From: "Danner, Tom" <tdanner@nacintl.com>
To: James Randall Hall <JRH@nrc.gov>
Date: 11/28/2006 2:02:50 PM
Subject: NAC Response to Comments from 11-16 phone call

Randy

The attached file is our response to the different comments that we had recorded during our phone call on November 16th. In the text response to the criticality comments there is reference to computer files requested by Carl Withee as an Attachment to this information supplement. I am transmitting these files by separate e-mail. It is my intent that this supplemental information provide closure for the identified comments, however, if you find that my wording of the comment or response is not complete I offer my commitment to a dedicated focus to expedite resolution. Thank you for your support in moving this licensing activity to successful completion.

Thanks again

Tom Danner

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Subject:	NAC Response to Comments from 11-16 phone call
Creation Date	11/28/2006 2:02:01 PM
From:	"Danner, Tom" <tdanner@nacintl.com>
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Junk Mail Handling Evaluation Results
Message is eligible for Junk Mail handling
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Junk Mail settings when this message was delivered
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NAC Response to NRC / NAC Phone Call 11-16-06 addressing MAGNASTOR review staff technical comments.

Criticality

Comment 1 of 4

Response to RAI-2 modified the SAR text to add a configuration containing the additional weld posts and removal of absorber sheets. Reviewer stated that NAC did not provide an updated input file containing this geometry.

Response:

NAC provides these input files as Attachment files to this information supplement.

Comment 2 of 4

Response to RAI-2 added a minimum orthogonal (x,y) tube pitch to the technical specifications. Reviewer comment stated that there was need for an input file matching this description and that there was a question of structural impact of the basket with the fuel assembly.

Response:

An input file for the minimum pitch (maximum reactivity) configuration is provided as an Attachment file to this information supplement.

The minimum pitch defined in the technical specification 4.1.1 (d) "Minimum fuel tube orthogonal (x,y) pitch" applies to the minimum tube spacing permitted by the basket drawings. Structural analysis for the basket applied the design dimensions and assures that the basket structure is maintained through all normal and accident loading conditions.

Comment 3 of 4

Structural evaluations were performed to system failure. System failure, in particular basket tube structure failure, can place load on the fuel assembly and modify the criticality analysis fuel geometry basis. This condition is not discussed in the license application.

Response:

No normal or accident condition event will result in basket structure instability and/or failure. Therefore, no external load is placed onto the fuel assembly. Basket structural stability evaluations are performed to define system failure modes and establish safety

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margins relative to geometric stability of the basket mechanical assembly. These structural analyses represent beyond-design-basis loadings and are not representative of normal or hypothetical accident condition system configurations requiring criticality evaluations.

<u>Comment 4 of 4</u>

Revisions of the bias calculation modified some data plots beyond those expected by the review staff. This includes a positive-to-negative reactivity slope shift on one of the plots. Please explain the data plot.

Response:

As demonstrated in the bias section, there is no significant trend of reactivity versus any of the system parameters. The linear correlation coefficient is less than 0.2 for the highest correlated parameter, indicating no trending of the data. Therefore, any modification of the data set has the potential to modify (or reverse) the slope of the linear regression analysis without effecting the results and conclusion of the data statistical evaluation.

When updating the bias calculation in response to RAI-2 it was noticed that not all relevant data was accounted for in each of the correlations plotted (data was accounted for in the USLSTATS evaluations). Original experiment review had restricted the data set applied in a given correlation to remove data sets that were designated as not necessarily applicable to the data set being correlated. This focus to address a refined applicable set of data resulted in an incomplete final set being documented in the original bias calculation. The complete experiment data set applicable to each of the correlated values was applied in the RAI-2 response update to the bias calculation. While the revised bias calculation modified the appearance of the data plots and the correlation coefficients, the conclusion of the analysis including the USL applied did not change. The data presented in the SAR represents the bias calculation of record.

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Structural

Comment 1 of 1

The analyses presented as the basis for defined structural stability safety margins, SAR Section 3.10.6, BWR Case B8 reports pin disengagement when the canister shell to cask liner gap is permitted to reach the range of 0.75 inches. Review of the system licensing drawings shows that the gap between the canister wall and the cask inner liner standoff is 0.75 inch. This physical condition appears to permit the cask tip over event to reach the threshold identified as the point of loosing basket geometric stability. Explanation of this conclusion being observed from the SAR and supplemental calculation is needed._

Response:

The basket displacement boundary is controlled by the canister shell and not the cask inner liner. The distance between the canister outside wall and the concrete cask liner of 0.75 inches is not a limiting dimension for the basket stability analysis. The analytical model and conservative boundary conditions adopted for the basket stability analysis and presented in SAR Section 3.10.6 are summarized below.

