4.0 THERMAL EVALUATION

I. Review Objective

The thermal review ensures that the cask and fuel material temperatures of the dry cask storage system (DCSS) will remain within the allowable values or criteria for normal, off-normal, and accident conditions. This objective includes confirmation that the temperatures of the fuel cladding (fission product barrier) will be maintained throughout the storage period to protect the cladding against degradation that could lead to gross rupture.This portion of the DCSS review also confirms that the thermal design of the cask has been evaluated using acceptable analytical and/or testing methods.

II. Areas of Review

This portion of the DCSS review evaluates the design and analysis of cask thermal performance for normal, off-normal, and accident conditions. Consequently, this chapter of the DCSS Standard Review Plan (SRP) provides guidance for use in reviewing thermal design criteria, design features, model specifications, and material properties. In addition, this chapter provides guidance for evaluating thermal analysis methods, including computer programs, temperature and pressure calculations, confirmatory testing, and independent evaluations done by staff.

As described in Section V, "Review Procedures," a comprehensive thermal evaluation *may* encompass the following areas of review:

1. spent fuel cladding
2. cask system thermal design
    a. design criteria
    b. design features
3. thermal load specification/ambient temperature
4. model specification
    a. configuration
    b. material properties
    c. boundary conditions
5. thermal analysis
    a. computer programs
    b. temperature calculations
    c. pressure analysis
    d. confirmatory analysis
6. supplemental information

III. Regulatory Requirements

10 CFR Part 72 requires an analysis and evaluation of DCSS thermal design and performance to demonstrate that the cask will permit safe storage of the spent fuel for a minimum of 20 years. The spent fuel cladding must be protected against degradation that may lead to gross ruptures. Thermal structures, systems, and components important to safety must be described in sufficient detail to permit evaluation of their effectiveness. Applicable thermal requirements are identified, in part, in 10 CFR 72.24(c)(3), 72.24(d), 72.122(h)(1), 72.122(l), 72.128(a)(4), 72.236(f), 72.236(g), and 72.236(h).

IV. Acceptance Criteria

In general, the DCSS thermal evaluation seeks to ensure that the given design fulfills the following acceptance criteria:

1. Fuel cladding (zircalloy) temperature at the beginning of dry cask storage should generally be below the anticipated damage-threshold temperatures for normal conditions and a minimum of 20 years of cask storage (Refs. 12 and 13).

2. Fuel cladding (zircalloy) temperature should generally be maintained below 570 °C (1058 °F) for short-term accident conditions, short-term off-normal conditions, and fuel transfer operations (e.g., vacuum drying of the cask or dry transfer). (PNL-4835[1])

3. The maximum internal pressure of the cask should remain within its design pressures for normal, off-normal, and accident conditions assuming rupture of 1 percent, 10 percent, and 100 percent of the fuel rods, respectively. Assumptions for pressure calculations include release of 100 percent of the fill gas and 30 percent of the significant radioactive gases in the fuel rods.

4. Cask and fuel materials should be maintained within their minimum and maximum temperature criteria for normal, off-normal, and accident conditions in order to enable components to perform their intended safety functions.

5. For each fuel type proposed for storage, the DCSS should ensure a very low probability (e.g., 0.5 percent per fuel rod) of cladding breach during long-term storage.

6. Fuel cladding damage resulting from creep cavitation should be limited to 15 percent of the original cladding cross-sectional area during dry storage. (UCID-21118)

7. The cask system should be passively cooled. [10 CFR 72.236(f)]

8. The thermal performance of the cask should be within the allowable design criteria specified in SAR Section 2 (e.g., materials, decay heat specifications) and SAR Section 3 (e.g., thermal stress analysis) for normal, off-normal, and accident conditions.

V. Review Procedures

One of the most important results of the DCSS thermal evaluation is confirmation that the fuel cladding temperature will remain sufficiently low to prevent unacceptable degradation during storage. The SAR should identify the allowable temperature levels for stored materials for long-term storage, as well as short-term storage and off-normal conditions.

Design features and criteria, initially presented in SAR Sections 1 and 2, should be reviewed for additional insight. Reviewers should examine heat loads from both contents and external sources, and should assess models used by the applicant for thermal analysis. Temperatures and pressures calculated in the SAR should be confirmed to evaluate compliance with design criteria and regulatory requirements.

Reviewers should also evaluate temperature distributions and criteria used to determine thermal stresses for all cask system components exposed to heat generated by the fuel. These components include the cask, transfer equipment, and any shielding components.

