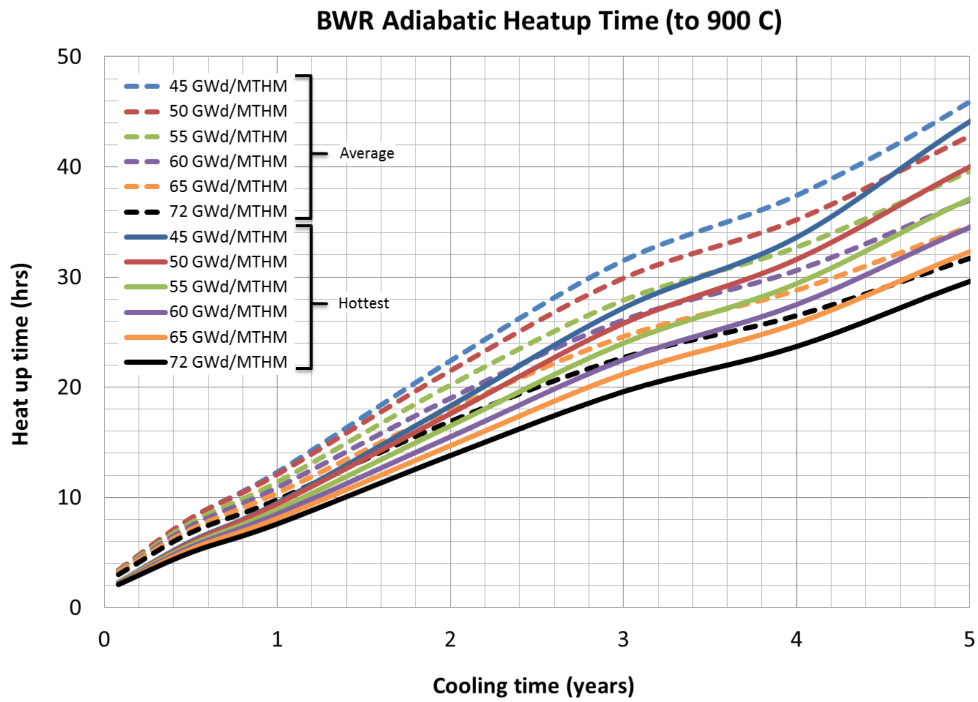

Figure 7: BWR fuel assembly adiabatic heatup time to 900°C

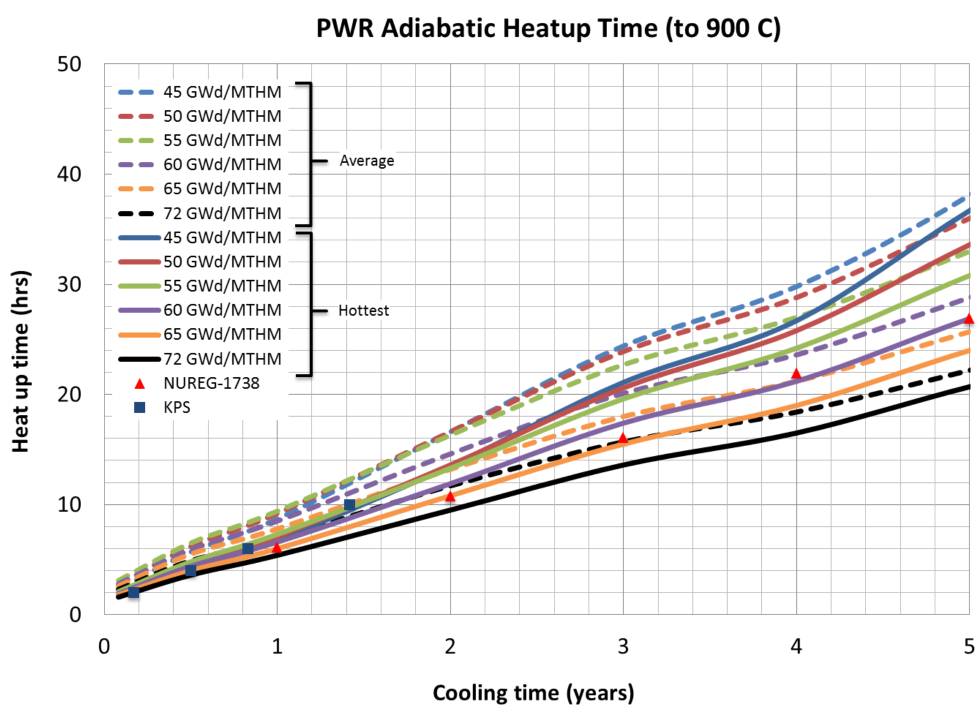

Figure 8: PWR fuel assembly adiabatic heatup time to 900°C

Figure 9 shows the impact of fuel configuration (radial heat transfer) as well as air cooling and oxidation for the BWR assembly. The inclusion of the rack component has a significant effect even on the adiabatic heatup time and is included in the radial heat transfer between rings 1 and 2 in the MELCOR calculation. All the MELCOR calculations are done using the average power from Figure 1 for a burnup of 60 GWd/MTHM. The heatup times calculated by MELCOR for the uniform configuration agree very well with the adiabatic predictions over the range of cooling times from 1 to 5 years. In the MELCOR uniform configuration model, the inlet and outlet of ring 1 are closed (see Figure 4) to disable convective natural circulation. The radial heat transfer is also disabled between rings 1 and 2, and for the case without the racks, the mass of the racks is reduced to zero in ring 1. The radiation heat transfer from the fuel rods to the channel boxes and finally to the inner surface of the racks