Maximum canister shell displacements defined from the canister tip-over analysis presented in SAR Section 3.7.1.3 are used as the conservative design basis boundary condition for the periodic basket stability model. The canister shell displacements were calculated using a tapered acceleration of 40 g's. This 40 g applied loading bounds the maximum acceleration at the top of the TSC and top of the fuel basket that were calculated from the LS-DYNA evaluation for the concrete cask tip-over on the pad. The maximum displacement of the canister shell under this loading is 0.35 inches at approximately 60 degrees counter clockwise (CCW) from the vertical symmetry plane. This maximum canister shell planar displacement is used as the design basis boundary condition for the basket stability analysis. Incorporating this displacement into the basket stability model as a displacement boundary condition is accomplished by moving the nodes defining the inside wall of the cask inner liner to the planar displacement profile thereby limiting the canister shell displacement in the periodic LS-DYNA model.

The base case, Case B2 for the BWR 45° orientation shows a maximum gap between the canister shell and the cask inner liner part of the model of 0.35 inches, which occurs approximately 60 degrees counter clockwise (CCW) from the vertical symmetry plane, (reference computer input – canister shell node 55622 to cask inner liner node 56162). By defining this profile that establishes a gap of 0.35 inches between the canister shell and the inner liner in the LS-DYNA model, the model limits the displacement of the canister shell to the same displacement as computed in the separate canister evaluation. To ensure that the major spikes of the acceleration time history are applied to the basket, the basket is vertically displaced towards the cask inner liner (the nodes on the cask inner liner are not altered in this operation) prior to the start of the analysis. The gap between canister shell and the cask inner liner is minimized to 0.003 inches at the point of impact on the symmetry plane, (reference canister shell node 55604 to inner liner node 56139).

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The difference in this gap between the different analyses was a result of the actual model shifting the canister shell and basket to capture the impact load and has no influence on the analysis results.

This maximum geometric boundary is conservatively defined for the duration of the impact and ignores the condition that the initial and final canister shell displacements are essentially zero. Additionally, the displacements used in the LS-DYNA model are the largest canister shell displacements at any single plane along the length of the canister shell, which occur only at about the 72 inch elevation. At this elevation, the actual basket accelerations are much less than the maximum accelerations occurring at the top of the basket. The maximum unfiltered accelerations of the basket were conservatively applied as the boundary condition for the LS-DYNA stability model.

Following the design basis analysis defined as Case B2 in Table 3.10.6-1, the nodes of the cask inner liner corresponding to the base condition, which were originally moved to represent the deformed shape of the canister shell, were further radially displaced non-mechanistically by 0.25 inches in Case B7. Case B7 was targeted to define the factor of safety for this mode of potential loss of basket stability.

The objective of Case B8 was to demonstrate a well behaved analytical solution through incremental increases in the boundary condition gap to the point where the defined criterion for loss in basket stability was observed. For Case B8, the nodes on the cask inner liner were all moved radially outwards non-mechanistically by 0.75 inches (from the design basis canister radius of 36 inches) to have a constant radius of 36.75 inches. In both cases, once the cask liner nodes were radially moved outwards, the basket and canister model were then translated towards the impact plane until the vertical gap between the canister shell and the inner surface of the cask liner was 0.001 inches. This small gap ensures that once the transient is started, the large acceleration spikes which occur early in the transient are experienced by the basket, another non-mechanistic and conservative boundary condition.

Calculation 71160-2010 Revision 1, Section 6.2, defines the canister shell and basket boundary conditions as presented in the SAR, and summarized above. The structural stability criterion for the basket is conservatively defined for the periodic model, ignoring the basket pinned ends when the pin displacement moves outside the adjacent tube slot. Review of the transient analysis results show that three corners of the adjacent tubes continue to be controlled by the pin-slot engagement when one of the pin-slot boundaries moves beyond the defined criteria. Consideration of the periodic model methodology, in addition to conservatively ignoring the stiffness of the full 3-dimensional structure with the top and bottom tube pinned interface, demonstrates the full robustness of the basket design, even with non-mechanistic and very conservative assumptions.