Temperatures and related distributions and pressures developed within the confinement cask should also be evaluated. (These values are further referenced and evaluated in Chapter 3, "Structural Evaluation," and Chapter 7, "Confinement Evaluation," of this SRP.) However, this thermal review does not encompass the evaluation of the computed stresses or loads on parts of the structure caused by either significant temperature gradients or the interaction of those materials at different temperatures each with possibly different coefficients of thermal expansion. These computations are reviewed as part of the structural evaluation discussed in Chapter 3 of this SRP.

Thermal performance of the cask under accident conditions, as evaluated in this portion of the DCSS review, is also addressed as appropriate in the overall accident analyses presented in Chapter 11.
In conducting a comprehensive thermal evaluation, reviewers should perform the established review procedures, as applicable, for each of the following areas of review:

1. Spent Fuel Cladding

The cask system must be designed to prevent degradation of fuel cladding that results in a type of cladding breach, such as axial-splits of ductile fracture, where irradiated UO_2 particles may be released. In addition, the fuel cladding should not degrade to the point where more than one percent of the fuel rods suffer pinhole or hairline crack type failure under normal storage conditions. The one percent failure assumption is for safety analysis purposes only, and relates to assumptions for thermal analysis, containment performance, and cask unloading operations. However, the cask design should ensure a very low probability of rod failure during normal storage. "Failed fuel" (failure occurring during dry storage) us defined as fuel with a breach of cladding from but not limited to, pinhole failure, hairline cracks, axial-splits, or ductile fracture.

The staff should verify that cladding temperatures for each fuel type proposed for storage will be below the expected damage thresholds for normal conditions of storage. Zircalloy fuel cladding temperature limits at the beginning of dry storage are typically below 380 °C for 5-year cooled fuel and 340 °C for 10-year cooled fuel for normal conditions and a minimum of 20 years of cask storage (PNL-4835, PNL-6189, PNL-6364[2], and LLNL UCID-21181). Currently, the staff accepts only the diffusion-controlled cavity growth (DCCG) method for establishing the temperature limits, with DCCG damage not to exceed 15 percent of the original cladding cross-sectional area during dry storage (UCID-21181).

However, it should be noted that fuel cladding temperature limits are a complex function of power history (including transients), cladding thickness, pre-pressurization of fuel rods during fabrication, burnup, fission gas, and hoop stress. Substantial variation in end-of-life internal rod pressures and fuel design characteristics may warrant temperature limits lower than those noted above for certain fuel types. Therefore, fuel cladding limits for each fuel type should be defined in the SAR with thermal restrictions in the DCSS technical specifications.

Evaluate the method used to determine the temperature limits and associated cladding hoop stresses. Hoop stress calculations should be established on the basis of fuel properties that are representative of the spent fuel to be stored (e.g., cladding dimensions, internal rod pressures). High-burnup of fuel (greater than 40,000 MWD/MTU) causes effects, such as wall thinning from increased oxidation and increased internal rod pressure from fission gas buildup, and changes in fuel dimensions that must be evaluated. The SAR should use conservative values for surface oxidation thickness. Oxidation may not be of a uniform thickness along the qxial length of the fuel rods and average values may under predict wall thinning. Temperature limits will be more restrictive with increased fuel cooling time (and/or increased burnup), largely as a result of creep cavitation.

For short term-accident conditions, the staff accepts zircalloy fuel cladding temperature generally maintained below 570 °C (1058 °F). The short-term accident temperature of 570 °C (1058 °F) for zircalloy-clad fuel is currently accepted as a suitable criterion for fuel transfer operations. However, this temperature limit may be lowered for fuel with hoop stresses exceeding the rods that were high-temperature tested (see Table 5 of PNL-4835). This is especially true for fuel with burnup greater than the tested rods (e.g., greater than ~28,000 MWD/MTU), as a result of increased internal rod pressure from fission gas buildup and release into the gap and/or different helium loadings. The applicant should verify that these cladding temperature limits are appropriate for all fuel types proposed for storage, and that the fuel cladding temperatures will remain below the limit for facility operations (e.g., fuel transfer) and the worst-case credible accident.

For cask unloading operations, cladding integrity should be maintained during reflooding, so as not to interfere with fuel handling and retrieval. The SAR should include a quench analysis supporting specified minimum quench fluid temperature and maximum fluid flow rate during re-flood. This analysis should also be referenced in Section 11 of the SAR as having been considered in the developing the model unloading procedures, and be included as appropriate in the Technical Specifications for the system use. The NRC accepts the fact that the total stress on the cladding must be maintained below the material’s minimum yield stress. The total stress includes the thermal stress combined with the cladding hoop stress from internal rod pressure and rod gas plenum temperature. The analysis should account for high burnup effects on the fuel (e.g., waterside corrosion, high internal rod pressure) and minimum manufacturing wall thickness.

