THERMAL ANALYSIS OF HIGH DECAY HEAT LOADING STRATEGIES IN THE MAGNASTOR SYSTEM

Spent Fuel and Waste Disposition

Prepared for
US Department of Energy
Spent Fuel and Waste Science and Technology

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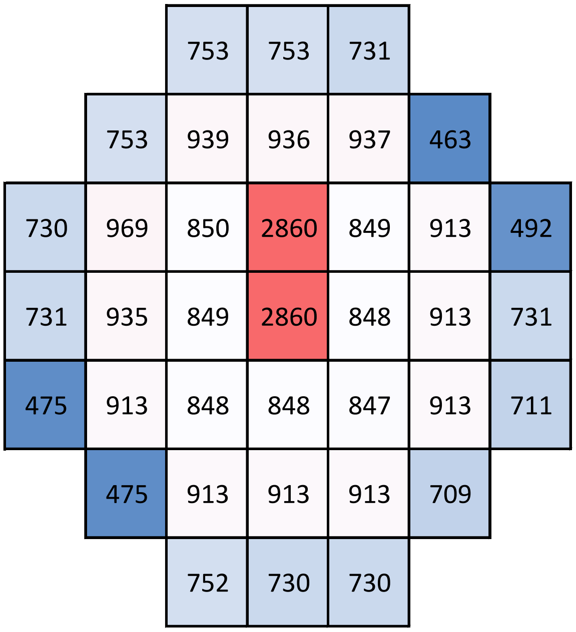
SUMMARY

The objective of this study is to analyze the sensitivities of the NAC International, Inc, (NAC) Modular, Advanced Generation, Nuclear All-purpose STORage (MAGNASTOR) module to different decay heat loading configurations. The main goal is to determine the highest fuel assembly decay heat load while keeping peak cladding temperatures (PCTs) at or below the 400 °C regulatory guidance limit as specified in Interim Staff Guidance (ISG) 11, Revision 3, (NRC 2003) and to determine the cladding temperature distribution under the various scenarios. While loading to the 400 °C limit is not recommended for design or operations, it is used here as an upper bound. Reduced loadings can produce cladding temperatures with desired margins.

Detailed models of the MAGNASTOR module developed with COBRA-SFS (Michener et al. 2017) were used to estimate PCTs with various decay heat loads. Ambient conditions consisted of 24.4 °C temperature with regulatory solar insolation. A conservative base heat loading case provided by Duke Energy and utilized previously in Fort et al. 2016 was used as a comparative base for zone loading adjustments. Also, the preferential design basis heat loading configurations from NAC 2011 were used as a comparative base for scaled total heat loading adjustments.

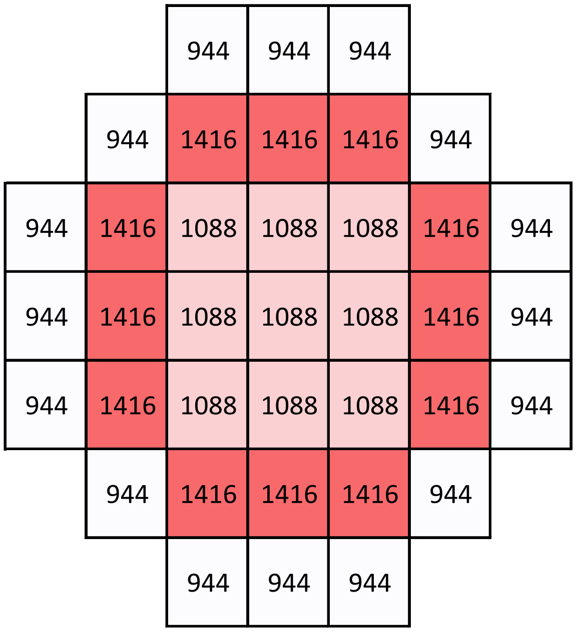
Six decay heat loading configurations were analyzed. PCTs responded differently in each case. A summary of the results for each case is provided in Table S.1. Two different configurations achieved the highest individual assembly heat load and highest total heat load separately. The highest individual fuel assembly decay heat load resulted when two assemblies were adjusted until the 400 °C PCT limit was reached. A map of the decay heat load is provided in Figure S.1. The decay heat on those assemblies reached 2860 W. The highest total heat load was achieved when utilizing the three-zone design basis configuration and scaling up the total heat load as shown in Figure S.2. The total heat load reached 41.9 kW when PCT was at the 400 °C limit.

Overall, the MAGNASTOR system shows the ability to store a small number of very high heat assemblies (>2500 W) while maintaining the majority of clad surface area below 400 °C. This would likely be true of similar pressurized canister system designs. In the future it would be beneficial to study real-world loaded systems with different loading patterns.



		753	753	731		
	753	939	936	937	463	
730	969	850	2860	849	913	492
731	935	849	2860	848	913	731
475	913	848	848	847	913	711
	475	913	913	913	709	
		752	730	730		

Figure S.1 Assembly 12 and 19 maximum decay heat load (W).



		944	944	944		
	944	1416	1416	1416	944	
944	1416	1088	1088	1088	1416	944
944	1416	1088	1088	1088	1416	944
944	1416	1088	1088	1088	1416	944
	944	1416	1416	1416	944	
		944	944	944		

Figure S.2 Three-zone design basis at maximum scaled decay heat load (W).

Table S.1 Summary of results.

Case Name	Description	Max Assembly Heat load (W)	Total System Heat Load (kW)	Peak Cladding Temperature (°C)	% Cladding Above 350°C
Conservative Base	Duke Energy estimate for actual load	969	29.5	314.0	0.0
Case One	Assemblies 12, 19 adjustment	2860	33.5	400.9	2.1
Case Two	Zone A adjustment	1675	36.9	399.1	10.9
Case Three	Zone B2 adjustment	2650	36.4	399.1	9.9
Case Four	Scaled Conservative Base	1168	35.5	360.5	1.8
3-Zone Design Basis	3-zone preferential design loading	1200	35.5	356.2	1.0
4-Zone Design Basis	4-Zone preferential design loading	1800	35.5	369.9	1.7
Case Five	Scaled 3-zone Design Basis	1416	41.9	403.0	26.0
Case Six	Scaled 4-Zone Design Basis	2034	40.1	403.2	20.1

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ACKNOWLEDGEMENTS

PNNL wishes to thank NAC International, Inc. for their cooperation, sharing of data information, and review of this document. Also, PNNL wishes to acknowledge the careful attention that Colleen Winters provided to get the report into its final form.

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ACRONYMS

CFD	Computational Fluid Dynamics
ISG	Interim Staff Guidance
kW	kilowatts
MAGNASTOR	Modular, Advanced Generation, Nuclear All-purpose STORage
NAC	NAC International, Inc.
NRC	Nuclear Regulatory Commission
PCT	peak clad temperature
PWR	pressurized water reactor
W	watts

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THERMAL ANALYSIS OF HIGH DECAY HEAT LOADING STRATEGIES IN THE MAGNASTOR SYSTEM

1. INTRODUCTION

In general, United States spent fuel storage systems have been loaded with large amounts of margin with respect to the peak clad temperature (PCT) limits outlined by the U.S. Nuclear Regulatory Commission (NRC) in Interim Staff Guidance (ISG)-11 rev.3 (NRC 2003). Recent improvements in thermal modeling have allowed cask vendors to push design basis temperatures closer to this limit. When this is coupled with improved decay heat modeling, utilities will be able to load fuel assemblies that have much higher decay heats (1-2 kW per pressurized water reactor (PWR) assembly) than previously seen in the U.S. For utilities this has a clear advantage because it allows an operating plant to offload the hottest assemblies from their fuel pool while retaining enough colder assemblies to actively increase shielding and lower worker and off-site dose. For a plant that is shut down, if fuel that has been cooled for as little as two years vs. five to ten years is able to be loaded, this could allow the spent fuel pool and related systems to be decommissioned much earlier. That capability eliminates reliance on safety related active cooling systems and could equate to large cost savings in the overall decommissioning and demolition process.

For transportation and disposal this increased heat load may pose significant challenges. Most systems currently in use have a significantly lower design basis decay heat in the transportation configuration than in the storage configuration. There are also potential cladding damage mechanisms such as radial hydride reorientation and creep that can be eliminated from consideration at low temperatures that may need to be reconsidered at elevated temperatures. It is useful to study how these increased assembly heat loads might impact peak and overall cladding temperatures. This study was undertaken to inform the Spent Fuel and Waste Science and Technology (SFWST) program within the Department of Energy Office of Nuclear Energy how PCT and temperature distributions vary under different loading scenarios. These temperature distributions, and especially the fraction of cladding above 350°C, will be used by the program to better perform experiments and analyses on cladding performance in extended storage, transportation, and geologic disposal.

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2. MODELING AND TESTING APPROACH

The results reported here build off the modeling and analyses done previously (Fort et al. 2016) on the NAC International, Inc. (NAC) Modular, Advanced Generation, Nuclear All-purpose STORage (MAGNASTOR) system loaded at the Duke Energy Catawba Nuclear Station in 2014[a]. To test the sensitivities of fuel rod cladding temperature to decay heat loading in the MAGNASTOR cask, both a conservative loading and design basis heat load configurations were utilized as base cases. The conservative loading (Figure 2.1) was estimated by Duke Energy for an actual loaded cask (Fort et al. 2016). The three-zone and four-zone design basis heat loading configurations (Figure 2.2 and Figure 2.3) were provided by NAC international in their *Final Safety Analysis Report* (NAC 2011). Utilizing these base cases, six different sensitivity cases were analyzed. Each case started with a base case and then the decay heats on different assemblies were increased until PCT reached the limit of 400ºC specified in ISG-11 rev. 3. This approach provides a “worst case scenario” for cladding temperatures with increased heat loads.

While loading to the 400ºC guidance limit is not recommended for design or operations, it is used here as an upper bound to inform the SFWST program. Reduced loadings can produce cladding temperatures with desired margins. Note finally, that the analysis performed in this report is for research purposes only and only was concerned with cladding temperatures and the effect on canister temperature. No effort was made to look at temperatures of other structures, systems, and components nor was dose taken into consideration. As such, this study cannot be used as the basis for licensing or safety analysis.

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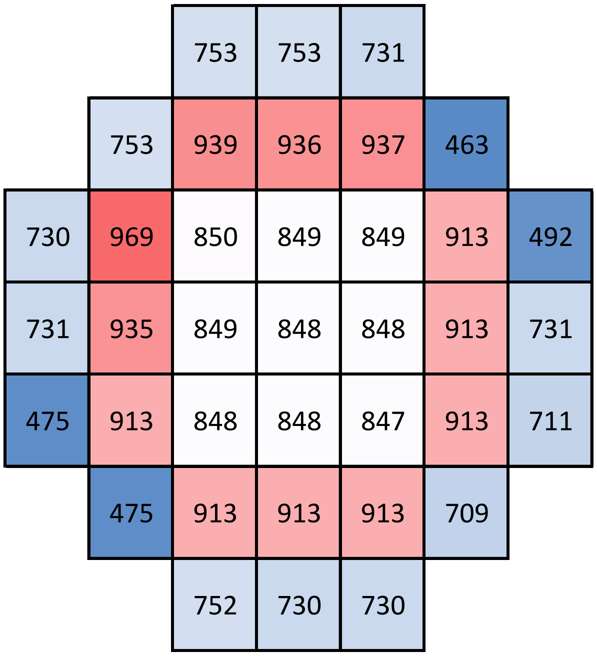
[a] The cases presented in this report use a general 17x17 fuel geometry and power profile. Previous reports used site-specific loading information and as such, may show minor temperature differences in the results.



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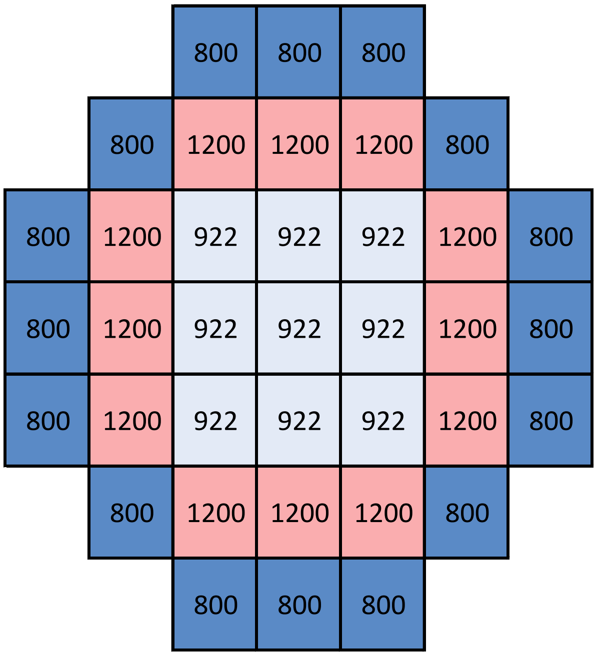
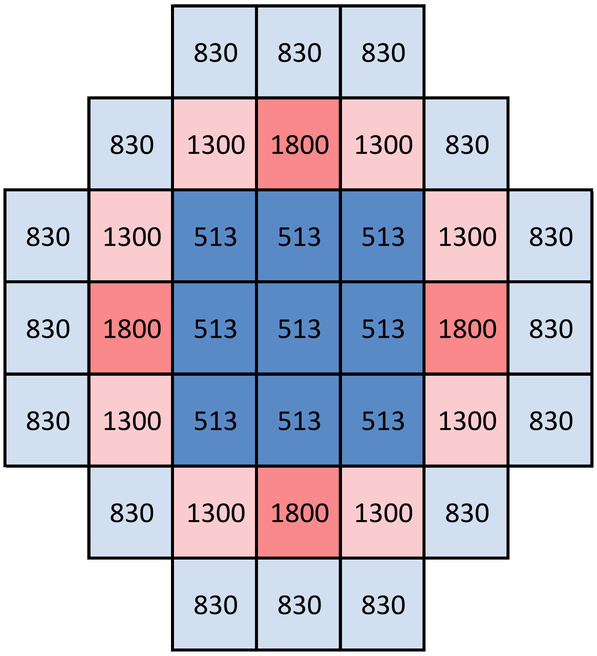
	475	913	913	913	709	
		752	730	730		

Figure 2.1. Conservative decay heat base case heat load (W) (Fort et al. 2016).



		800	800	800		
	800	1200	1200	1200	800	
800	1200	922	922	922	1200	800
800	1200	922	922	922	1200	800
800	1200	922	922	922	1200	800
	800	1200	1200	1200	800	
		800	800	800		

Figure 2.2. Three-zone design basis preferential heat loading (W).



		830	830	830		
	830	1300	1800	1300	830	
830	1300	513	513	513	1300	830
830	1800	513	513	513	1800	830
830	1300	513	513	513	1300	830
	830	1300	1800	1300	830	
		830	830	830		

Figure 2.3. Four-zone design basis preferential heat loading (W).

For sensitivity cases one through three, the conservative base case in Figure 2.1 was used as a starting point and then the decay heats on individual assemblies 12 and 19, all of Zone A, and all of Zone B2 were increased respectively. The location of assemblies 12 and 19 are shown in Figure 2.4 and the location of the zones are shown in Figure 2.5 and Figure 2.6. For each case the heat load on the remaining assemblies in the conservative base case were not adjusted. The fuel rod cladding temperatures were then compared to the initial conservative base case and the PCT limit. These decay heat loading cases provide insight into fuel rod cladding temperature response to increasing assembly decay heat in a variety of different loading scenarios.