In summary:

- The physical clearance between the canister and concrete cask is not the physical control boundary for basket stability.

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- The design basis loading and physical boundary assumptions adopt a conservative combination of acceleration at the top of the basket with maximum canister shell displacement developed approximately 6 feet from the base.

- Determination of the margin of safety relative to the canister shell boundary displacement incorporated a very conservative and non-mechanistic additional canister shell displacement of 0.25 inches, while applying the maximum system acceleration occurring only at the top of the basket over the entire length of the canister.

With these very conservative and non-mechanistic assumptions, significant safety margin has been demonstrated and is a fundamental property of the mechanical basket assembly contained in the canister shell.

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Thermal

Comment 1 of 10

Identify when the vacuum drying system was made part of the SAR application.

Response:

Both vacuum drying and pressurized helium drying systems have been part of the operational design and application from the original submittal in August 2004. The thermal analysis discussion presented in Section 4.4.3 subheading "Transfer Condition" identifies the vacuum drying cycle as a limiting condition for the canister processing cycle from pool loading to placement into the concrete cask; Section 9.1.1 "Loading and Closing the TSC" step 57 describes vacuum drying to a vapor pressure of ≤10 torr for 10 minutes followed by further decrease in vacuum to ≤3 torr prior to backfilling the canister with 99.995% (minimum) pure helium; Technical Specifications Surveillance, Section SR3.1.1.1 addresses criteria defining dry for vacuum and recirculating helium systems.

Comment 2 of 10

Define the thermal modeling for the canister in the transfer cask.

Response:

SAR Section 4.4.1.5 presents the thermal analysis for the transfer operations. Discussion is presented for each phase of the transfer operation from the time that the cask is removed from the spent fuel pool to the time that the TSC is placed into the concrete cask. The system modeling for each phase of the transfer operation is described in the following subsections of SAR Section 4.4.1.5:

- Evaluation of the Water Phase
- Evaluation of the Drying Phase- Pressurized Helium Drying System
- Evaluation of the Drying Phase-Vacuum Drying System
- Evaluation of the Helium Phase
- Evaluation of Moving the TSC into the Concrete Cask.

Comment 3 of 10

Validate that the system operation meets ISG-11, Revision 3 maximum temperature cycle limit of 117°F. Table 4.4.-4 implies the limit is not met.

Response:

Table 4.4-4 is titled "Maximum Fuel Temperatures for the Transfer Operations for

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Design Basis Heat Load". This presentation of results in this table was not intended to demonstrate full compliance with ISG-11, Revision 3 guidance relative to cycling conditions during the drying operation. Maintaining the maximum thermal cycling range of 117°F is addressed in SAR Section 4.4.1.5 "Evaluation of the Drying Phase -Vacuum Drying System." The thermal analysis presented in SAR Sections 4.4.1.5, and the defined vacuum drying operation and procedures ensure that full compliance with ISG-11, Revision 3 guidance is achieved.

<u>Comment 4 of 10</u>

The SRP identifies 3 torr for 30 minutes as a procedure for drying the canister and removing oxidizing gas to less than 1 mole based on PNL 6365. The 10 torr for 10 minutes does not appear to meet SRP and PNL references - justify the basis for 10 torr for 10 minutes as an acceptable drying criterion.

Response:

The MAGNASTOR system drying and inert backfill procedures are designed to ensure that the conditions limiting water vapor and oxidizing gas, as recommended by the PNL report and as intended by the SRP are achieved. The MAGNASTOR drying and backfill procedures and criteria are essentially identical to procedures approved for both the NAC-MPC and NAC-UMS systems. In addition, there is no physical difference between the MAGNASTOR operating procedures and the SRP definition to achieve a dry inert cavity. There is a difference in the sequence of how the intended final condition of a dry inert canister cavity is achieved. The MAGNASTOR procedures define verification of the removal of free water from the cavity to be performed as a separate sequence, which is then followed by a further reduction in the cavity internal pressure to less than 3 torr and backfilling with 99.995% pure helium to a pressure of > 4 atm. Implementing the defined operational sequence is an effective and efficient operational path to achieve to intended final condition.

