

Appendix 1 Thermal Hydraulics

1.0 Spent Fuel Heatup Analyses

Spent fuel heatup analyses model the decay power and configuration of the fuel to characterize the thermal hydraulic phenomena that will occur in the SFP and the building following a postulated loss of water accident. This appendix reviews the existing studies on spent fuel heatup and zirconium oxidation, the temperature criteria used in the analyses, and how it applies to decommissioned plants.

1.1 Spent Fuel Failure Criteria

Several different fuel failure criteria have been used in previously NRC-sponsored SFP accident studies. Benjamin, et. al. used the onset of runaway fuel clad oxidation as the fuel failure criterion in NUREG/CR-0649 [Ref. 1]. This criterion was criticized because clad rupture can occur at a relatively low temperature causing a gap release. The consequences of gap release can be significant if the radioactive iodine has not yet decayed to insignificant amounts. SHARP calculations [Ref. 2] used the onset of clad swelling as an acceptance criterion for prevention of fuel failure. The onset of clad swelling leading to gap release occurs at approximately 565 °C, which corresponds to the temperature for 10-hour creep rupture time [Ref. 3]. A cladding temperature of 570 °C is used as a thermal limit under accident conditions for licensing of spent fuel dry storage casks.

The most severe fuel damage would be caused by rapid, runaway zirconium oxidation. This would lead to significant fission product release even after the gap activity has become insignificant. The onset of rapid oxidation may occur as low as 800 °C [Ref. 4]. Runaway oxidation can raise clad and fuel temperatures to approximately 2000 °C which corresponds to the melting temperature of zirconium. The release of fission products trapped in the fuel can occur at fuel temperatures of approximately 1400-1500 °C. Runaway oxidation starting in a high powered channel could also propagate through radiative and convective heat transfer to lower power assemblies because of the large heat of reaction in zirconium oxidation.

There are several other temperature thresholds that may be of concern in SFP accidents. The melting temperature of aluminum, which is a constituent in BORAL poison plates in some types of the spent fuel storage racks, is approximately 640 °C. No evidence was found that boron carbide will dissolve in the aluminum forming a eutectic mixture that liquefies at a temperature below the melting point of aluminum. However, if it is possible for a molten material to leak from the stainless steel spent fuel storage rack case, melting and relocation of the aluminum in the boron carbide-aluminum composite may cause flow blockages that increase hydraulic resistance. No realistic evaluation of melting and relocation of aluminum or aluminum/boron carbide eutectic has been performed.

Another concern is the structural integrity of the fuel racks at high temperatures. Several eutectic mixtures known from reactor severe accident research [Ref. 5] may be important in SFP accidents. As previously stated, the formation of a eutectic mixture allows liquification and loss of structural integrity for a mixture of materials at a lower temperature than the melting point of any of the component materials. Steel and zirconium form an eutectic mixture at

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approximately 935 °C. Steel and boron carbide form a eutectic mixture at approximately 1150 °C. The steel racks may also not be able to maintain structural integrity because of the sustained loads at high temperature. Loss of rack integrity may affect the propagation of a zirconium fire.

If the gap radioactivity inventory is significant, then the spent fuel cladding temperature must be kept below 565 °C. If the consequences of aluminum/boron carbide relocation are acceptable, then 800 °C is a reasonable deterministic acceptance temperature if uncertainties are less than the margin to 800 °C and the effects of higher temperatures on the material are modeled. Otherwise the temperature must be lower than the aluminum melting point (640 °C) or the aluminum/boron carbide eutectic melting point.

Based on the large uncertainties in heatup calculations and the low level of sophistication and poor quality of heatup calculations submitted by licensees the staff proposes an acceptance temperature of 600 °C if the radioactive iodine has decayed to the point where the gap activity is a significant contributor to offsite doses.