increases the heatup time (see adiabatic heatup times with and without the racks in Figure 9). For the hottest assemblies, the increase can range from 2-3 hours early in the cooling time (≤ 1 year) to 8.6 hours at 3 years.

For the checkerboard and 1x4 configurations, only radiation heat transfer between rings 1 and 2 is enabled. The analysis shows that the heatup time is increased by a factor of 1.3 early in the cooling time (≤ 1 year) to about 1.1 at 3 years for the checkerboard pattern. This difference is mainly due to the decay of recently discharged assemblies compared to the previous offload; in other words, the differences between decay heat of 1 and 3 year old assemblies is more than the one between 3 and 5 year old assemblies as shown in Figure 1. The effect of the air cooling calculations (with potential for air oxidation at higher temperatures but without radial heat transfer) shows that the heatup times are bounded by the uniform configuration where racks are taken into account.

Figure 10 shows the impact of the racks for the PWR heatup calculations.

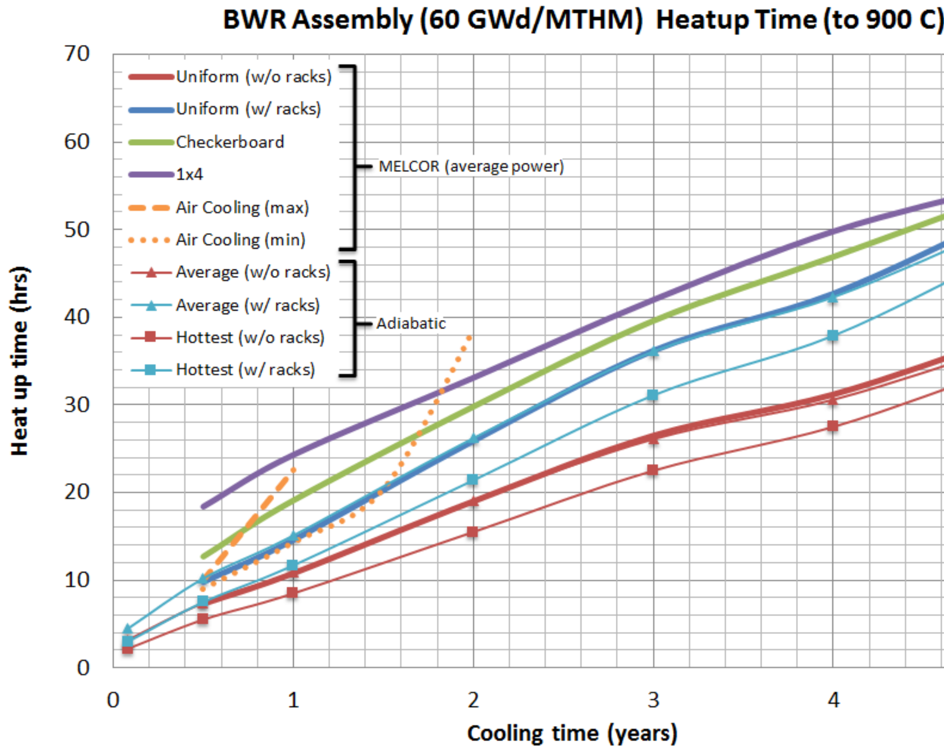

Figure 9: BWR assembly heatup time sensitivity to radial heat transfer and air cooling