During the normal system closure operational sequence, the closure lid is welded and inspected, followed by a hydrostatic test. The cavity water is then removed from the cavity using pumping assisted with a nitrogen or helium cover gas, or by nitrogen or helium blow down. After the gross removal of the cavity water, the vacuum drying system is connected to the vent and drain ports and the cavity is evacuated.

During vacuum drying, the residual moisture and free water in the cavity are vaporized as the internal pressure is reduced and removed from the cask through the vent and drain port by the vacuum pump. The internal decay heat of the fuel contents assists in the vaporization process as the cask internals and fuel temperatures increase. The vacuum pumping operation is continued until the cavity pressure is reduced to below 10 torr, which corresponds to one-half the vapor pressure of water at 72°F. It is fully expected that under all loading conditions the actual temperatures of the cask internals will exceed this temperature. The cavity is then isolated from the vacuum pump and the pump is

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turned off. If free water exists in the cavity, the water will vaporize and increase the cavity pressure to above the 10 torr acceptance criterion during the dryness verification minimum hold period of 10 minutes. This dryness criterion has been successfully utilized on numerous transportation casks and on the NAC-MPC and NAC-UMS storage systems.

Upon successful completion of the dryness verification, the vacuum pump is restarted and the cavity is continued to be evacuated until a pressure of less than 3 torr is reached. The final cavity pressure prior to backfill with helium corresponds to the minimum cavity pressure recommended in NUREG-1536. The continued reduction of the cavity pressure from 10 torr to less than 3 torr removes any residual non-condensing and oxidizing gases to a level of less than 1 mole, including any residual traces of water vapor. Upon reaching a minimum cavity internal pressure of less than 3 torr, the cavity is backfilled with high purity helium to a positive pressure.

Throughout the MAGNASTOR design process, the operational procedures and equipment have been designed to prevent the introduction of oxygen or other oxidizing gases into the cavity at any point in the sequence.

Therefore, the major difference between the recommendation of NUREG-1536 and the proposed procedures and Technical Specifications for MAGNASTOR is the performance of the dryness verification at a higher pressure. However, as has been shown, the final evacuation of the cavity to less than 3 torr after the dryness verification, followed by the immediate backfilling of the cavity with high-purity helium to a positive pressure, provides reasonable assurance that the final cavity atmosphere contains less than 1 mole of oxidizing gases and the residual oxidizing gas concentration is less than 0.25 vol%, as recommended in the PNL 6365 report.

Comment 5 of 10

Justify the statement that the thermal analysis for the VCC blocked case is a bounding thermal configuration for the canister in the transfer cask following the lid closure and helium backfill operation.

Response:

The transient evaluation performed for the canister in the concrete cask with the all-vents-blocked condition is the bounding thermal response for the canister in the transfer cask due to the following system thermal properties:

1) In the all-vents-blocked condition, the heat transfer from the top and bottom of the concrete cask is virtually adiabatic. In the transfer condition, the heated top of the canister, which is six feet in diameter, is facing upwards and is permitted to reject heat to the ambient. Due to the size of the surface and the surface facing upward, the heat transfer is expected to be in the turbulent range. If the transfer cask rests on the concrete floor, heat can be rejected through the doors to the cooler floor. If

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the transfer cask is lifted, heat can still be rejected from the heated door surface facing downward, even though it may be in the laminar flow regime. These differences in thermal performance between the concrete cask all-vents-blocked condition and transfer cask support the conclusion that adopting the heat up rate from the all-concrete cask vents-blocked condition as a limiting condition for time in the transfer cask is conservative.

2) The condition for radiation between the canister surface and the transfer cask or the canister surface and the concrete cask are similar since both surfaces of the casks are carbon steel. Both casks (transfer cask and concrete cask) can reject heat in the radial direction through the wall. However, the insulating layer in the transfer cask (the NS4FR conductivity is .031 BTU/hr-in-°F)) is 2.25 inches thick while the concrete (concrete conductivity is 0.089 BTU/hr-in-°F) layer is 26 inches thick. The ratio of the conductance of the transfer cask is more than a factor of three greater than the conductance of the concrete cask in the radial direction. This difference in thermal heat rejection demonstrates that the transfer cask would reject significantly more heat through the radial surface than the concrete cask and that the use of the heat up rate for the concrete cask all-vents-blocked condition for the canister response in the transfer cask is conservative.
3) In addition to the demonstrated conservative difference in thermal performance of the two different shells, the analysis of the all-vents-blocked condition uses the conservative heat load of 40 kW to calculate the heat up rate used to define acceptable transient time as compared to the design basis heat load of 35.5 kW.