1.2 Evaluation of Existing Spent Fuel Heatup Analyses

In the 1980's, severe accidents in operating reactor SFPs were evaluated to assess the significance of the results of some laboratory studies on the possibility of self-sustaining zirconium oxidation and fire propagation between assemblies in an air-cooled environment, and also to assess the impact of the increase in the use of high density spent fuel storage racks on severe accidents in spent fuel pools. This issue was identified as Generic Safety Issue (GSI) 82. SNL and Brookhaven National Laboratory (BNL) used the SFUEL and SFUEL1W computer codes to calculate spent fuel heatup in these studies. While decommissioned plants were not addressed in the study, many of the insights gained from these studies are applicable to decommissioned plants.

More recently, BNL developed a new computer code, SHARP, that was intended to provide a simplified analysis method to model plant-specific spent fuel configurations for spent fuel heatup calculations at decommissioned plants. Some of this work was built on the assumption used by SNL and BNL in their studies in support of GSI 82.

1.2.1 SFUEL Series Based Analyses

Extensive work on the phenomena of zirconium oxidation in air for a SFP configuration was performed by SNL and BNL in support of GSI 82. SNL investigated the heatup of spent fuel, the potential for self-sustaining zirconium oxidation, and the propagation to adjacent assemblies [Ref. 1, 6]. SNL used SFUEL and SFUEL1W computer codes to analyze the thermal-hydraulic phenomena, assuming complete drainage of the SFP water. In NUREG/CR-4982 [Ref. 4], BNL extended the SNL studies on the phenomenology of zirconium-air oxidation and its propagation in spent fuel assemblies. The SFUEL series of codes include all modes of heat transfer, including radiation. However, radiation heat transfer may have been underestimated due to the assumed fuel bundle arrangement.

In NUREG/CR-0649, SNL concluded that decay heat and configuration are important parameters. SNL found that key configuration variables are the baseplate hole size,

downcomer width, and the availability of open spaces for air flow. They also found that building ventilation is an important configuration variable.

The draft SNL report investigated the potential for oxidation propagation to adjacent assemblies. If decay heat is sufficient to raise the clad temperature to within approximately one hundred degrees of oxidation, then the radiative heat from an adjacent assembly that did oxidize could raise its temperature to the oxidation level. The report also discusses small-scale experiments involving clad temperatures greater than 1000 °C. SNL hypothesized that molten zirconium material would slump or relocate towards the bottom of the racks and consequently would not be involved in the oxidation reaction. NUREG/CR-4982 did not allow oxidation to occur at temperatures higher than 2100 °C to account for the zirconium melting and relocation. Otherwise, temperatures reached as high as 3500 °C. It was felt that not cutting off the oxidation overstated the propagation of a zirconium fire because of the fourth power temperature dependence of the radiation heat flux. The SFUEL series of codes did not model melting and relocation of materials.

In NUREG/CR-4982, BNL reviewed the SFUEL code and compared it to the SNL small-scale experiments and concluded that SFUEL was a valuable tool for assessing the likelihood of self-sustaining clad oxidation for a variety of spent fuel configurations in a drained pool. SNL reported the following critical decay times in NUREG/CR-0649 based on having no runaway oxidation. Critical decay time is defined as the length of time after shutdown when the most recently discharged fuel temperature will not exceed the chosen fuel failure criteria when cooled by air only.

700 days	PWR, 6 kW/MTU decay power per assembly, high density rack, 10.25" pitch, 5" orifice, 1 inch from storage wall
280 days	PWR, same as above but for 1 foot from storage wall
180 days	BWR, 14 kW/MTU decay power per assembly, cylindrical baskets, 8.5" pitch, 1.5" orifice
unknown	BWR, high density rack, SFUEL1W code was limited to computation of BWR low density racks.