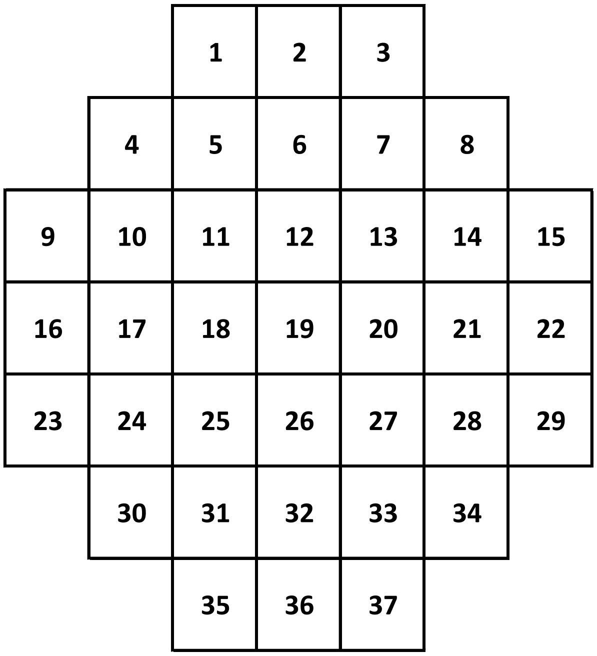


Figure 2.4. MAGNASTOR fuel assembly numbering.

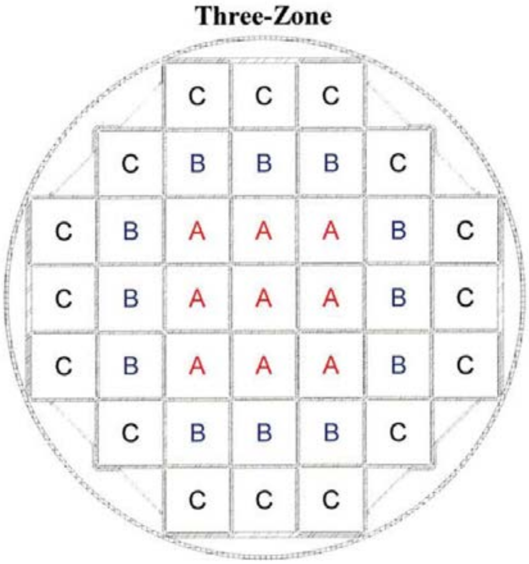


Figure 2.5. Three-zone heat loading map.

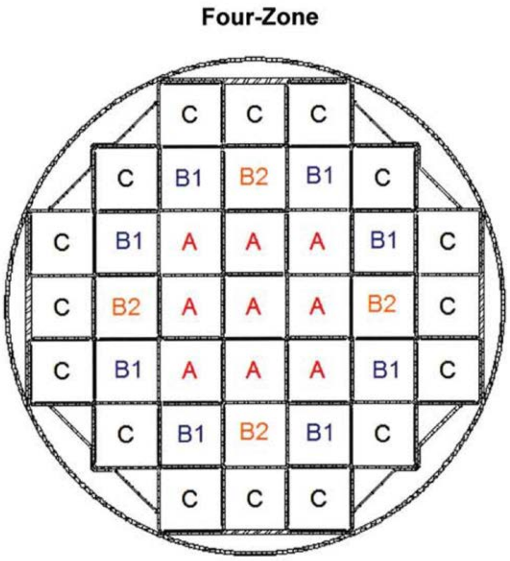


Figure 2.6. Four-zone heat loading map.

In case four all the assemblies in the conservative base heat load were increased by the same percentage to reach the design basis total heat load of 35.5 kW. The resulting PCTs of the scaled conservative base heat load can be compared to the design basis PCTs.

Next, three-zone (Figure 2.2) and four-zone (Figure 2.3) design basis decay heat loadings were analyzed. These design basis heat loading configurations were used as a base case for sensitivity cases five and six respectively. In cases five and six all assemblies in their respective preferential design basis load configuration were increased by the same percentage until the PCT limit was reached, effectively scaling the heat load. From this, the heat load margin between the design basis and regulatory limit was able to be determined.

3. MAGNASTOR COBRA-SFS MODEL DESCRIPTION

The COBRA-SFS model used for this work is fully described in Fort et al 2016. COBRA-SFS (Michener et al. 2017) is a validated Computational Fluid Dynamics (CFD) code specifically designed for modeling spent fuel storage systems. One key feature that makes it useful for this work is the run time, allowing numerous sensitivity analyses to be performed on a fast time scale. The computational time for a typical model run takes less than two hours utilizing one processor core. This model consisted of 804 solid nodes, 12,040 fluid channel nodes, 10,693 rod/guide tube nodes divided into 43 axial levels for a total of 1,012,091 computational nodes. A pictorial representation of the node map slice is shown in Figure 3.1.

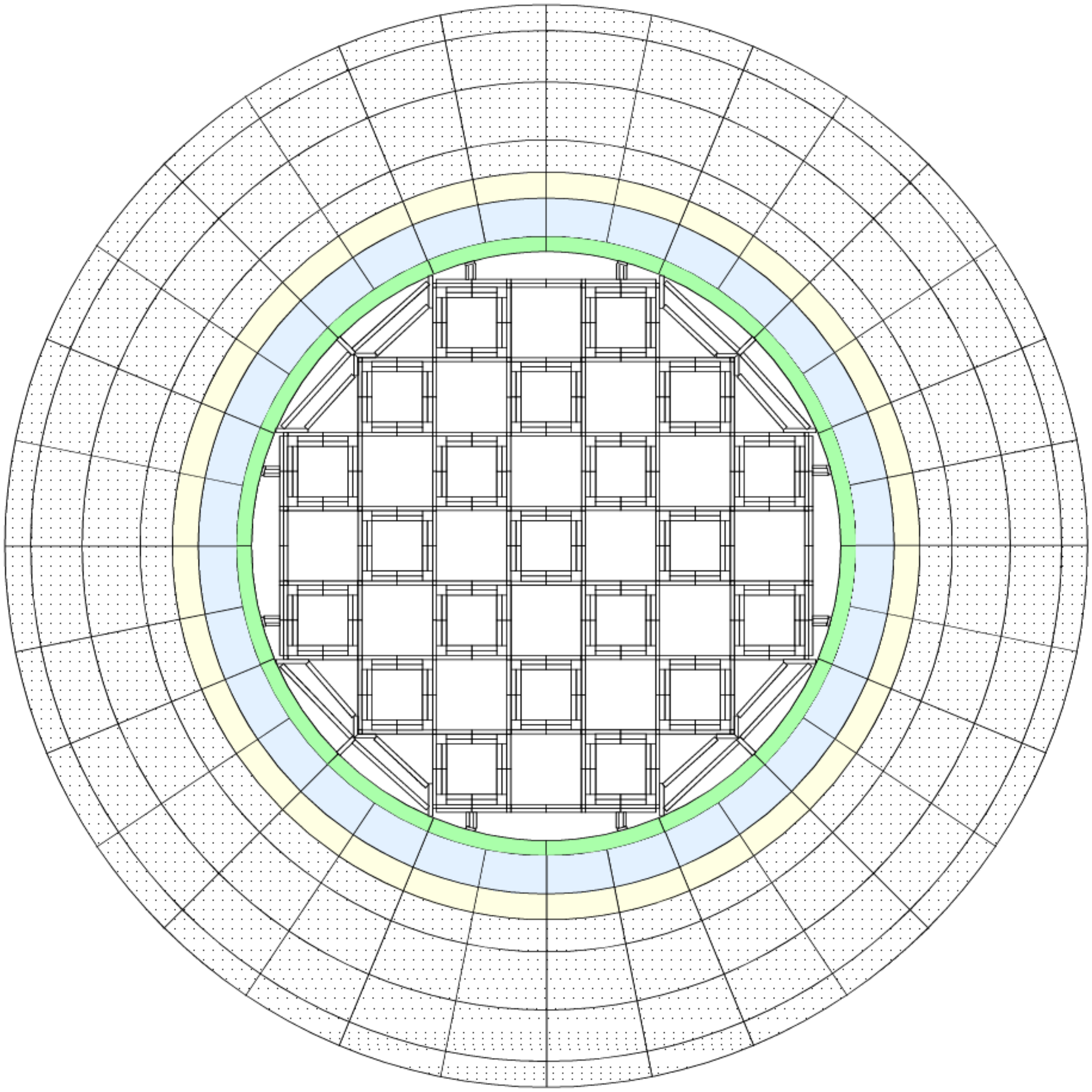


Figure 3.1. MAGNASTOR node map (not to scale).

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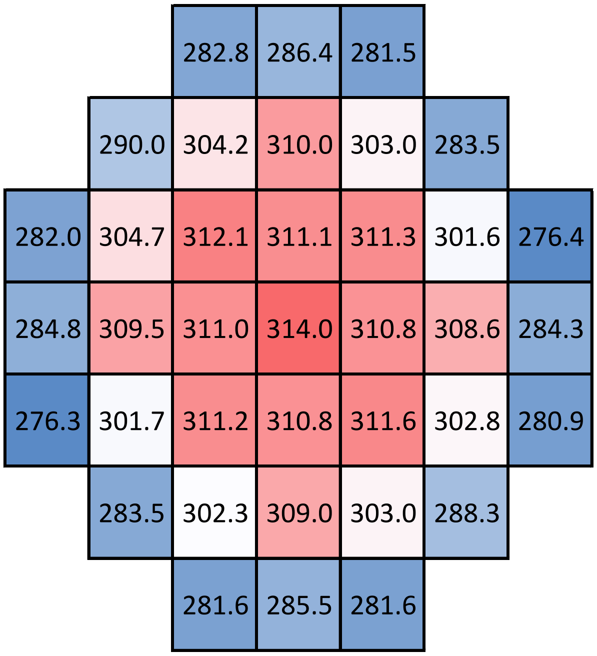
4. CONSERVATIVE BASE MODEL RESULTS

The conservative base model results consist of the decay heat base case and three follow-on cases. Clad temperature and canister temperature results are presented for each case. Although COBRA-SFS is validated for these systems there are known weaknesses in predicting local temperatures at the axial top and bottom of a model. This may cause some spurious results in the upper and lower canister temperatures reported.

4.1 Conservative Decay Heat Base Case

Using the conservative heat loading configuration shown in Figure 2.1, modeled PCTs are shown in Figure 4.1. The PCT is estimated to be 314ºC which is significantly lower than the regulatory limit of 400ºC. The total heat loading is 29.5 kW which is 6 kW below the design basis total heat load. This margin will allow significant increases of decay heat to determine the heat load necessary to reach a 400ºC PCT.



		282.8	286.4	281.5		
	290.0	304.2	310.0	303.0	283.5	
282.0	304.7	312.1	311.1	311.3	301.6	276.4
284.8	309.5	311.0	314.0	310.8	308.6	284.3
276.3	301.7	311.2	310.8	311.6	302.8	280.9
	283.5	302.3	309.0	303.0	288.3	
		281.6	285.5	281.6		

Figure 4.1. Conservative base decay heat load PCTs (°C).

In this loading configuration there is an even cladding temperature distribution in terms of overall clad surface area with each 10ºC temperature bin accounting for around 6% to 8% of the total fuel rod cladding (Figure 4.2). The difference between the hottest assembly clad temperature and the coolest assembly clad temperature is 37.7ºC. A contributing factor to the even cladding temperature distribution is the even decay heat distribution. There is a 506-Watt difference between the highest heat assembly and lowest heat assembly. There are only four assemblies at about 475 W that make up the lowest heat assemblies, so if those assemblies are ignored there is a 239-Watt difference between the highest and lowest heat assembly in this loading configuration.

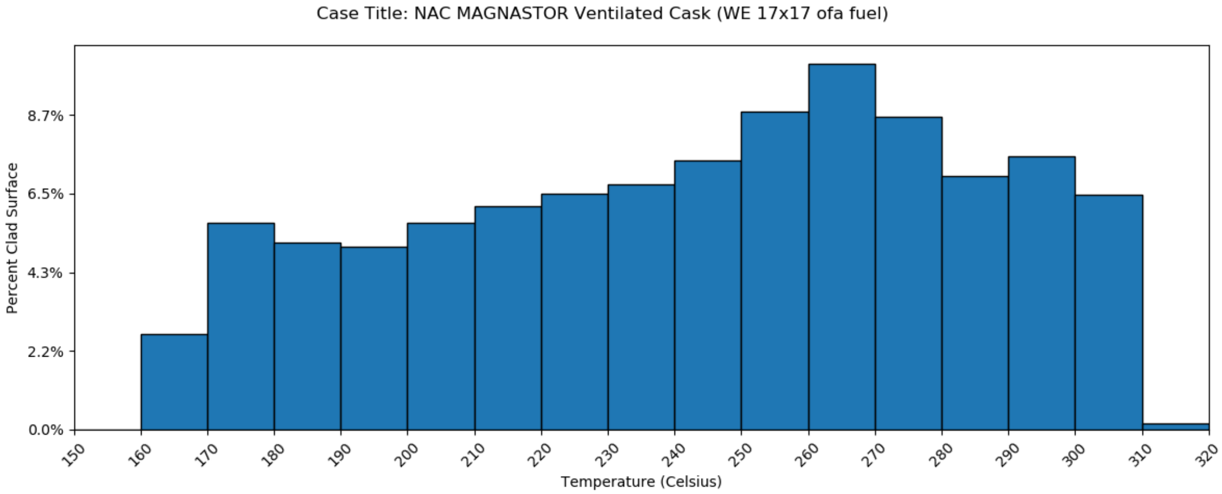


Figure 4.2. Cladding temperature distribution for conservative heat load.

The canister wall axial temperature profile is shown in Figure 4.3. The resulting temperature profile is typical for a ventilated cask between relative height y/H = 0.1 and y/H = 0.9 due to the steadily increasing ventilation air temperature as it moves upward through the annulus. The range between the coolest portion and the hottest portion is about 96°C. The coolest wall temperature occurs near the bottom of the wall while the hottest wall temperature of 222°C occurs at the top of the wall. The total heat loading in this case is relatively low, which results in lower canister wall temperatures.