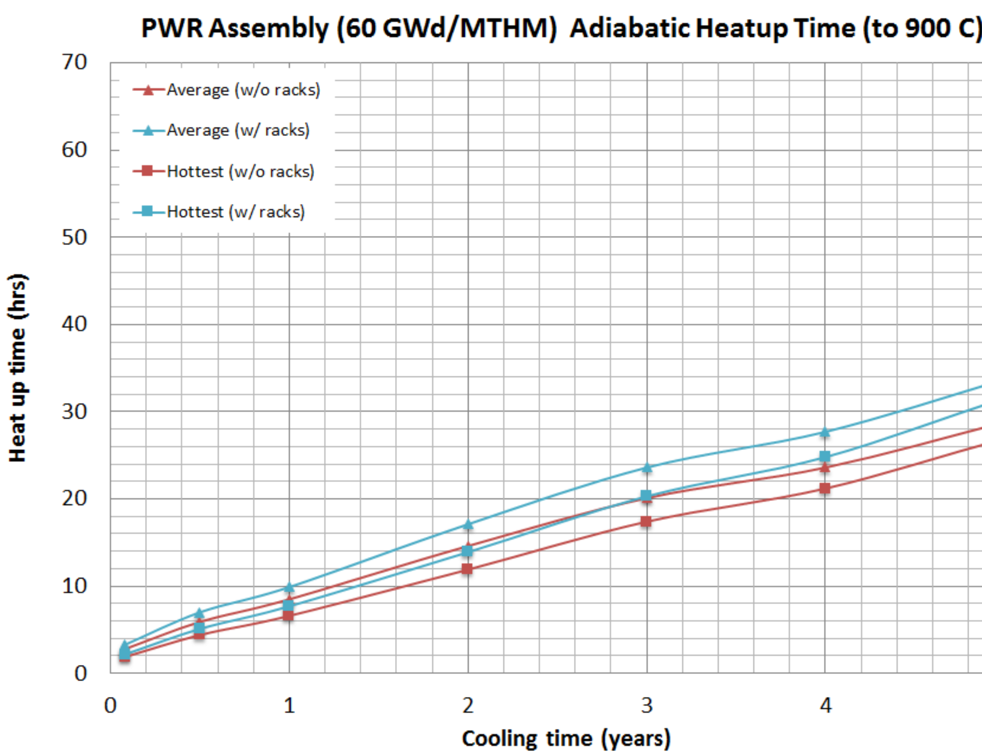

Figure 10: PWR fuel assembly heatup time sensitivity to presence of the rack

5.0 SUMMARY AND CONCLUSIONS

A summary of the heatup times (to 900°C) for the hottest BWR and PWR assemblies is shown in Table 1. The numbers in the parentheses for the adiabatic heatups represent the burnup of 60 GWD/MTHM. The values in the tables are based on the data in Figures 7 and 8. For more favorable configurations, the cooling times required will be even less than the adiabatic heatup values with the racks based on insights from Figure 9 for the more detailed MELCOR calculations for the BWR assemblies.

Table 1: Cooling time (years) required for 10-hour heat up time (to 900°C)

	BWR assembly	PWR assembly
Adiabatic (w/o racks)	1.06 – (1.21) – 1.39	1.48 – (1.64) – 2.12
Adiabatic (w racks)	0.61 – (0.80) – 0.92	1.27 – (1.37) – 1.77
Checkerboard or 1x4 (for 60 GWD/MTHM burnup)	< 0.8 (MELCOR estimate)	< 1.37 (based on BWR insights)

It should be noted that the heatup start time is based the time when all cooling is lost to the spent fuel, and conservatively does not consider the initiating event. As such, the time from initiating event to the time when loss of both water and air cooling can occur may range from several hours to days depending on the initiating event and potential damage to the pool walls, spent fuel cooling time, etc., thus providing significant additional time in some cases for licensee to initiate mitigation measures. In SFPS [2], the earliest heatup started at 2.5 hours for moderate leak scenarios post outage compared to about 24 hours for a small leak case.

The results for heatup time of 565°C is shown in Table 2 that considers potential for cladding failure at lower temperatures and can be compared to licensee calculations (see for example Reference [5]).

Table 2: Cooling time (years) required for 10-hour heat up time (to 565°C)

	BWR assembly	PWR assembly
Adiabatic (w/o racks)	1.94 – (2.25) – 2.60	2.54 – (2.97) – 4.16
Adiabatic (w/ racks)	1.37 – (1.57) – 1.78	2.20 – (2.50) – 3.35

6.0 REFERENCES

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