High density racks with a 5-inch orifice are the most representative of current storage practices. A critical decay time for high density BWR racks was not provided due to code limitations. Low density and cylindrical storage rack configurations are no longer representative of spent fuel storage. All currently operating and recently shutdown plants have some high density racks in the pool. For an assembly in a high density PWR rack with an 5-inch orifice, a decay power below 6 kW/MTU did not result in zirconium oxidation. All of these estimates were based on perfect ventilation (i.e., unlimited, ambient-temperature air) and burnup rates of 33 GWD/MTU. Currently, some PWRs are permitted to burn up to 62 GWD/MTU and some BWRs to 60 GWD/MTU. For fuel burnup of 60 GWD/MTU, the staff estimates the decay time for a bundle to reach 6 kW/MTU will increase from 2 years to approximately 3 years. Therefore, the staff expects the difference between critical decay times for PWRs and BWRs to decrease and that the BWR critical decay time for current burnups and rack designs would now be longer than the SNL estimate for high density PWR racks. The SNL calculations also do not appear to have included grid spacer loss coefficients which can have a significant effect since the

resistance of the grid spacers is greater than the resistance of a 5 inch orifice. There is no mixing between the rising air leaving the fuel racks and the relatively cooler air moving down into the pool. Including the grid spacer resistance, accounting for mixing and limiting the building ventilation flow to rated conditions will result in the critical decay power to be less than 6 kW/MTU. The SNL calculations may have understated the effective radiation heat transfer heat sink due to the assumed fuel geometry in the calculations. A more realistic fuel configuration pattern in the SFP would give a better estimate of the radiation heat sink and raise the critical decay power needed for significant oxidation.

While the studies in support of GSI 82 provided useful insights to air-cooled spent fuel assemblies, it is the opinion of the staff that they do not provide an adequate basis for exemptions. The studies were not meant to establish exemption criteria and lack sufficient information for all the parameters that could affect the decay time. Additionally, the reports are based on burnup values at that time. Since burnup values have increased, the results may not be directly applicable to today's spent fuel.

The general conclusions and the phenomena described in the studies assist in assessing issues for decommissioned plants. However, the calculated decay time values do not represent current plant operational and storage practices.

1.2.2 SHARP Based Analyses

In NUREG/CR-6451 [Ref. 6], BNL investigated spent fuel heatup that could lead to a zirconium fire at permanently shutdown plants. BNL developed a new computer code, SHARP (Spent Fuel Heatup Analytical Response Program), to calculate critical decay times to preclude zirconium oxidation for spent fuel. The code was intended to study thermal hydraulic characteristics and to calculate spent fuel heatup up to temperatures of approximately 600 °C. SHARP is limited to low temperatures since it lacks models for radiation heat transfer, zirconium oxidation, and materials melting and relocating. SHARP also lacks modeling for grid spacer losses and neglects mixing between the rising hot air and the falling cooler air in the SFP. BNL reported the following generic critical decay times using the SHARP code.

17 months for a PWR, high density rack, 60 GWD/MTU burnup; 10.4" pitch; 5" orifice
7 months for a BWR, high density rack, 40 GWD/MTU burnup; 6.25" pitch; 4" orifice

The above decay times are based on a maximum cladding temperature of 565 °C. The parameters listed with the critical decay times are generally representative of operating practices. Current fuel burnups in some plants, however, have increased to values higher than those used by BNL and perfect ventilation was assumed, which could lead to an underestimation of the critical decay times.

The SHARP code was not significantly benchmarked, validated or verified. The critical decay times above are shorter than those calculated in NUREG/CR-0649 and NUREG/CR-4982, particularly when the lower cladding temperature used for fuel failure and the higher decay heats used in the earlier analyses are taken into account. This appears to be driven in part by the fact that the decay heat at a given burnup in the SHARP calculations is significantly lower than what is used in the SFUEL calculations. The staff has identified several areas that require code modifications, which will increase the calculated critical decay times. The staff has determined that the code will be used as a scoping tool by the staff. It is not adequate for use as

technical bases by licensees without further code modifications and verification. NUREG/CR-6541 was intended as an assessment to steer rulemaking activities. The report was neither intended nor was it structured to provide a basis for exemptions. The staff does not rely on this study for heatup analysis information due to the code that the decay time conclusions were based on.