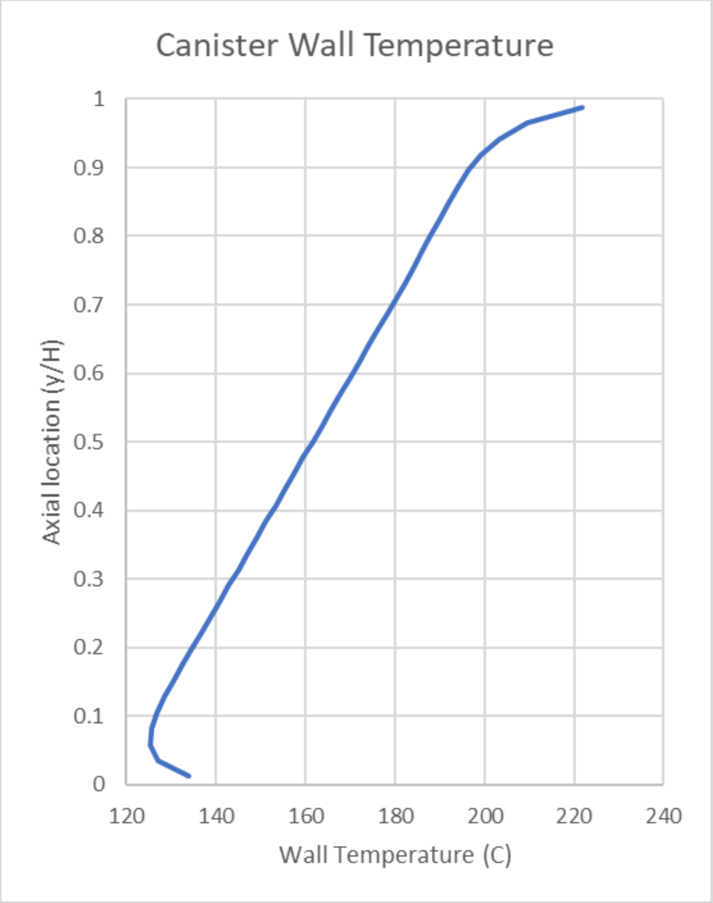
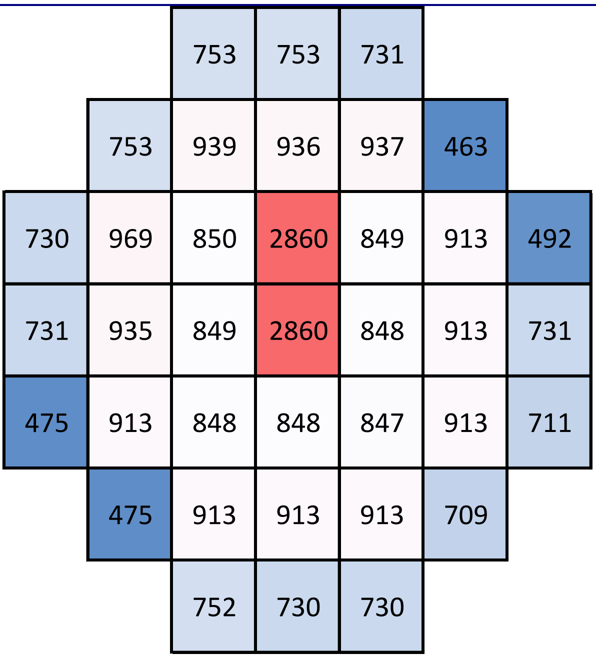


Figure 4.3. Canister wall temperature for conservative heat load.

4.2 Case One, Sensitivity to Assembly 12 and 19 Heat Load

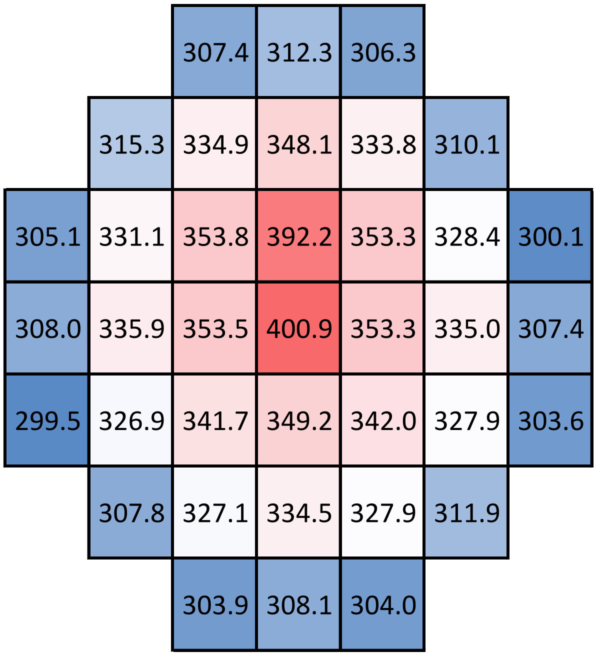
To show the effect of a very small number of high heat assemblies on PCT, the decay heat on the center assembly and the assembly directly above (assemblies 12 and 19 as shown in Figure 4.4) were increased until a PCT of 400ºC was reached. The PCT limit was achieved when the decay heat in assemblies 12 and 19 was increased to 2860 W (Note: the FSAR limit is 1200 W). The resulting total heat load was 33.5 kW. Note that the total heat load is below the design basis heat loading of 35.5 kW.



		753	753	731		
	753	939	936	937	463	
730	969	850	2860	849	913	492
731	935	849	2860	848	913	731
475	913	848	848	847	913	711
	475	913	913	913	709	
		752	730	730		

Figure 4.4. Assemblies 12 and 19 loading for 400°C PCT (W).

The PCT for each assembly in this case is shown in Figure 4.5. The PCT is located on the center assembly (19), which is expected due to the high decay heat in that assembly and its location furthest from the canister wall. The PCTs in the surrounding assemblies are significantly lower than in assemblies 12 and 19. There is a 100°C drop from the hottest assembly PCT to the coolest assembly PCT. This is quite a bit higher than the 37°C difference in the base case PCTs.



		307.4	312.3	306.3		
	315.3	334.9	348.1	333.8	310.1	
305.1	331.1	353.8	392.2	353.3	328.4	300.1
308.0	335.9	353.5	400.9	353.3	335.0	307.4
299.5	326.9	341.7	349.2	342.0	327.9	303.6
	307.8	327.1	334.5	327.9	311.9	
		303.9	308.1	304.0		

Figure 4.5. PCTs with 2860W heat loading on assemblies 12 and 19 (°C).

Figure 4.6 shows that most of the cladding temperatures for this case fall between 170°C and 350°C. Increasing the decay heat on only two assemblies shifts the cladding temperature distribution slightly hotter than in the conservative base case. The portion of the cladding that is anywhere near the cladding temperature limit only exists on the high heat assemblies. This is evidenced by the insignificant clad temperature distribution above 350ºC. Overall, the MAGNASTOR system with a small number of high heat fuel assemblies generates a clad temperature distribution with the majority of surface area below 350°C.

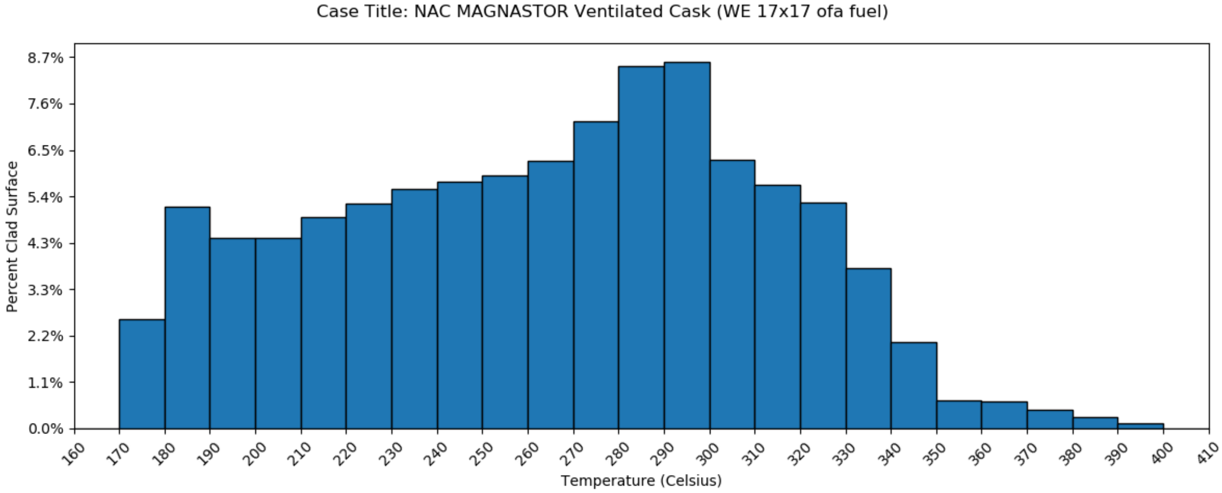


Figure 4.6. Rod cladding temperature distribution with PCT of 400 °C.

The canister wall temperature distribution shown in Figure 4.7 is slightly hotter than in the conservative base case. In this case the peak wall temperature is 24ºC hotter than the base case at 246 °C. A contributing factor to this is the higher overall heat load. Also, the shape of the canister wall temperature profile is similar to the base case due in part to the heat load on the outer assemblies all being unchanged.

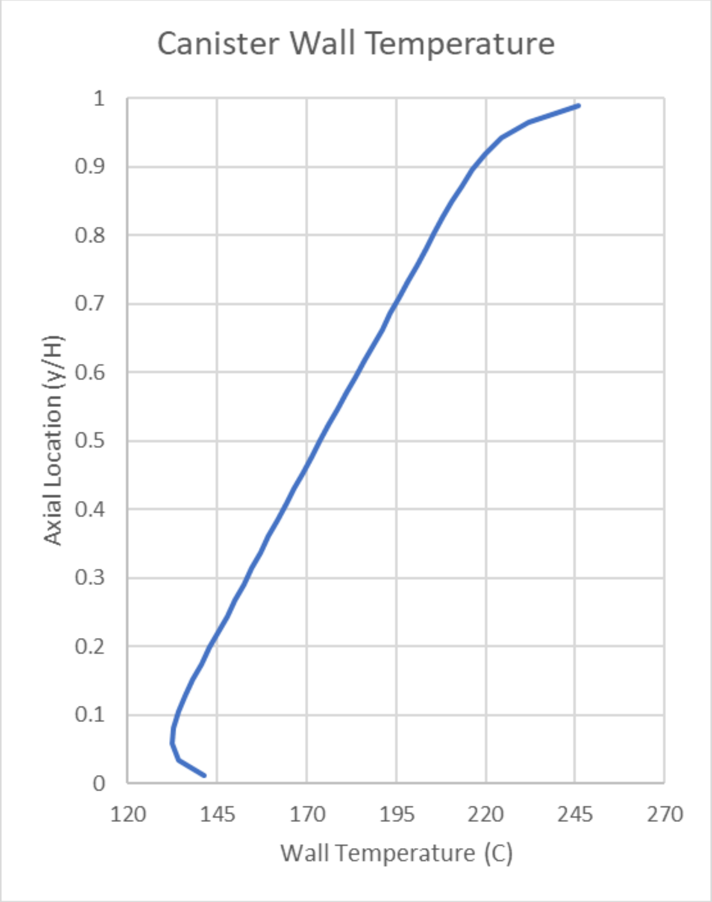
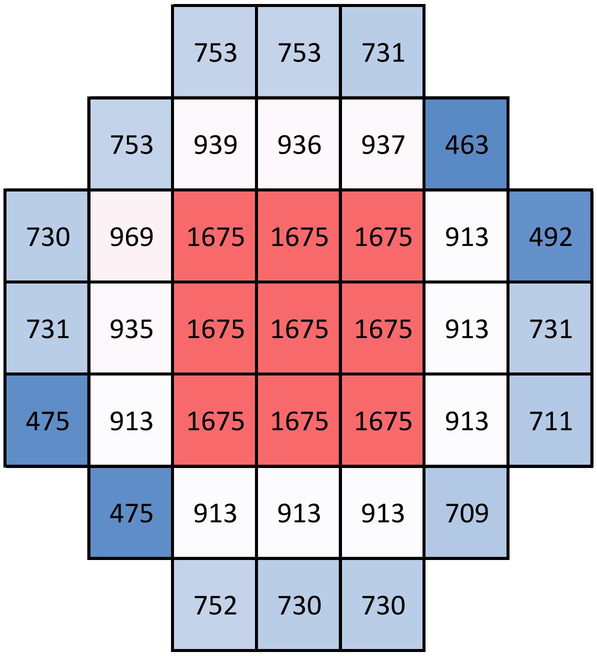


Figure 4.7. Canister wall temperature assemblies 12 and 19 at 400 °C PCT.

4.3 Case Two, Sensitivity to Zone A Decay Heat Increases

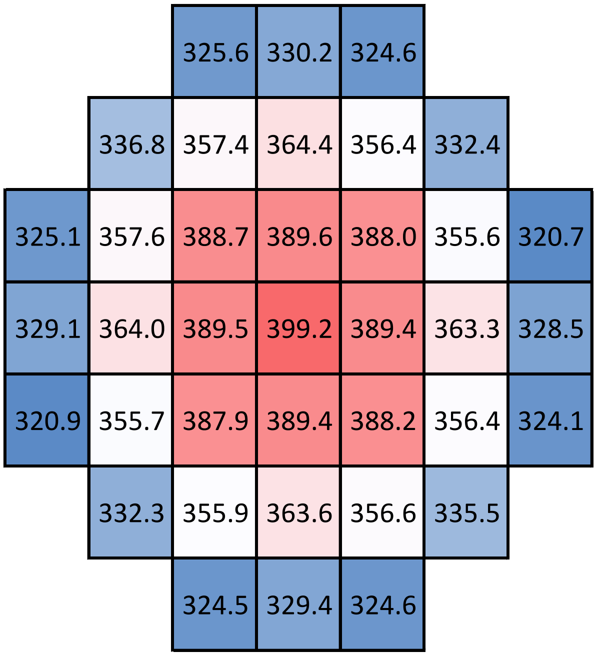
In this loading configuration the heat load on the assemblies in Zone A (Figure 4.8), the innermost assemblies, were adjusted until a PCT of 400°C was reached. The heat loading on Zone A was increased to 1675 W before reaching the PCT limit (Figure 4.9). This resulted in a total heat load of 36.9 kW. The heat distribution of this loading configuration is relatively even due to a smaller difference in decay heat between the highest heat and lowest heat assembly. Although there are four assemblies that have less than 500 W of decay heat, 33 assemblies are above 700 W.



		753	753	731		
	753	939	936	937	463	
730	969	1675	1675	1675	913	492
731	935	1675	1675	1675	913	731
475	913	1675	1675	1675	913	711
	475	913	913	913	709	
		752	730	730		

Figure 4.8. Zone A heat loading for PCT of 400˚C (W).

The hottest PCTs are concentrated in the central Zone A assemblies as expected. The assembly PCTs step down radially outward. The coolest assembly PCT at about 321ºC occurs in one of the outermost assemblies. Also, this assembly has one of the lowest decay heats as well. There is about an 80ºC difference between the hottest assembly PCT and coolest assembly PCT.



		325.6	330.2	324.6		
	336.8	357.4	364.4	356.4	332.4	
325.1	357.6	388.7	389.6	388.0	355.6	320.7
329.1	364.0	389.5	399.2	389.4	363.3	328.5
320.9	355.7	387.9	389.4	388.2	356.4	324.1
	332.3	355.9	363.6	356.6	335.5	
		324.5	329.4	324.6		

Figure 4.9. Assembly PCT with Zone A at 1675 W (˚C).

Most of the fuel cladding temperatures range from 190ºC to about 350ºC and then smaller portions fall into the bins hotter than 350ºC (Figure 4.10). The assembly PCTs located in Zone A are significantly hotter than in the other zones. The nine assemblies in Zone A account for a significant number of assemblies in the canister, which contributes to a smaller but significant portion of the cladding temperature falling into the bins above 350ºC. A very small portion of the cladding temperature is above 390ºC.

In this case a larger number of assemblies were adjusted, resulting in lower maximum individual assembly decay heat loads but a higher total decay heat load. This contributed to a uniform decay heat loading and a somewhat uniform cladding temperature profile.