Therefore, it can be concluded that adopting the transient evaluation performed for the canister in the concrete cask all-vents-blocked condition is the bounding thermal response for the canister in the transfer cask.

<u>Comment 6 of 10</u>

Provide justification for the drying criteria specified for the Pressurized Helium Drying System.

Response:

Drying criteria for the pressurized helium drying is defined in Technical Specification Surveillance criteria SR 3.1.1.1. The criterion for defining dryness is to circulate helium through the TSC cavity until the differential dew point temperature between the gas entering the TSC is within 1°F of the dew point of the gas exiting the TSC at ≤45°F.

The technical basis for this drying criterion is a direct application of the ideal gas law. A mixture of helium and water vapor behaves according to the ideal gas law where each constituent also behaves according to the ideal gas law based on its partial pressure. As the temperature of the mixture drops, so does the pressure for a fixed volume. The dew point occurs when the vapor partial pressure drops to the saturation pressure of water. Given a dew point of 45 °F, the saturation pressure of water is 0.1475 psi and the number

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of moles in a given volume is defined by:

n_vapor = P_vapor*V/R/T

A differential of one degree would correspond to an increase in the moles of vapor in a given volume according to:

45°F = 504.67°R   46°F = 505.67°R
Δ_{moles} = P_vapor(@ 46F)*V/R/505.67 - P_vapor(@ 45F)*V/R/504.67

Therefore, each cubic foot of helium that experiences a one degree increase in its dew point contains 0.0005 gmol of water vapor added as a result of drying. This establishes a rate of evaporation once the terminating condition has been achieved--8.74 mg of water/cubic foot of helium. Applying a conservative pressurized helium drying system flow rate of 5 ft^3/min yields a flow rate of 0.7 mg/s of water vapor at the 1°F differential criterion.

Applying a system operating temperature of 200°F and a maximum water quantity of 1 gmole (as indicated by the SRP for oxidizing material), water would vaporize at a rate of 548 g/s (with larger volumes vaporizing at proportionally higher rates). With the evaporation rate of 584 g/s the exiting flow should also contain 584 g/s unless the system is already at its dew point.

This demonstrates that at the 1°F differential criterion the remaining water in the system is much smaller than the 1 gmol.

<u>Comment 7 of 10</u>

Lack of operating experience with the Pressurized Helium Drying System leads to the need for a detailed functional description – provide details on component and integrated system performance.

Response:

The Pressurized Helium Drying (PHD) System is categorized as a Category NQ system in accordance with NAC's Quality Assurance Program. However, as the dryness performance requirements for the PHD system are defined in the MAGNASTOR system, the required measuring and test equipment (M&TE) will be specified, calibrated and controlled in accordance with NAC's M&TE procedures. The specified M&TE include the flow meter, the hygrometer, and the temperature controller, which will ensure that the dryness acceptance criterion of LCO 3.1.1 is satisfactorily met.

In addition, in accordance with NAC's standard practices, NAC will prepare and utilize a PHD System Performance Specification for the procurement, assembly and mock-up performance testing of the system to ensure that the system satisfactorily performs its design functions. NAC has utilized similar performance specifications for the procurement and testing of other NQ systems utilized for dry cask storage system processing, including Vacuum Drying Systems, Remote/Automated Welding Systems, Canister Weld Removal Systems, Heavy-Haul Trailers, etc.

The mock-up performance testing will be performed under the oversight of planned MAGNASTOR users to assure that the system will perform at their facilities as intended and specified.

<u>Comment 8 of 10</u>

Other applicants using a pressurized helium drying system have made it a requirement for loading high burnup fuel – what is the basis for implementing the use of this system with MAGNASTOR? Consideration of this application relative to the reviewer experience leads to the question -Does vacuum drying meet thermal limits for high burnup fuel?