1.3 Heatup Calculation Uncertainties and Sensitivities

The phenomenology needed to model spent fuel heatup is dependent on the chosen cladding temperature success criteria and the assumed accident scenario. Many assumptions and modeling deficiencies exist in the current calculations. The staff reviewed the models to assess the impact of those modeling assumptions. Some of these uncertainties for the SFUEL series codes are further discussed in NUREG/CR-4982. For cases of flow mixing, decay heat, bundle flow resistance and other severe accident phenomena, additional information is provided here.

Calculations performed to date assume that the building, fuel, and rack geometry remain intact. This would not be a valid assumption if a seismic event or a cask drop damaged some of the fuel racks or the building. Rack integrity may not be a good assumption after the onset of significant zirconium oxidation due to fuel failure criteria issues discussed in Section 2.2.1. The building may also be hot enough to ignite other materials. Assuming that the racks remain intact is the most optimistic assumption that can be made about the rack geometry. Any damage to the racks or the building could significantly reduce the coolability of the fuel.

Previous SFUEL, SFUEL1W, and SHARP calculations used in the resolution of GSI 82 and decommissioning studies used a perfect ventilation assumption. With the perfect ventilation assumption an unlimited amount of fresh, ambient-temperature air is available. This assumption would be valid if the building failed early in the event or if large portions of the walls and ceilings were open. If the building does not fail, the spent fuel building ventilation flow rate would dictate the air flow available. Mixing between the rising hot air and the descending cooler air in the spent fuel pool is not modeled in the codes.

The spent fuel building ventilation flow rate is important in determining the overall building energy balance. Air flow through the building is an important heat removal mechanism. Most of the air would recirculate in the building and the air drawn under the racks would be higher than ambient temperature and, therefore, less heat removal would occur. Airflow also provides a source of oxygen for zirconium oxidation. Sensitivity studies have shown that heatup rates increase with decreasing ventilation flow, but that very low ventilation rates limit the rate of oxidation. Other oxidation reactions (fires) that occur in the building will also deplete available oxygen in the building. Zirconium-Nitrogen reaction modeling is not included in the SFUEL code and may have had an impact on zero and low ventilation cases. GSI 82 studies concluded that the perfect ventilation assumption was more conservative than no ventilation because the oxidation reaction became oxygen starved with no ventilation. These studies did not consider the failure modes of the building under high temperature scenarios. Intermediate ventilation rate results were not studied and give longer critical decay times than the perfect ventilation case.

A key fuel heat removal mechanism is buoyancy-driven natural circulation. The calculated air flow and peak temperatures are very sensitive to flow resistances in the storage racks, fuel bundles and downcomer. The downcomer flow resistance is determined by the spacing

between the fuel racks and the wall of the SFP. The storage rack resistance is determined by the orifice size at the bottom entrance to the fuel bundle. Smaller inlet orifices have higher flow resistance. As shown by SFUEL and SHARP calculations, changes in the rack-wall spacing and the orifice size over the range of designs can shift critical decay times by more than a year. The fuel bundle flow resistance is determined by the rod spacing, the grid spacers, intermediate flow mixers and the upper and lower tie plates. SFUEL and SHARP calculations have neglected the losses from the grid spacers, intermediate flow mixers and the tie plates. These flow resistances will be higher than those from the rack inlet orifice in some cases. Therefore inclusion of this additional flow resistance may significantly extend the critical decay time for some cases. NUREG/CR-4982 concluded that the largest source of uncertainty was due to the natural circulation flow rates.