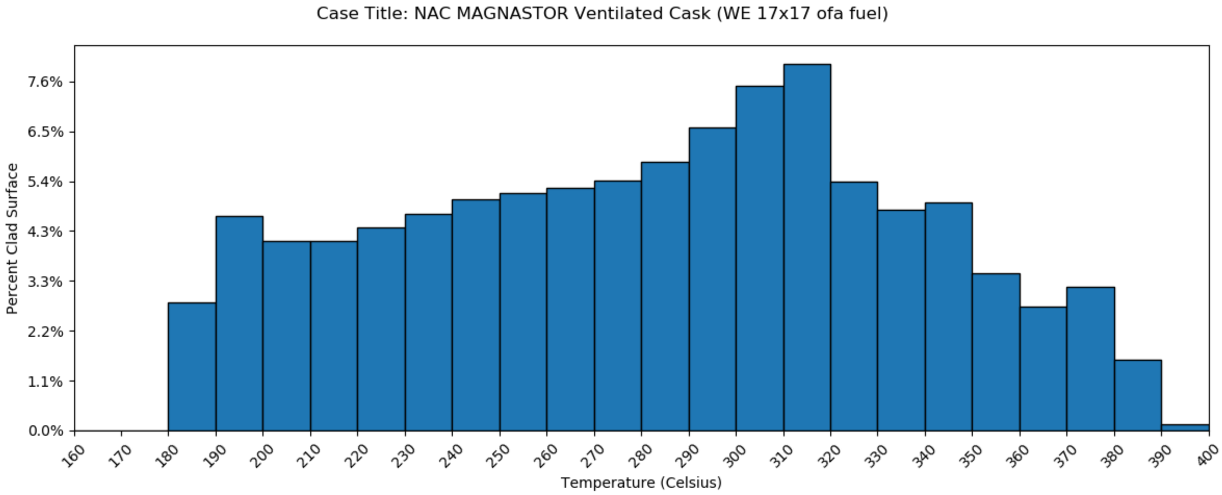


Figure 4.10. Zone A loading cladding temperature distribution.

Figure 4.11 shows the canister wall temperature profile for the Zone A loading configuration where PCTs reached 400°C. The lower section of the wall exhibits similar temperatures as in the conservative base but at the top the temperatures are significantly hotter. In this case canister wall temperatures reached about 246°C where in the conservative base the temperatures reached about 221°C. The increased heat loading in this configuration caused a larger temperature gradient from the bottom to the top of the canister wall.

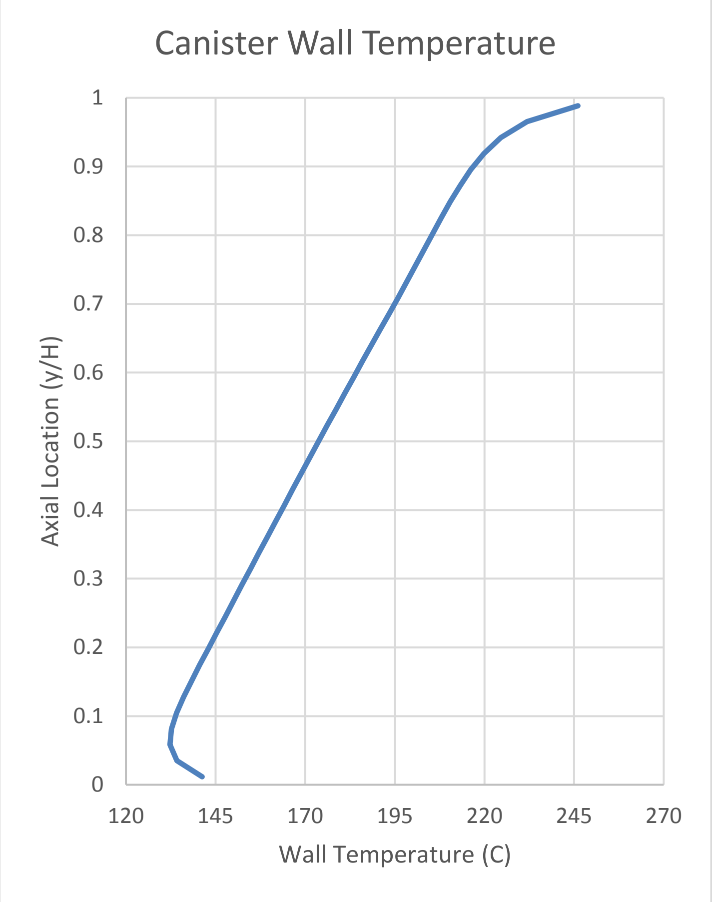
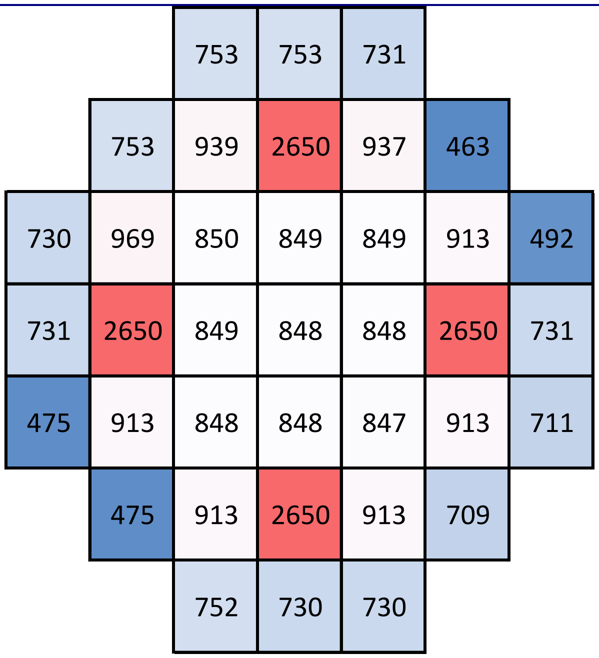


Figure 4.11. Average canister wall temperature profile for increased heat load on Zone A.

4.4 Case Three, Sensitivity to Zone B2 Decay Heat Increases

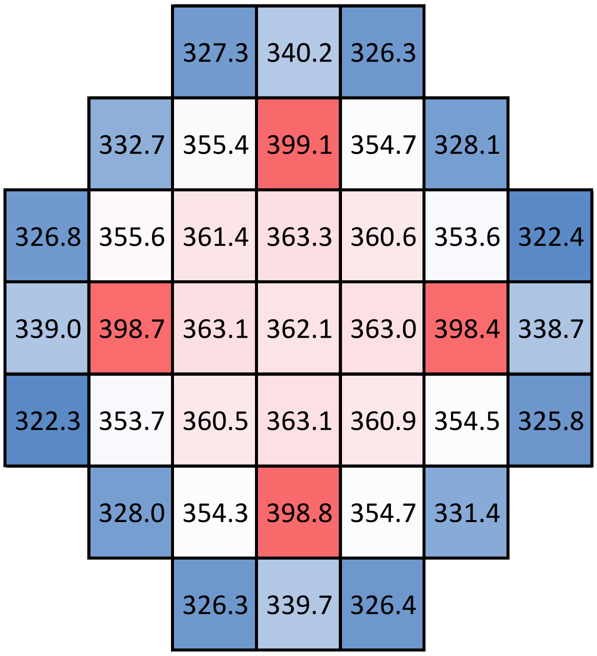
This loading configuration consisted of increasing the decay heats on the Zone B2 assemblies (Figure 2.6). The heat load in Zone B2 was increased to 2650 W to reach the PCT limit. The total heat load in this configuration is 36.4 kW and the heat loading configuration is shown in Figure 4.12. The high individual assembly heat load in this configuration is similar to case one where assemblies 12 and 19 were adjusted but in this case the total heat loading is about 3 kW higher. Zone B2 is located closer to the side of the canister, which is a contributing factor to the higher maximum individual assembly heat load and maximum total heat load in this case.



		753	753	731		
	753	939	2650	937	463	
730	969	850	849	849	913	492
731	2650	849	848	848	2650	731
475	913	848	848	847	913	711
	475	913	2650	913	709	
		752	730	730		

Figure 4.12. Zone B2 heat loading for 400ºC PCT (W).

In this loading case the hottest assembly PCTs are located on the assemblies within Zone B2 shown in Figure 4.13. The surrounding assembly PCTs are significantly lower. An interesting thing to note is the center most assemblies are relatively cooler in this loading configuration. The temperature distribution as well as the assembly heat distribution is mostly concentrated on the high heat loaded Zone B2.



		327.3	340.2	326.3		
	332.7	355.4	399.1	354.7	328.1	
326.8	355.6	361.4	363.3	360.6	353.6	322.4
339.0	398.7	363.1	362.1	363.0	398.4	338.7
322.3	353.7	360.5	363.1	360.9	354.5	325.8
	328.0	354.3	398.8	354.7	331.4	
		326.3	339.7	326.4		

Figure 4.13. PCTs with Zone B2 at 2650 W (°C).

Most of the fuel cladding temperature falls between 180ºC and 360ºC (Figure 4.14). The only assemblies that have any portion of cladding temperature above 365ºC are the assemblies in Zone B2. The cladding temperature profile in this case is similar to the cladding temperature profile in the case where assemblies

12 and 19 were adjusted as shown in Figure 4.6. In this case the distribution is shifted higher and a greater percentage of PCTs are above the uniform distribution lump in the B2 case. This stems from a higher overall heat load and having four assemblies at the maximum PCT versus two assemblies for the assembly 12 and 19 adjustment case. Very little cladding reaches temperatures hotter than 360°C so this configuration offers a similar temperature margin to sensitivity case one.

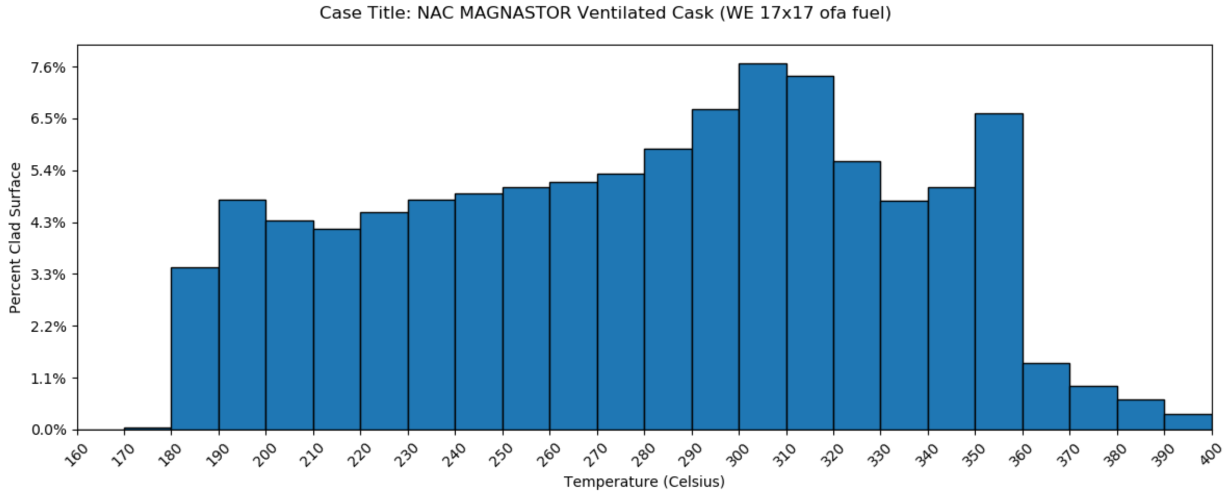


Figure 4.14. Zone B2 loading cladding temperature distribution for PCT 400ºC.

The circumferential average canister wall temperature in this configuration was higher than in sensitivity cases one and two at 260ºC as shown in Figure 4.15. There is only one assembly between the assemblies in Zone B2 and the side of the canister which contributes to the higher canister wall temperatures.

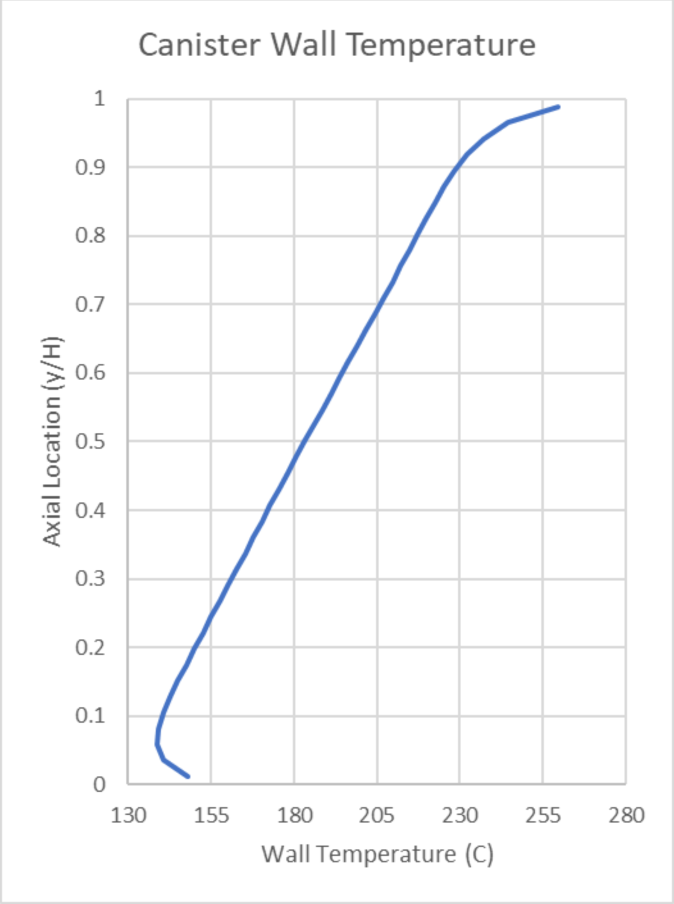
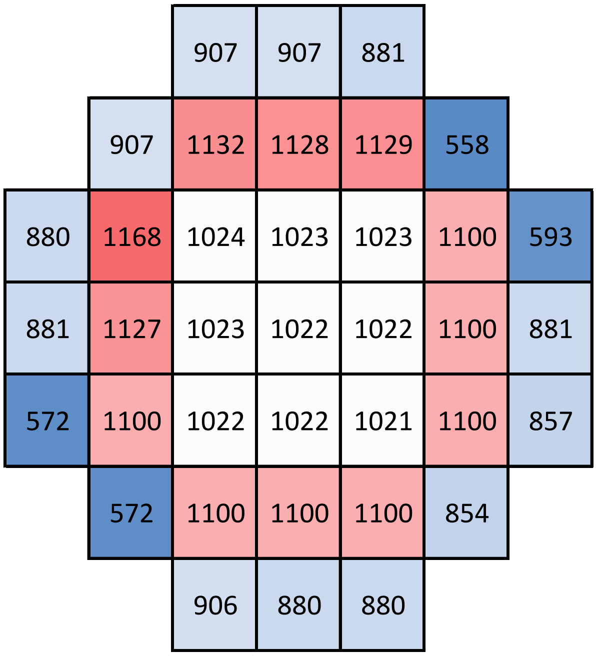


Figure 4.15. Average canister wall temperature axial profile for B2 heat loading.

The B2 loading case packed four assemblies at 2650 W and a total heat load of 36.4 kW while remaining at the PCT limit of 400°C. In this loading configuration the maximum assembly decay heat is 200 W lower than in case one, but there are two more assemblies at the maximum assembly decay heat in this case. Overall a very small portion of the cladding temperatures are over 390°C with the vast majority being below 360°C, which indicates this loading configuration is well suited to storing high decay heat assemblies.