Response:

NAC has extensive experience in the utilization of Vacuum Drying Systems (VDS) and performance of vacuum drying operations on both storage and transport cask systems. Vacuum drying technology has proven to be an effective method to efficiently and safely remove residual free standing water from a cask cavity following cask draining and blow down operations. One concern with high heat load fuel assembly contents has been the allowable time available to complete the drying process while maintaining the fuel cladding temperature below ISG-11, Revision 3 limits, and the limited cycle time for second and subsequent vacuum drying cycles based on meeting the allowable cycling temperature of 117°F for high burnup fuel.

NAC has a high confidence that the current calculated initial vacuum drying cycle allowable time will be sufficient to effectively dry the MAGNASTOR system. This confidence is based on the following factors:

- The MAGNASTOR basket assembly minimizes horizontal surfaces that could retain water following canister draining;
- A larger drain sump is provided in the canister base plate; and
- Higher allowable content decay heat will increase basket temperatures faster, increasing the water vaporization process (at higher vacuum pressures).

For comparison, the average vacuum drying times for the UMS System, which has up to 59 horizontal heat transfer and support disks, and weldments, are approximately 25-30 hours utilizing identical vacuum dryness verification criteria as proposed for MAGNASTOR. It is important to note that these average times are for significantly lower heat loads (approximately 12 kW), and NAC-performed UMS TSC draining tests have shown that the horizontal disk basket design can result in upwards of 15+ gallons of water being retained following vertical draining operations. Therefore, the UMS drying times have been significantly impacted by the large quantity of residual free water and

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lower internal basket temperatures. The retained water in the MAGNASTOR canister cavity is expected to be significantly less (approximately 25% of the measured UMS volume) that will correlate directly to shorter vacuum drying times.

The PHD system was initiated and developed to provide an alternative to vacuum drying for prospective users to meet their specific canister drying needs. However, for a majority of intended users, the simplicity and low cost of the proven vacuum drying systems will be the selected method to effectively dry loaded MAGNASTOR canisters. As defined in SAR Chapter 9, the first cycle drying times range from 60 hours for contents less than 15 kW to 23 hours for the maximum content heat load. As discussed above, these vacuum drying times are expected to provide sufficient time with margin to dry the MAGNASTOR TSCs within the fuel cladding temperature and temperature cycling limits of ISG-11, Revision 3.

<u>Comment 9 of 10</u>

The reviewer commented that NAC should justify the statement in the thermal evaluation of the canister in the transfer cask that the storage condition can also be applied for the condition of the canister drying configuration using the pressurized helium drying system.

Response:

The geometric configuration of the fuel, the basket and the canister are the same for the sealed canister in both system configurations. Since the geometric configuration is the same the flow resistances are therefore expected to be the same for both configurations. A bounding condition for the canister in the transfer cask during system drying with the pressurized helium drying system is when the valve to the canister is shut off. The forced convection boundary in the canister would be stopped and no helium would enter or leave the canister, which is the storage condition, a sealed system. If any helium is permitted to enter into the canister from the drying system, and then exit the canister having absorbing heat from the fuel, heat is being rejected other than through the canister shell wall. Since the design of the pressurized helium drying system is to remove moisture, it will simultaneously remove heat. Such a configuration would reduce the temperature of the fuel. This operational system performance for heat removal validates that the temperatures corresponding to the condition of the helium flow through the fuel for the pressurized helium drying system will be bounded by the temperatures based on the methodology used for the natural convection condition in the stored canister.

<u>Comment 10 of 10</u>

Chapter 9 describes an operational step of removing 70 gallons of water from the canister. The thermal evaluation of the transfer condition with water in the canister assumes that the water will circulate. If 70 gallons of water is removed, confirm that the assumption of

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the water circulation used in the thermal evaluation is a valid boundary condition.

Response:

Removal of the 70 gallons of water from the canister creates a space at the top of the basket for water thermal expansion during the closure lid welding operation that is approximately 4 inches high. The PWR top plenum formed between the top of the fuel tubes and the bottom of the canister lid is approximately 3.5 inches. Consideration of this operational configuration was part of the PWR basket design and water flow holes were added to each fuel tube approximately 6 inches from the top of each tube to maintain a water circulation path such that the thermal response of the water mass would be uniform. In addition to the circulation flow path designed into the basket, as the water temperature increases the water will expand to increase the water height above the top of the fuel tubes permitting free circulation across the top surface of the basket. Both the fuel tube water circulation holes and thermal expansion into the top plenum provide validation for this thermal boundary.