The downcomer and bundle inlet air temperatures and mass flow rates are important in determining the peak cladding temperature. The extent of flow mixing will determine the air temperatures at the downcomer and bundle inlet. The SFUEL and SHARP calculations assume a well mixed building air space. The downcomer inlet temperature is set equal to the building temperature. This assumption neglects the mixing that occurs between the hot air rising from the bundles and the cooler air descending down the SFP wall. Computational fluid dynamics calculations performed by the NRC Office of Research (RES) using the FLUENT code and Pacific Northwest National Laboratory using the TEMPEST code indicate that the well mixed building is not a good assumption. The mixing that occurs between the cool air flowing down into the pool and the hot air flowing up out of the fuel bundles can significantly increase peak cladding temperatures. Even using different turbulent mixing models can affect the peak temperatures by approximately 100 °C. The calculations indicate that fully 3-dimensional calculations may be needed to accurately predict the mixing because unrealistic flow topologies in 2-dimensional approximations may overstate the mixing. The calculations also indicate that the quasi-steady state assumptions for conditions above the fuel rack may not be appropriate. Time varying temperature fluctuations on the order of 100 °C have been observed in 3D calculations.

Radiation heat transfer is important in zirconium oxidation calculations. Radiation heat transfer can affect both the onset of a zirconium fire and the propagation of a fire. Both the SFP loading pattern and the geometry of the fuel racks can affect the radiation heat transfer between adjacent bundles. Simple gray body calculations show that at clad temperatures of 800 °C, a temperature difference of 100 °C between adjacent bundles would cause the radiation heat flux to exceed the critical decay power of 6 kW/MTU. Therefore, the temperature difference that could be maintained between adjacent bundles is highly constrained by the low decay heat levels. SFUEL calculations performed by SNL and BNL included radiation heat transfer, but the radiation heat transfer was underpredicted since the spent fuel placement is two-dimensional and the hottest elements are in the middle of the pool with cooler elements placed progressively toward the pool walls. Heat transfer between hotter and cooler assemblies has the potential to be significantly higher if the fuel bundles were intermixed in a realistic loading pattern.

At temperatures below 800 °C the SFP heat source is dominated by the spent fuel decay heat. SNL and BNL found that, for high density PWR racks, that 6 kW/MTU was the critical decay heat level for a zirconium fire to occur in configurations resembling current fuel storage practices. At the fuel burnups used in the calculations, this critical decay heat level was reached after two years. Decay heat calculations in NUREG/CR-5625 [Ref. 8] were performed to be the basis for calculating fuel assembly decay heat inputs for dry cask storage analyses.

These decay heat calculations are consistent with the decay heat used in SFUEL calculations. Extrapolation of the decay heat calculations from NUREG/CR-5625 to current burnups indicate that approximately 3 years will be needed to reach a decay heat of 6 kW/MTU. The extrapolation has been confirmed to provide a reasonable decay heat approximation by performing ORIGEN calculations that extend to higher burnup. The critical decay heat may actually be as low as 3kW/MTU when in-bundle peaking effects, higher density rack configurations and rated build ventilation flows are taken into account.

Several licensees have proposed using the current Standard Review Plan (NUREG-0800) Branch Technical Position ASB 9-2 decay heat model for SFP heatup calculations. Using ASB 9-2 decay heat with a "k factor" of 0.1 produces non-conservative decay heat values in the range of 1 to 4 years after shutdown. ASB 9-2 explicitly states that it is good for times less than 10,000,000 seconds (~ 116 days). The basis of ASB 9-2 is the 1971 ANS draft decay heat standard. The standard gives "k factors" to use beyond 10,000,000 seconds. The staff has found that a "k factor of 0.2" will produce conservative decay heat values compared to ORIGEN calculations for the range of 1 to 4 years after shutdown.