4.5 Case Four, Margin Between Conservative Heat Load and Design Basis Total Heat Load

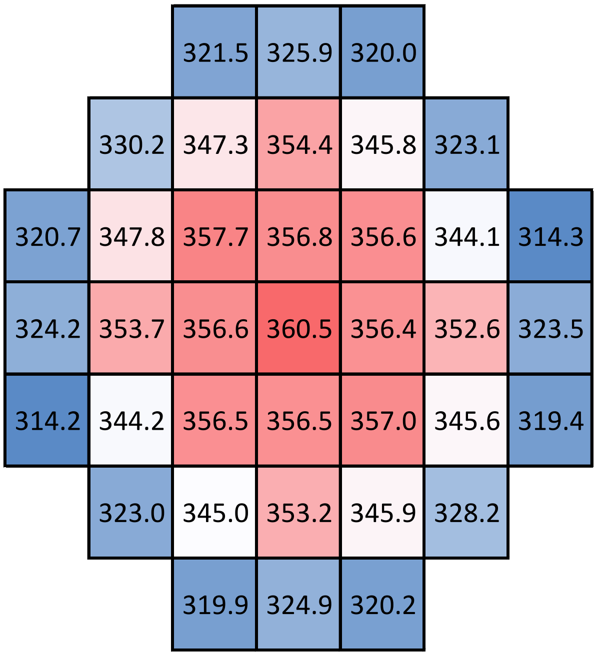
The loading configuration analyzed in this section is the conservative base load configuration (Figure 2.1) increased by about 20% in each assembly to get a total heat load at the design basis of 35.5 kW. The resulting heat loading configuration is shown in Figure 4.16. This heat load configuration is similar to the heat load for the three-zone preferential design basis load in Figure 2.2. Overall, the heat loading distribution in this case is more uniform, with a smaller difference between the highest and lowest heat assemblies. There are four assemblies in the outer zone that have a significantly lower heat load than the other assemblies.



		907	907	881		
	907	1132	1128	1129	558	
880	1168	1024	1023	1023	1100	593
881	1127	1023	1022	1022	1100	881
572	1100	1022	1022	1021	1100	857
	572	1100	1100	1100	854	
		906	880	880		

Figure 4.16. Conservative base loading scaled to the design basis total heat load of 35.50 kW.

In this loading configuration the maximum assembly PCT reached 360.5ºC as shown in Figure 4.17, which is about 46.5ºC higher than the initial base case. This max assembly PCT is well below the PCT limit of 400°C. The assembly PCTs are uniform with smaller changes in the radial direction.



		321.5	325.9	320.0		
	330.2	347.3	354.4	345.8	323.1	
320.7	347.8	357.7	356.8	356.6	344.1	314.3
324.2	353.7	356.6	360.5	356.4	352.6	323.5
314.2	344.2	356.5	356.5	357.0	345.6	319.4
	323.0	345.0	353.2	345.9	328.2	
		319.9	324.9	320.2		

Figure 4.17. PCTs of the conservative base scaled to design basis total heat loading (°C).

The uniform heat load and PCT profile also contributes to an even cladding temperature distribution (Figure 4.18). There is a significant lump in the temperature range from 290ºC to 350ºC. Overall this heatloading profile offers cladding temperature well below the PCT limit while meeting the design basis heat loading.

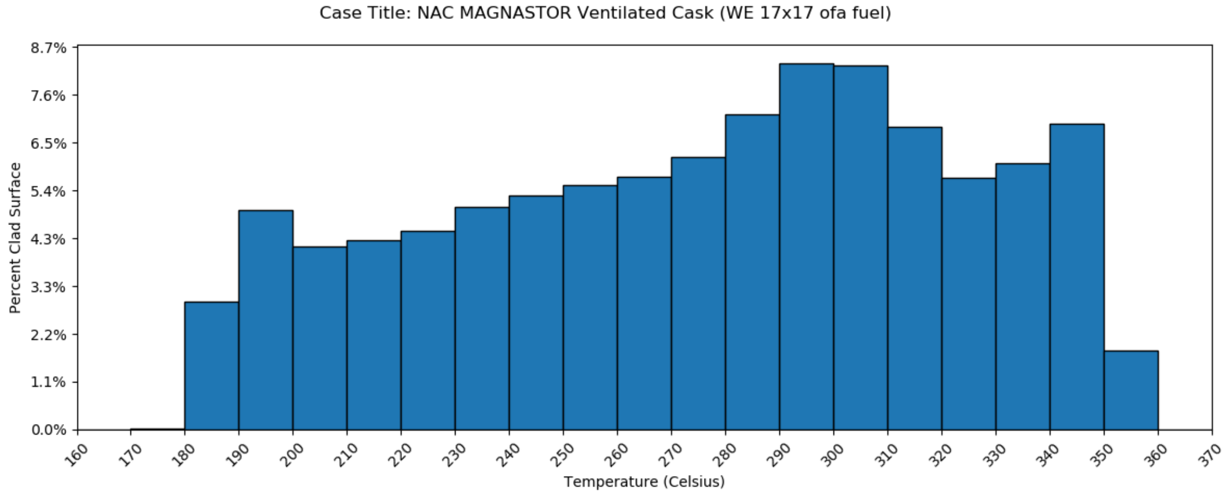


Figure 4.18. Cladding temperature distribution conservative base loading scaled to design basis total heat load.

For the scaled conservative base case the canister wall temperature profile is shown in Figure 4.19. Because this case is a scaled version of the conservative base, this profile is very similar to the previous conservative base case. The scaled-up heat load in this case pushed the canister wall temperatures up by about 10°C. The maximum average canister wall temperature for this configuration was about 260°C.

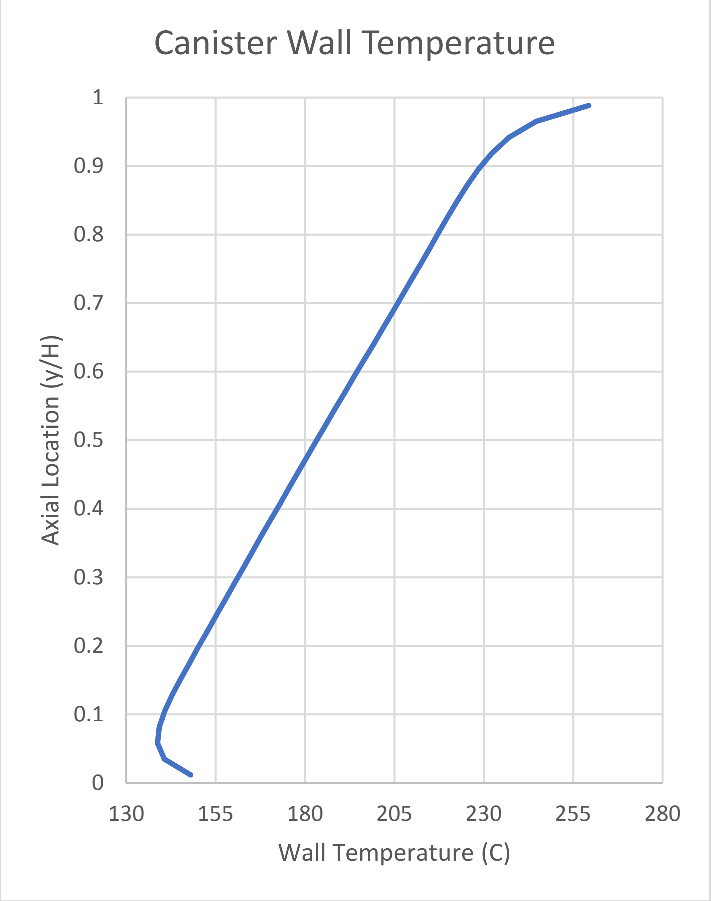


Figure 4.19. Average canister wall temperature profile for the scaled conservative base loading configuration.

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5. DESIGN BASIS HEAT LOAD MODEL RESULTS

The design basis heat load model results consist of the three-zone and four-zone design basis base cases and two follow-on cases. Although COBRA-SFS is validated for these systems there are known weaknesses in predicting local temperatures at the axial top and bottom of a model. This may cause some spurious results in the upper and lower canister temperatures reported.

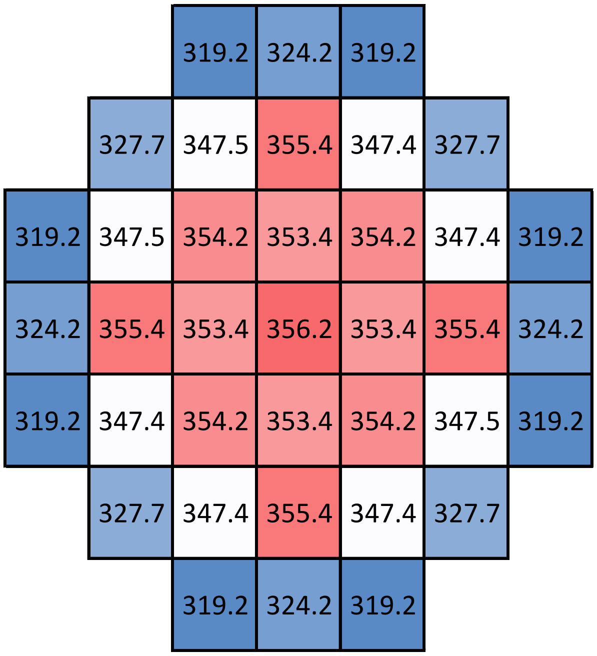
5.1 Three-Zone Design Basis Base Case

The three-zone design basis base case heat load configuration is shown in Figure 2.2 and summarized in Table 5.1. This base case loading configuration is fairly uniform, with the difference between the highest heat assembly and lowest heat assembly being 400 W. The highest heat assemblies are at 1200 W and are in the middle Zone B (Table 5.1). The total heat loading for this configuration is 35.5 kW.

Table 5.1. Three-zone design basis preferential loading configuration (NAC 2011).

Zone (see Figure 2.5)	Designator	Maximum Heat Load (W/assembly)	# Assemblies
Inner Zone	A	922	9
Middle Zone	B	1200	12
Outer Zone	C	800	16

The three-zone design basis loading case offered the lowest peak cladding temperature of the design basis loading configurations. The PCT for this loading configuration is 356.2ºC and it is located on the center assembly shown in Figure 5.1. All the middle and inner assembly PCTs were within about 10ºC of each other. The assembly PCTs located on the outside were significantly cooler.



		319.2	324.2	319.2		
	327.7	347.5	355.4	347.4	327.7	
319.2	347.5	354.2	353.4	354.2	347.4	319.2
324.2	355.4	353.4	356.2	353.4	355.4	324.2
319.2	347.4	354.2	353.4	354.2	347.5	319.2
	327.7	347.4	355.4	347.4	327.7	
		319.2	324.2	319.2		

Figure 5.1. PCTs for three-zone design basis base case heat load (°C).

The cladding temperature profile for this configuration is relatively uniform with each 10ºC temperature range accounting for a similar portion of the cladding (Figure 5.2). There is a peak from 290ºC to 350ºC.

This temperature range is just below the PCT of all the interior assemblies and is right at the PCT for the outer assemblies. Some portion of every rod lies within this temperature range. An interesting note is the temperature range of 340ºC to 350ºC accounts for a significant portion of cladding as seen in Figure 5.2. This temperature profile is very similar to the previous case where the conservative base decay heat load is scaled to the design basis total heat load. The 340°C to 350° temperature range is right in range of the PCTs for all the interior assemblies. The uniform heat loading is a contributing factor to the even distribution of cladding temperatures.

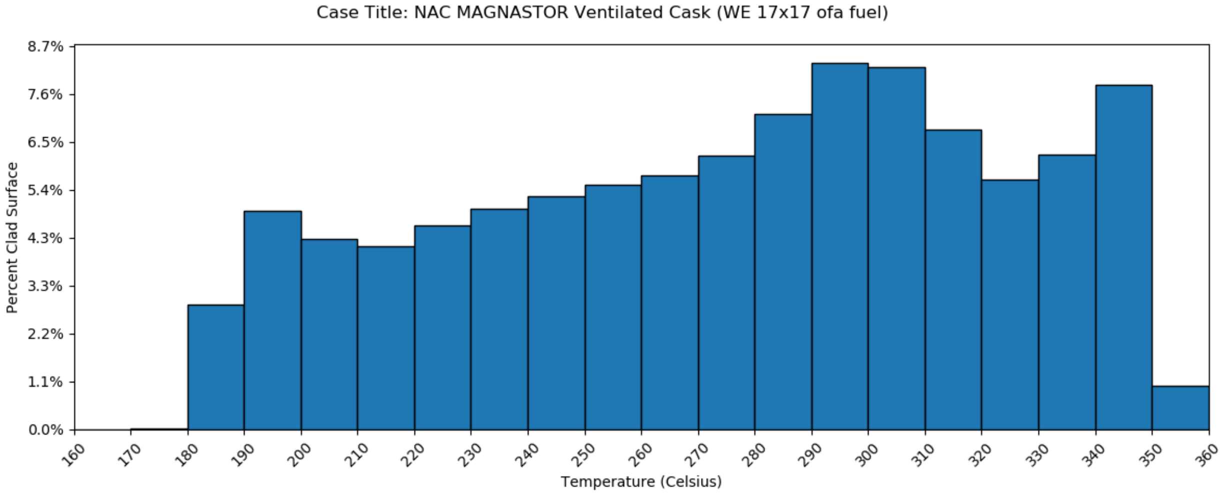


Figure 5.2. Zone design basis cladding temperature distributions.

To provide a comparison, the average canister wall temperature profile is provided in Figure 5.3. The maximum canister wall temperature reached about 250°C. The difference between the hottest and the coolest circumferential average is about 111°C. This is a similar range to the previous case where the conservative base load was scaled to the design basis heat load. This is a logical result since the total heat load is the same and loading configuration between the two cases is similar.

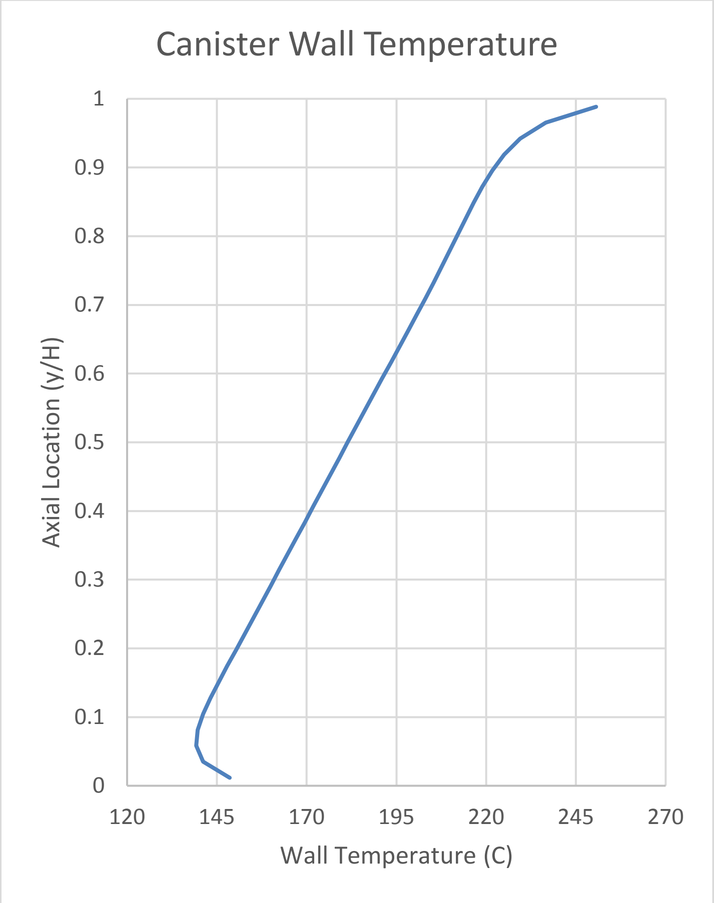


Figure 5.3. Average canister wall temperature profile for 3-zone design basis loading configuration.