Verify that the applicant includes technical specifications which ensure that the maximum allowed initial cladding temperatures will not be exceeded during normal operations. Technical Specifications should also identify the maximum time permitted for fuel to be submerged in a cask which has been removed from the pool (i.e. when the cask has not been evacuated and sealed). A series of curves for cladding temperature versus time for differing decay heat payloads is acceptable.

2. Cask System Thermal Design

a. Design Criteria

Review the principal design criteria, as well as the structure, system, and component specifications presented in the SAR Section 2 and any additional detail provided in Section 4.

b. Design Features

Review the description of the significant thermal design features and operating characteristics of pertinent DCSS subsystems. Design features typically include the cask body, thermal fins, shielding materials, fuel baskets, impact limiters if installed, containment seals, drain and vent ports, and pressure relief devices, among others. Verify that the thermal design features will adequately perform their intended safety functions during normal, off-normal, and accident conditions.

All thermal design features should be passive. Review the cask system component specifications for inclusion of material composition and thermal properties, operating pressures and criteria for any relief devices or rupture disks. Review the general description of the cask presented in SAR Section 1, as supplemented by the additional information provided in SAR Section 4. In addition to the material compositions, dimensions of the cask components, and spacing of fuel assemblies in the basket, the thermal design may include external air passages. Rupture disks may be used on cask components, such as shielding, to ensure that elevated temperatures do not cause thermal expansion or phase changes resulting in structural damage to the cask shell. All drawings, figures, and tables should be sufficiently detailed to support in-depth staff evaluation.

Any instrumentation used to monitor cask thermal performance should also be described in sufficient detail to support in-depth staff evaluation. The monitoring instrumentation components should have a safety classification commensurate with their function, and the safety classification (presented in SAR Section 2) should be justified. Applicable operating controls and criteria, such as temperature criteria and surveillance requirements, should be clearly indicated in SAR Section 12, discussed in the SER, and included in the license or certificate of compliance, as appropriate.

3. Thermal Load Specification/Ambient Temperature

Examine the specification for the design-basis fuel decay heat presented in SAR Section 2. Ensure that this decay heat is consistent with the specified burnup and cooling times, if included. Decay heat is generally calculated using the same computer codes as those used to determine radiation source terms. Coordinate the review of fuel source terms for consistency with the shielding review, as appropriate. Alternatively, the decay heat from the design-basis fuel may also be derived from Regulatory Guide (RG) 3.54.[3] Except for neutrino energy, all decay heat should be considered to be deposited in the fuel.

If control components or other assembly hardware (e.g., shrouds) are included with the fuel assemblies, their heat loads should be specified and justified.

In general, the NRC staff accepts insolance presented in 10 CFR Part 71[4] for 10 CFR Part 72 applications. Because of the large thermal inertia of a storage cask, the values listed in 10 CFR Part 71.71 may be treated as the average insolance, calculated by averaging over a 24-hour day the reported 10 CFR 71 values for insolance over a 12-hour solar day, in a steady-state calculation. If a less conservative approach is presented, the SAR shall thoroughly describe and justify its use.

Review the ambient temperatures used to calculate temperature distributions and maxima for normal and off-normal conditions, as well as "design-basis" natural phenomena. The SAR should clearly state the assumed temperatures and temperature variations over time. These assumptions establish criteria for comparison with recorded data and projections for potential installations of the cask system at specific sites.

When calculating maximum thermal gradients and temperature differences within individual components or between locations, temperature changes over time may need to be determined. These changes should consider the types of material, the thermal properties, including thermal conductivity; heat capacity; and density of specific components. Statements about assumed bounding temperature ranges, ambient temperature conditions, and variations of external heat sources over time should be defined so that they may be easily compared with available site or regional data.

For those cask system components for which material properties and performance vary with temperature, review the assumptions used in determining temperature maxima, minima, gradients, and differences for the cask system. Also review the assumptions used to determine fuel cladding temperatures. The assumed temperature changes over time should result in the bounding conditions for the structural analysis. The calculated temperatures in the various cask system components should be compared to the limiting temperature criteria for the appropriate materials. Ferritic materials are subject to failure by

brittle fracture at low temperatures. Review the assumed low temperatures for cask system handling operations for consistency with material properties. Ambient temperature restrictions may be appropriate for cask handling operations. Any limiting conditions regarding ambient temperatures should be addressed in SAR Section 12 as well as SER Section 12, and should be included as a limiting condition of operation (e.g. tech. spec.)in the license or certificate of compliance, as appropriate.