At temperatures below the onset of self-sustaining oxidation, the heat source is dominated by the decay heat of the fuel. When zirconium reaches temperatures where air oxidation is significant, the heat source is dominated by oxidation. The energy of the reaction is 262 kcal per mole of zirconium. In air, the oxidation rate and the energy of the reaction is higher than zirconium-steam oxidation. Much less data exists for zirconium-air oxidation than for zirconium-steam oxidation. A large amount of data exists for zirconium-steam oxidation because of the large amount of research performed under the ECCS research program [Ref. 9]. If all of the zirconium in a full 17x17 PWR fuel bundle fully oxidizes in air over the period of an hour, the average power from the oxidation is 0.3 MW. The critical decay heat as determined with SFUEL is approximately 2.7 kW for the bundle. The oxidation power source would amount to approximately 60 MW if the whole core was burning. A 20,000 cubic feet per minute (CFM) air flow rate is needed to support that reaction rate based on 100-percent oxygen utilization. The SFUEL oxidation rate was modeled using several parabolic rate equations based on available data. SFUEL had limited verification against SNL experiments that studied the potential of zirconium fire propagation. BNL determined that although they could not find a basis for rejecting the oxidation rate model used in SFUEL, uncertainties in oxidation of zirconium in air could change the critical decay heat by up to 25-percent. It was found that the onset of runaway zirconium oxidation could occur at temperatures as low as 800 °C. Different alloys of zirconium had oxidation rates that vary by as much as a factor of four. Apparently it was found that oxidation in air was worse than oxidation in pure oxygen. This suggests that the nitrogen concentration can have a significant impact on the oxidation rate. Since the relative concentration of oxygen and nitrogen varies as oxygen is consumed this causes additional uncertainty in the oxidation rate. The oxidation was cut off at 2100 °C in the BNL calculations in support of GSI 82. This was done to simulate zirconium clad relocation when the melting point of zirconium was reached. If the oxidation was not cut off temperatures could be as high as 3500 °C. It was felt the propagation to adjacent bundles was overpredicted if no cutoff temperature is used due to the fourth power dependence of temperature on the radiation heat fluxes.

The combustion literature discussed in Section 2.1 also shows that there is a large range in the temperature for zirconium ignition in air. Evidence cited from the literature states that bulk zirconium can not ignite at temperatures lower than 1300-1600 °C. It is known from the

extensive emergency core cooling system (ECCS) and severe accident research programs that zirconium-steam runaway oxidation occurs at temperatures below 1300 °C. Since oxidation in air occurs more rapidly than oxidation in steam, temperatures in this range are not credible for the onset of runaway oxidation in air. Correlations listed [Ref. 10] give ignition temperatures for small zirconium samples in the range of runaway oxidation computed by the SFUEL series codes when the geometry factors calculated from zirconium cladding are input into the correlations. Only one reference [Ref. 11] appears to be applicable to zirconium oxidation in sustained heating of fuel rods. In the referenced test, sections of zirconium tubing were oxidized at temperatures of 700 °C, 800 °C and 900 °C for 1 hour. The average oxidation rate tripled for each 100 °C increase in temperature. This is consistent with the change in oxidation rates predicted by the parabolic rate equations examined in NUREG/CR-4982. The zirconium combustion literature reviewed for ignition temperature did not discount or provide alternate oxidation rates that should be used in the SFUEL calculations.

As discussed earlier, current operating plants burn fuel to higher levels than used in the evaluations. The BNL and SNL studies in support of GSI 82 represented operating practices of the 1980's with burnup level around 33 GWD/MTU. In NUREG/CR-6451, BNL used burnup values of 40 and 60 GWD/MTU for BWRs and PWRs, respectively. While these values are closer to current operating practices, they still underestimate peak burnup values. Additionally, the decay heat at the same burnup level used in the SHARP analyses is significantly lower than that used in the SFUEL analyses. Given that burnup is an important parameter for determining the critical decay time, this is a significant change. The increase in burnup level will increase the critical decay time needed to ensure that air cooling is sufficient to maintain the zirconium cladding below the oxidation temperature.

The BNL and SNL studies in support of GSI 82 represented storage practices of the 1980's when plants were starting to convert to high density storage racks. The studies did not address high density BWR racks, and the high density PWR racks in the reports were not as dense as the designs used by many plants today. The higher density racking currently used will decrease the air flow available for heat removal. Therefore, lower decay heat values are needed to ensure that air cooling is sufficient to maintain the zirconium clad below the oxidation temperature.