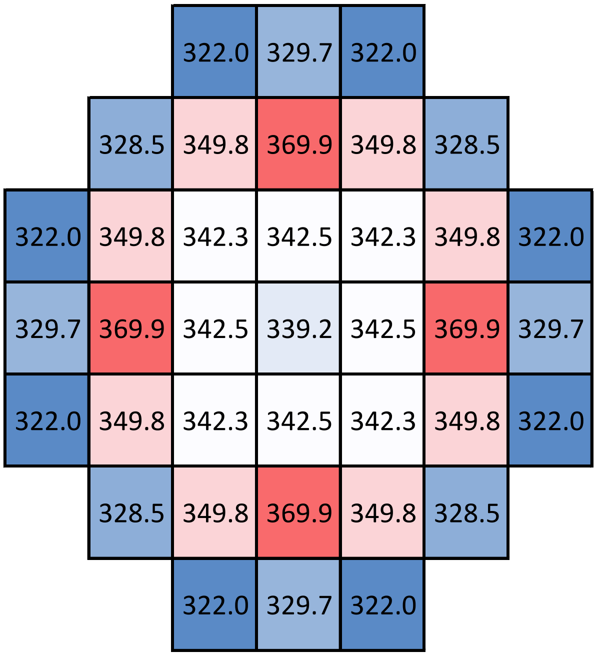
5.2 Four-Zone Design Basis Base Case

The second preferential design basis loading configuration contains four zones with different decay heat values in each zone. This configuration is similar to the three-zone configuration except this configuration has a lower interior assembly decay heat and higher heat assemblies in Zone B2. The four-zone design basis heat load is shown in Figure 2.3 and summarized in Table 5.2. This loading configuration is not as uniformly distributed as the three-zone case. There is a significant amount of heat concentrated in Zone B2 with those assemblies at 1800 W (Table 5.2). The difference between the highest heat assembly and the lowest heat assembly is about 1300 W. The total heat load in this configuration is the same as the three-zone design basis at 35.5 kW.

Table 5.2. Four-zone design basis preferential loading (NAC 2011).

Zone Description (see Figure 2.6)	Designator	Maximum Heat Load (W/assembly)	# of Assemblies
Inner Zone	A	513	9
Middle Zone	B1	1300	8
	B2	1800	4
Outer Zone	C	830	16

In this configuration the PCTs are in the higher heat Zone B2 assemblies (Figure 5.4). The interior assemblies are significantly cooler due to the lower decay heat in those assemblies. The assembly decay heat in Zone A is only 513 W. The Zone A assembly PCTs are about 20ºC to 30ºC cooler than Zone B2 assemblies. In this configuration the hottest assembly PCT is 13ºC warmer than in the three-zone design basis configuration.



		322.0	329.7	322.0		
	328.5	349.8	369.9	349.8	328.5	
322.0	349.8	342.3	342.5	342.3	349.8	322.0
329.7	369.9	342.5	339.2	342.5	369.9	329.7
322.0	349.8	342.3	342.5	342.3	349.8	322.0
	328.5	349.8	369.9	349.8	328.5	
		322.0	329.7	322.0		

Figure 5.4. Four-zone design basis base case assembly PCT (°C).

The cladding temperature distribution is not as uniform in this four-zone loading configuration as it is in the three-zone loading configuration (Figure 5.5). There is a 10ºC temperature range from 330ºC to 340ºC that accounts for a significant percentage of cladding. All the assembly PCTs on the interior and middle assemblies have a similar PCT right around 340ºC which contributes to this higher portion of cladding in this temperature range. A small portion of the fuel cladding reaches temperatures higher than 350ºC. Temperatures above 350ºC are in the four B2 assemblies.

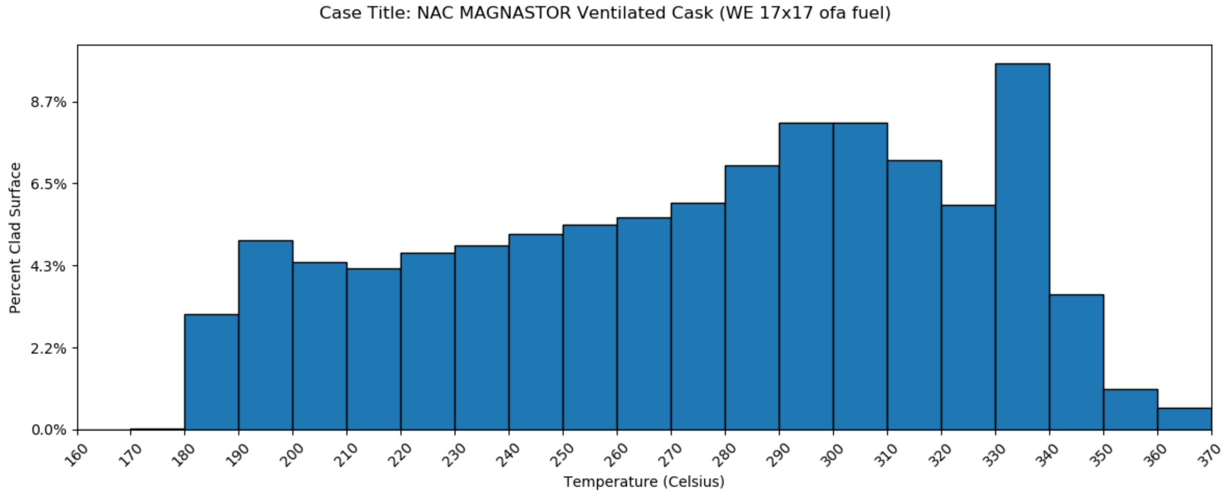

Case Title: NAC MAGNASTOR Ventilated Cask (WE 17x17 ofa fuel)

Figure 5.5. Four-zone design basis heat load cladding temperature distribution.

The circumferential average canister wall temperature profile is shown in Figure 5.6. The temperature profile for this four-zone design base case is almost the same as the three-zone configuration. This is interesting because in this four-zone case there is more heat concentrated in zone B2 which is closer the canister wall.

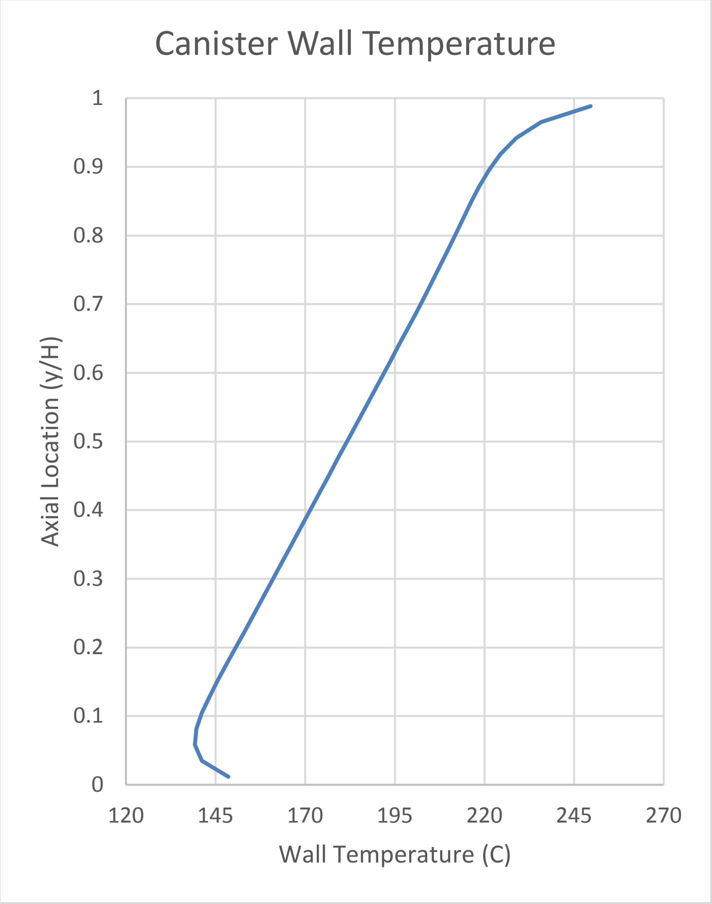
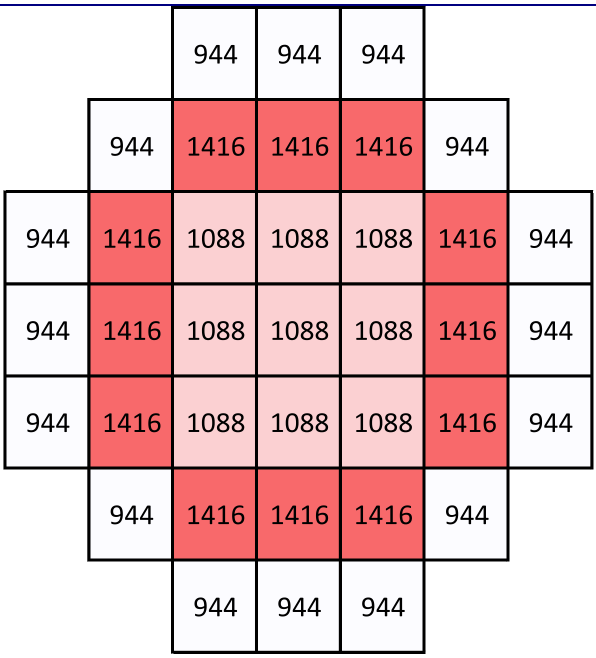


Figure 5.6 Average canister wall temperature for 4-zone design basis loading configuration.

5.3 Case Five, Three-Zone Design Basis Decay Heat Increase

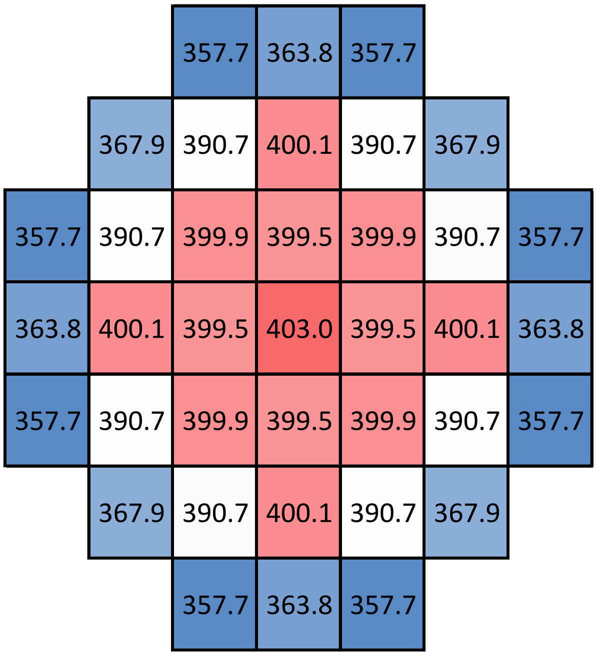
The total heat load in this scaled three-zone design basis loading configuration was increased 18% over the design basis load for a total heat load of 41.9 kW before reaching the PCT limit (Figure 5.7). This is the highest allowable heat load while meeting the PCT limit investigated in this study. This loading configuration lent itself well to a high total heat load due to a relatively uniform assembly decay heat load. There is a 472-Watt difference between the highest heat assembly and lowest heat assembly, which is a relatively small difference compared to other sensitivity cases.



		944	944	944		
	944	1416	1416	1416	944	
944	1416	1088	1088	1088	1416	944
944	1416	1088	1088	1088	1416	944
944	1416	1088	1088	1088	1416	944
	944	1416	1416	1416	944	
		944	944	944		

Figure 5.7. Three-zone loading design basis configuration scaled to reach 400ºC PCT (W).

The assembly PCTs in the interior of the canister are all right at the PCT limit (Figure 5.8). There is a significant drop in PCT from the interior assemblies to the outer assemblies. The outer assembly PCTs are still relatively hot with all Zone C assembly PCTs above the maximum PCT in the three-zone design basis heat load configuration. The PCT in this configuration is 46.9ºC higher than the design basis PCT.



		357.7	363.8	357.7		
	367.9	390.7	400.1	390.7	367.9	
357.7	390.7	399.9	399.5	399.9	390.7	357.7
363.8	400.1	399.5	403.0	399.5	400.1	363.8
357.7	390.7	399.9	399.5	399.9	390.7	357.7
	367.9	390.7	400.1	390.7	367.9	
		357.7	363.8	357.7		

Figure 5.8. Scaled three-zone design basis PCTs at total heat load of 41.89 kW (°C).

The temperature distribution in this configuration is uniform, with a significant portion of the cladding temperatures above 320ºC (Figure 5.9). This cladding temperature profile is similar to the three-zone design basis base case, but the cladding temperature distribution is shifted up by about 40ºC. This shift correlates to the PCT being 46.9ºC hotter than in the three-zone design basis base case. This indicates a significant overall decay heat margin in the three-zone design basis configuration. Due to a uniform cladding temperature distribution, a significant amount of cladding surface is right at the cladding temperature limit. With a significant number of assembly PCTs at the limit, there is less margin than in sensitivity case one where only two assemblies were at the PCT limit.

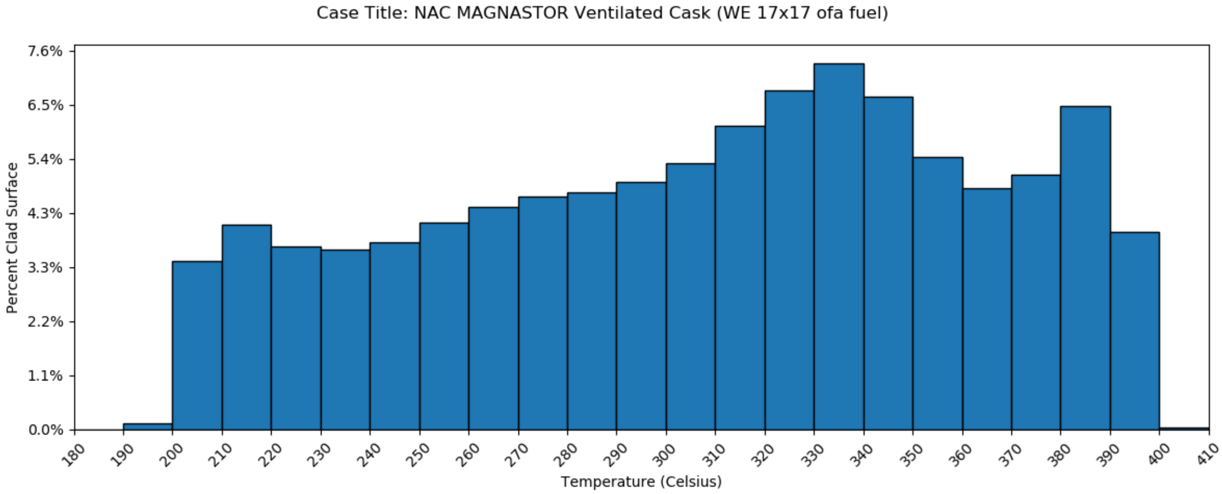


Figure 5.9. Scaled three-zone design basis cladding temperature distribution.