1.4 Estimated Heatup Time of Uncovered Spent Fuel

The staff recognized that the decay time necessary to ensure that air cooling was adequate to remain below the temperature of self-sustaining zirconium oxidation was a conservative criteria for the reduction in emergency preparedness criteria. Using the fact that the decay heat of the fuel is reducing with time, credit could be given, if quantified, for the increasing length of time for the accident to progress after all water is lost from the SFP. The staff sought to quantify the decay time since final shutdown such that the heatup time of the fuel after uncovering was adequate for effective protective measures using local emergency response.

The heatup time of the fuel depends on the amount of decay heat in the fuel and the amount of heat removal available for the fuel. The amount of decay heat is dependent on the burnup. The amount of heat removal is dependent on several variables as discussed above that are difficult to represent generically without making a number of assumptions that may be difficult to confirm on an plant and event specific basis.

For the calculations, the staff used a decay heat per assembly and divided it equally among the pins. It assumed a 9X9 assembly for the PWRs and a 17x17 assembly for the BWRs. All design values are in Appendix 11. Decay heats were computed using an extrapolation of the decay power tables in NUREG/CR-5625 [Ref. 8]. The decay heat in NUREG/CR-5625 is based on ORIGEN calculations. The tables for the decay heat extend to burnups of 50 GWD/MTU for PWRs and 45 GWD/MTU for BWRs. The staff recognizes that the decay heat is only valid for values up to the maximum values in the tables, but staff ORIGEN calculations of the decay power with respect to burnup for values in the table indicate that extrapolation provides a reasonable and slightly conservative estimate of the decay heat for burnup values beyond the limits of the tables. The BWR decay heat was calculated using a specific power of 26.2 MW/MTU. The PWR decay heat was calculated using a specific power of 37.5 MW/MTU. Both the PWR and BWR decay heats were calculated for a burnup of 60 GWD/MTU and include an uncertainty factor of 6 percent.

Calculations assuming an instant draindown of the pool and air cooling only show a heatup time to fission product release of 10 to 15 hours at 1 year after shutdown.

1.5 Critical Decay Times to Reach Sufficient Air Cooling

Based on the above discussion the staff concludes the following with respect to critical decay times. Calculations using the SFUEL code in support of GSI-82 have determined a critical specific decay heat of 6 kW/MTU is needed for the onset of runaway zirconium oxidation. The 6 kW/MTU estimate calculated using SFUEL in a high density storage rack configuration is reasonable and is based on the best calculations to date. However, this estimate is based on perfect ventilation conditions in the building and lower density rack configurations than exist today.

For high burnup PWR and BWR fuel, the staff estimates it will take approximately 3 years to reach the critical decay heat level cited in NUREG/CR-4982. Better modeling of flow mixing and accounting for the grid spacer and tie plate flow resistance could reduce the critical decay power level and increase the critical decay time beyond 3 years, but this may be counterbalance by increased radiation heat transfer from realistic fuel bundle loading. Other assumptions such as imperfect ventilation could extend the critical decay time for the onset of a zirconium fire by 1 to 2 years. The critical decay heat may actually be as low as 3kW/MTU when in bundle peaking effects and higher density rack configurations are taken into account. Accounting for imperfect ventilation and higher density spent fuel storage in the racks, the staff estimates it will take approximately 4 to 5 years to reach a decay heat of 3kW/MTU for current plant fuel burnups. Plant-specific calculations using fuel decay heat based on the actual plant operating history and spent fuel configurations could yield significantly shorter critical decay times. Calculations performed using checkerboard fuel loadings indicate that the critical decay time can be reduced by one year or more if the highest power fuel is interspersed with low powered fuel or empty rack spaces.

1.6 Fire Propagation

The staff has not performed a sufficient amount of research to understand and predict the propagation of zirconium fires in a spent fuel pool. Based on the limited amount of work

performed to date the propagation is probably limited to less than 2 full cores at a time of 1 year after shutdown.

References:

- 1 Benjamin, A.S., McCloskey, D.J., Powers, D.A., and Dupree, S.A, "Spent Fuel Heatup Following Loss of Water During Storage," NUREG/CR-0649 (SAND77-1371), March 1979.
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