In this loading configuration the circumferential average temperature of the canister wall reached 279ºC which is the hottest wall temperature of any other loading configuration at the PCT limit (Figure 5.10). The higher wall temperature aids heat rejection and is a contributing factor to the high total heat load of this configuration.

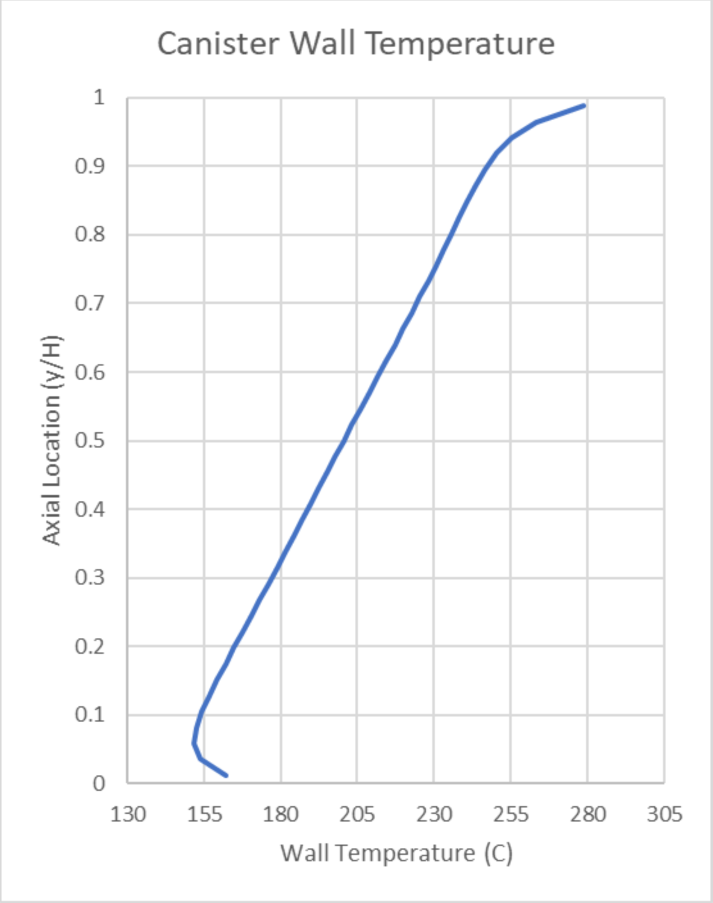
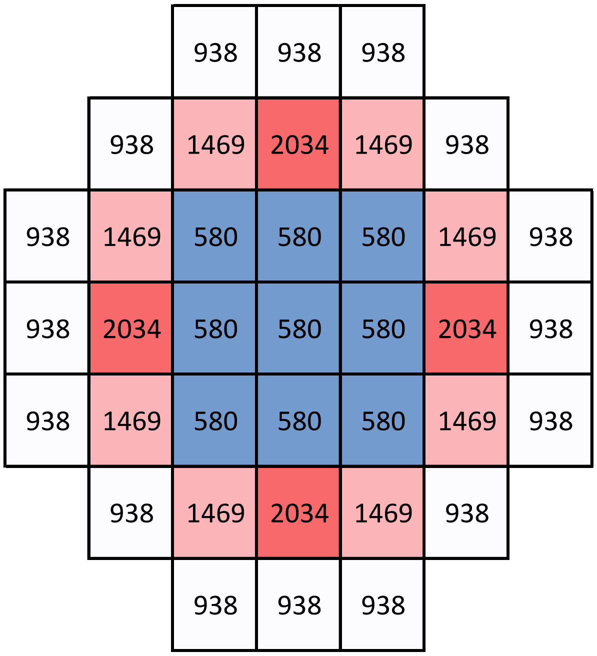


Figure 5.10. Average canister wall temperature for scaled three-zone design basis heat loading.

5.4 Case Six, Four-Zone Design Basis Decay Heat Increase

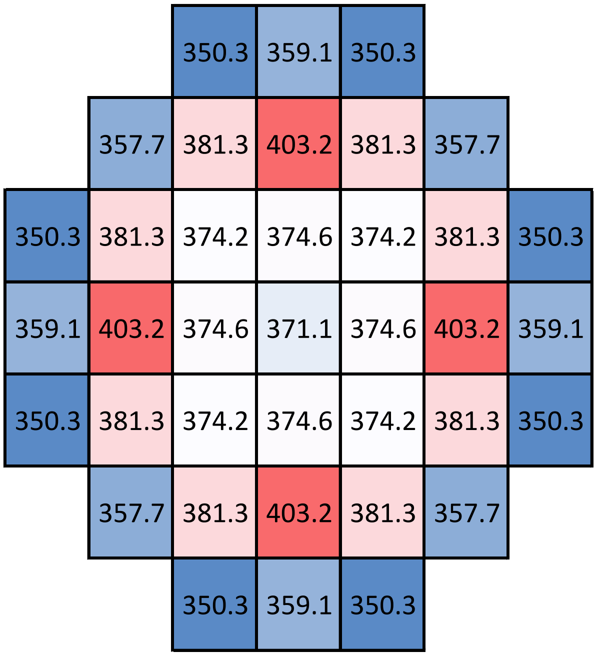
In this configuration the four-zone design basis total decay heat was increased by 13 percent to reach a total heat load of 40.1 kW at the PCT limit shown in Figure 5.11. This was achieved by increasing the decay heat in each assembly by 13%. The higher heat loads concentrated in the Zone B2 assemblies are a limiting factor on the total heat load due to those assemblies reaching the PCT limit. Despite the heat concentrated in the Zone B2 assemblies, the total decay heat load in this configuration was close to the three-zone case with only 1.8 kW less total heat.



		938	938	938		
	938	1469	2034	1469	938	
938	1469	580	580	580	1469	938
938	2034	580	580	580	2034	938
938	1469	580	580	580	1469	938
	938	1469	2034	1469	938	
		938	938	938		

Figure 5.11. Scaled four-zone design basis maximum heat loading (W).

The maximum PCTs are on the assemblies located in Zone B2. The higher heat on those assemblies and the low heat on the Zone A assemblies contributed to the higher assembly PCTs in Zone B2. The surrounding assembly PCTs are about 25ºC to 50ºC cooler (Figure 5.12). The PCTs in this loading configuration are 33.3ºC higher than the four-zone design basis base case.



		350.3	359.1	350.3		
	357.7	381.3	403.2	381.3	357.7	
350.3	381.3	374.2	374.6	374.2	381.3	350.3
359.1	403.2	374.6	371.1	374.6	403.2	359.1
350.3	381.3	374.2	374.6	374.2	381.3	350.3
	357.7	381.3	403.2	381.3	357.7	
		350.3	359.1	350.3		

Figure 5.12. Four-zone maximum heat loading assembly PCTs (°C).

The rod cladding temperature profile is uniform within the range of 200ºC to 360ºC shown in Figure 5.13. An interesting note is a spike in cladding temperature distribution in the 360ºC to 370ºC temperature range. All the interior assembly PCTs fall within this range, which contributes to this higher portion of cladding temperature. Also, a small percentage of the cladding is above 380ºC. The portion of the cladding temperature that is above 380ºC is only on the four-zone B2 assemblies that are at the PCT limit. This loading configuration offers a better margin over case five due to most of the cladding being below 380ºC.

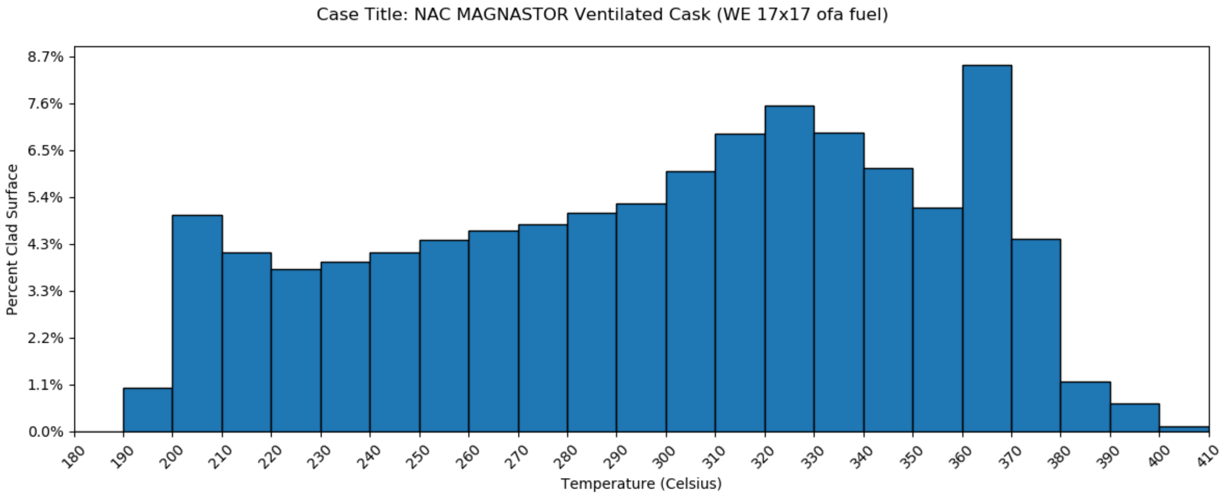


Figure 5.13. Scaled four-zone design basis heat load clad temperature distribution at PCT of 400ºC.

In this configuration the peak circumferential average canister wall temperature remains about 10ºC cooler than in the scaled three-zone configuration at the PCT limit. The peak circumferential average canister wall temperature reached about 270ºC as shown in Figure 5.14. The outer assembly PCTs are around 10ºC cooler than in the scaled three-zone maximum heat load configuration. The peak canister wall temperature is still significantly hotter than in sensitivity cases one through three due to the significantly higher total heat load in this configuration.

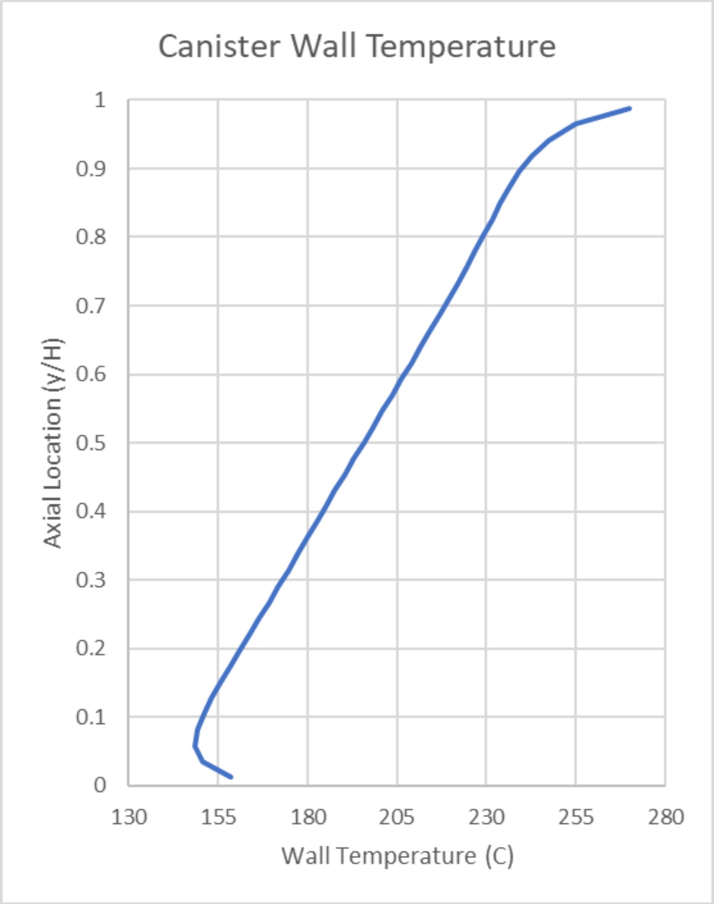


Figure 5.14. Average canister wall temperature distribution scaled four-zone loading configuration.

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6. LOADING SENSITIVITIES

After adjusting the heat load in assemblies 12 and 19, Zone A, and Zone B2, the resulting PCTs as a function of total heat load were plotted. From this plot, the slope of the line was determined. The slope of the line is the correlation between change in heat load and PCT. For each sensitivity case, the heat loading affects the fuel rod PCT differently. When only assemblies 12 and 19 were adjusted, the canister was significantly more sensitive to increases in heat loading versus the case where only Zone A assemblies were adjusted. This is indicated by the total heat load when the PCT limit was reached as well as the plot slopes of PCT versus total heat load. Total heat load is a normalized value that can be easily compared between different heat loading cases.

For the case in which the heat load on assemblies 12 and 19 were adjusted there exists a linear relationship between total heat load and PCT. The PCT changes about 21.4ºC per Kilowatt of total heat load (Figure 6.1). The PCT in this configuration is on assembly 19, which is one of the assemblies where the heat loads were adjusted.

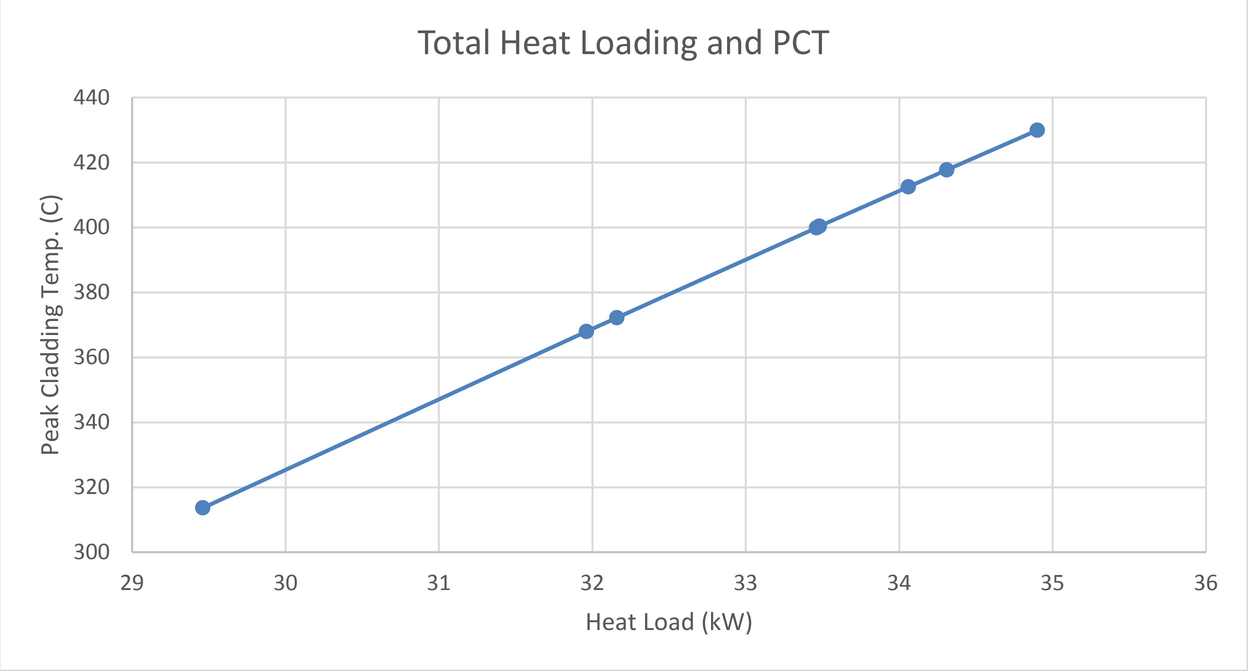

Figure 6.1. Assemblies 12 and 19 adjustment case total heat load vs. PCT.

PCTs are not as sensitive to adjustments in heat loading on Zone A and Zone B2 than in case one where assemblies 12 and 19 were adjusted. For these configurations the PCT changes about 11ºC and 13ºC per kW of total heat load respectively as shown in Figure 6.2, and Figure 6.3. This is significantly lower than 21°C/kW in the previous case where assemblies 12 and 19 were adjusted. Different loading configurations have significant effects on the fuel rod PCT response.

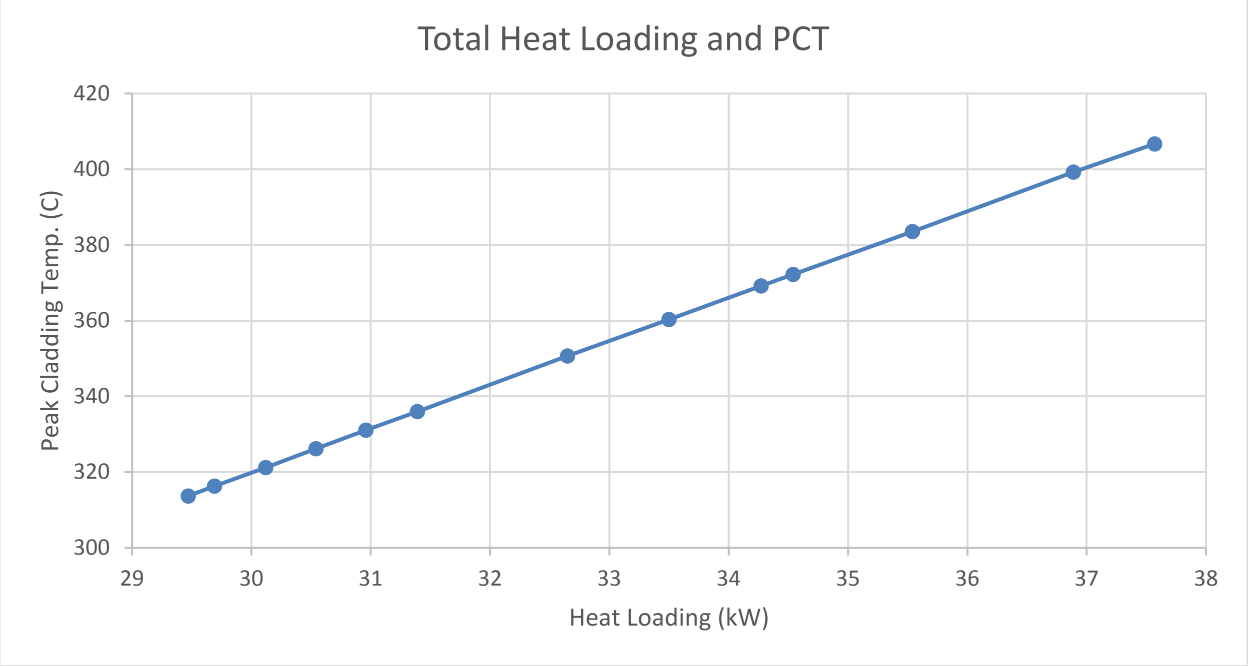

Figure 6.2. Zone A adjustment case total heat load vs. PCT.

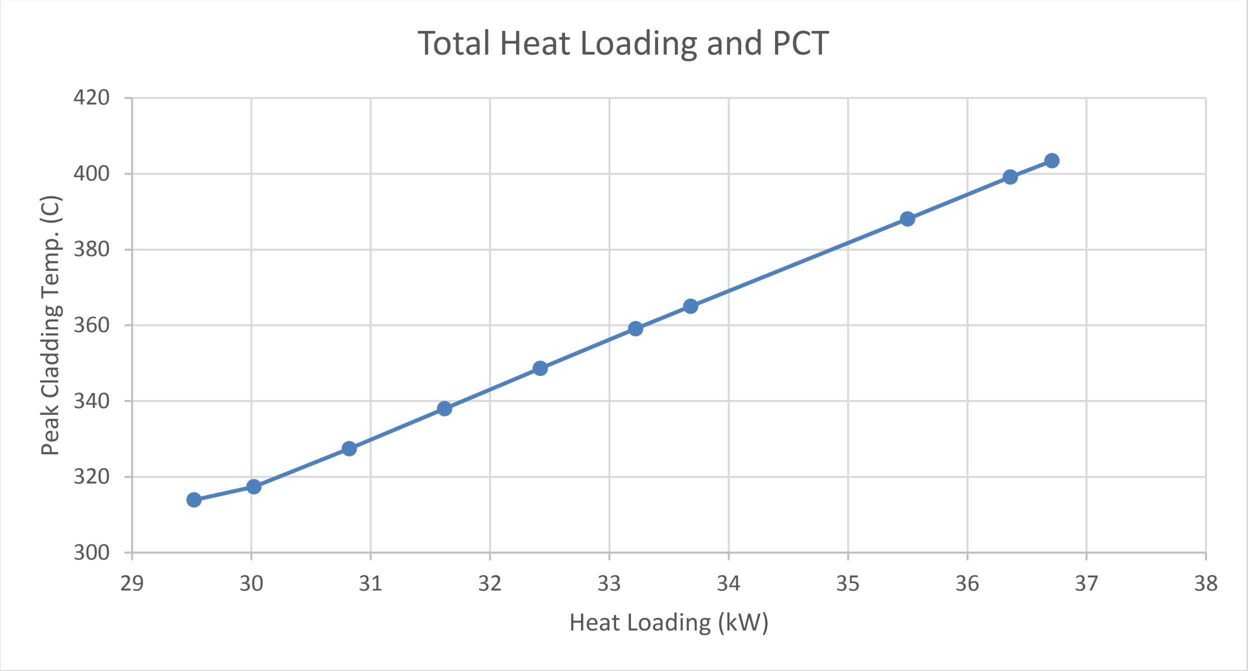

Figure 6.3. Zone B2 adjustment case total heat load vs. PCT.

The loading configuration for case one adjusting assemblies 12 and 19 and case three adjusting Zone B2 are very similar to each other. In both cases a high heat load is concentrated on a small number of assemblies. Case one has the highest individual assembly decay heat at 2860 W and case three has the next highest individual assembly decay heat at 2650 W when PCTs are at the limit. Yet, there is a significant difference between the PCT sensitivities in these two cases. The PCT change in case one is 8.7^{o}C/kW more than in case three. The location of Zone B2 in the canister is a factor in allowing a higher total heat load at the PCT limit. This results in case three being less sensitive to decay heat loading adjustments than case one.

Figure 6.4 and Figure 6.5 show the sensitivity of peak clad temperature to changes in total heat load for the scaled design basis base loading cases discussed earlier in sensitivity cases five and six. In this case all the assemblies in the three-zone and four-zone design basis loading configurations were increased by the same percentage. The uniform increase in assembly heat loading resulted in a lower heat load sensitivity. For both loading cases, the PCT changes by about 7^{o}C per Kilowatt of total heat load increase. In the three-zone and four-zone design basis loading configurations, the starting total heat load and how the heat load is increased was the same. This is a contributing factor to those cases having very similar sensitivities to total heat load increases.

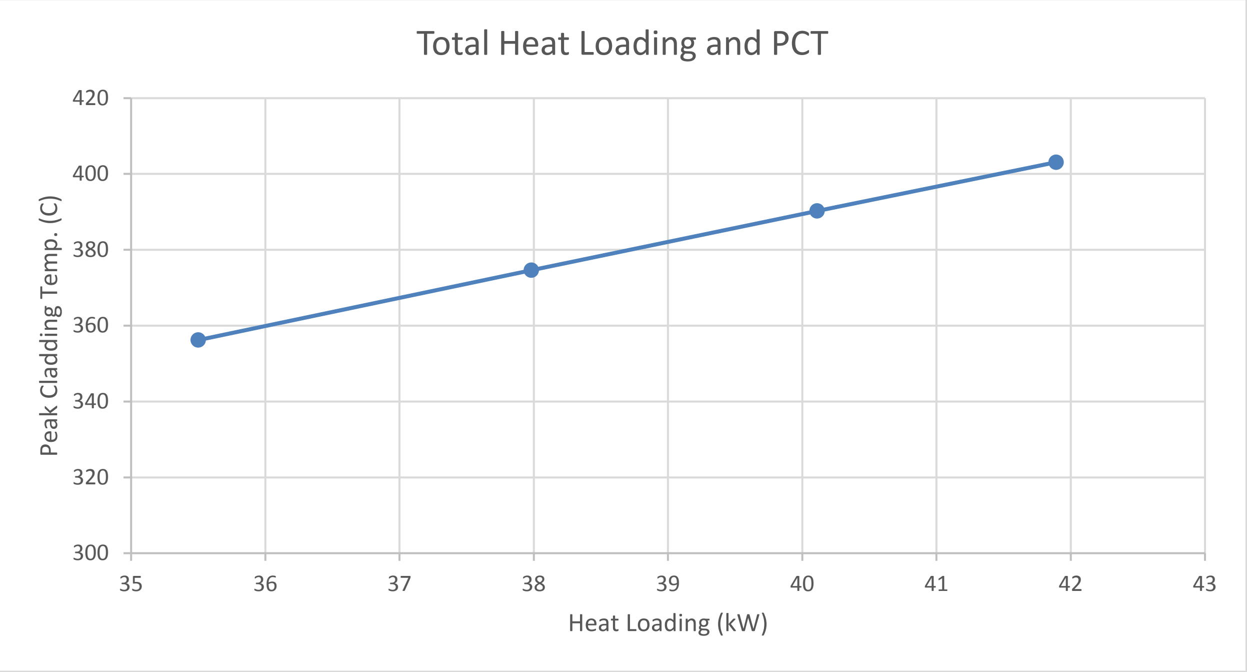

Figure 6.4. Scaled three-zone design basis total heat load vs. PCT.

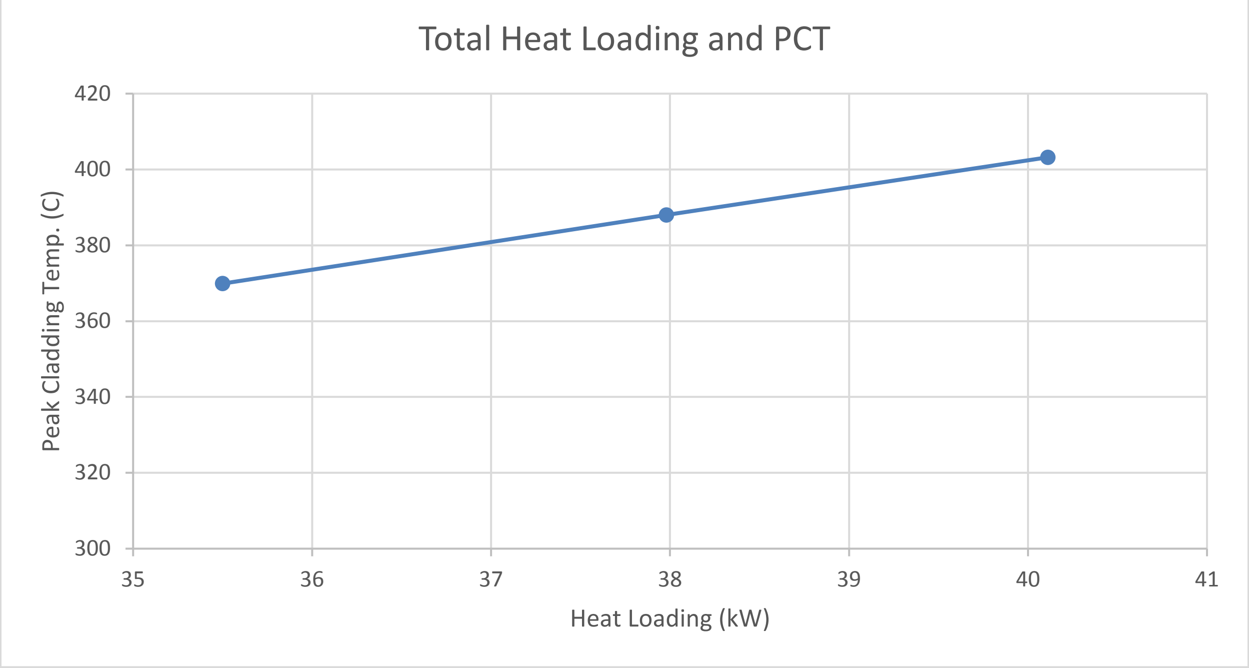

Figure 6.5. Scaled four-zone design basis total heat load vs. PCT.

7. CONCLUSIONS AND RECOMMENDATIONS

Decay heat loading configurations have a significant effect on fuel rod cladding temperature in the MAGNASTOR canister. Through modeling the MAGNASTOR canister with COBRA-SFS, the effects of different loading configurations on cladding temperatures and temperature distributions were analyzed. A summary of this analysis can be found in Table 7.1. The highest decay heat assemblies that the canister could hold while remaining within the ISG 11 PCT limit (NRC 2003) were determined by this method.

Overall the MAGNASTOR system shows an ability to load small numbers of very high heat load assemblies (>2.5 kW) with the four-zone loading configuration and stay within the regulatory limits. This would likely be true for similar pressurized canister system designs. For this type of loading the overall clad temperature distribution stayed low with only the four assemblies at >2.5 kW reaching the PCT limit compared to the scaled three-zone design basis loading configuration where most of the assemblies reached the PCT limit. This is an important result because it shows the current industry push to increase cell limits for loading small numbers of increasingly hot assemblies may not have a detrimental effect on overall clad temperatures. This is in contrast to the goal of loading maximum numbers of assemblies and maximum total decay heats resulting in high overall clad temperatures. The more traditional approach will result in higher clad temperature distributions when casks are loaded near their design basis heat load.

The authors recommend studying actual loaded systems utilizing the four-zone MAGNASTOR decay heat loading configurations along with loading strategies used in similar storage systems to further determine the impacts of these strategies on more realistic loading scenarios.

Table 7.1. Summary of results.

Case Name	Description	Max Assembly Heat load (W)	Total System Heat Load (kW)	Peak Cladding Temperature (°C)	% Cladding Above 350°C
Conservative Base	Duke Energy estimate for actual load	969	29.5	314.0	0.0
Case One	Assemblies 12, 19 adjustment	2860	33.5	400.9	2.1
Case Two	Zone A adjustment	1675	36.9	399.1	10.9
Case Three	Zone B2 adjustment	2650	36.4	399.1	9.9
Case Four	Scaled Conservative Base	1168	35.5	360.5	1.8
3-Zone Design Basis	3-zone preferential design loading	1200	35.5	356.2	1.0
4-Zone Design Basis	4-Zone preferential design loading	1800	35.5	369.9	1.7
Case Five	Scaled 3-zone Design Basis	1416	41.9	403.0	26.0
Case Six	Scaled 4-Zone Design Basis	2034	40.1	403.2	20.1

8. REFERENCES

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