During wet fuel transfer operations, the liquid in the cask should not be permitted to boil. This practice avoids uncontrolled pressures on the cask and the connected dewatering, purging, and recharging system(s), unacceptable discharge of liquids which may be providing radiation shielding, and a potentially unacceptable reduction in the safety margin (K_{eff}) that prevents inadvertent criticality. The reviewer should ensure that to prevent any of the above conditions, an adequate subcooling margin is identified in both the SAR and corresponding operating procedures to prevent boiling. This margin may be cask-specific, depending on the design of the fuel basket and key assumptions used in the criticality analysis. Review the heatup and time-to-boil calculations and assess whether any technical specification or limiting conditions for operation are needed. Heatup calculations should be established on the basis of the spent fuel pool's technical specification maximum temperature limit (typically 115 $^\circ$F).

If the fuel cladding temperature calculation is based on heatup over a limited time period for cask drying operations, verify that limiting conditions for the operations have been imposed in the technical specifications. Such limiting conditions should ensure that the temperature will remain acceptable during the operations, and that normal cooling will begin before the temperature criterion is exceeded.

For unloading operations, evaluate temperature and pressure calculations supporting procedural steps presented in SAR Section 8 for cask cooldown and reflooding of the cask internals. To ensure that the cask does not overpressurize and that the fuel assemblies are not subjected to excess thermal stresses, the applicant's analysis should specify and justify the appropriate temperature and flow rate of the quench fluid, assuming maximum fuel cladding temperatures in the unloading configuration. The NRC accepts that the total stress on the cladding is maintained below the material's minimum yield stress (see the spent fuel cladding review procedures in this section). Other assembly components should also be examined in a similar manner. Engineering judgement combined with relevant industry operational experience with unloading spent fuel from transportation and storage casks may support the basis for limits on quench fluid temperature and flow rate. This review should be coordinated with the structural review (SRP Chapter 3) and procedure review (SRP Chapter 8).

Analysis for accident-level ("design-basis") temperatures should not be considered to envelop the analysis of normal or off-normal temperatures. Normal and off-normal temperature demands for structural capacity have different acceptance criteria. Therefore, all three conditions should be analyzed. In addition, the duration over which accident temperature conditions may exist should be evaluated. Because material properties may be functions of temperature and time, long-term temperature elevations can cause gradual degradation of material properties.

4. Model Specification

a. Configuration

Verify that the model used in the thermal evaluation is clearly described. Separate models may be used for the evaluation of normal and accident conditions. Coordinate with the structural review (SRP Chapter 3) to evaluate any damage that may result from accidents or natural phenomena events. All models should be shown to be conservative.

Examine the sketches or figures of the model used for thermal calculations. Verify that the dimensions and materials of the model are consistent with those in the drawings of the actual cask, as presented in SAR Section 1. If possible, examine computer inputs to verify consistency with the model sketches and engineering drawings. Differences between the actual cask configuration and the model should be identified, and the model should be shown to be conservative.

Pay particular attention to gaps between cask components. Tolerances should be considered so that the thermal resistance of each gap is treated conservatively. Gases (e.g., air, helium) assumed to be present in the gap shall be described and justified. If a specific gas other than air in the cask cavity or gaps between cask components is relied upon for heat removal, the applicant should show that the gas is retained *and* that the gas is not diluted by other gases having lower thermal conductivities during the entire storage period. For cask components that are important to heat removal, manufacturing techniques

for joining components, surface roughness, contact pressures, and gap conductance values should be adequately described and justified.

Review the decay heat load axial distribution. Ensure that decay heat generated in the spent fuel is limited to the active fuel region of the assemblies. The model should specifically account for the peaking in the central region. Heat from control components, if applicable, should also be distributed appropriately. In addition, the positions of heat sources relative to other cask components should be identified.

Examine the heat transfer processes used in the analysis. Conduction and radiation are typically defined as the primary heat transfer mechanisms within the cask itself. Convection by natural circulation should be limited to that between the external surface of the cask and the ambient environment. The staff has not previously approved specific thermal models for natural circulation internal to the cask because of the difficulty in modeling and the lack of test data. Applicants seeking NRC approval of specific internal convection models should propose, in the SAR, a comprehensive test program to demonstrate the adequacy of the cask design and validation of the convection models. Actual spent fuel properties and uncertainties (e.g., friction factors, crud and oxide buildup, eccentricities, non-uniform axial and radial decay heat profiles) should also be addressed. Applicants using an effective thermal conductivity for the cover gas (e.g., helium) in lieu of a specific convection model should also justify values used in the analysis.

Use of effective thermal conductivity coefficients for regions within the confinement cask other than the fuel (e.g., gaps) may overestimate heat transfer. If effective thermal conductivity is used in this manner, verify that the same values have been determined from test data that are representative of similar geometry, materials, temperatures, and heat fluxes used in current application. Pay particular attention to the effective thermal conductivity of neutron shield regions, such as those embedded with thermal fins. Voids or gaps typically exist, as a result of either tolerances or shrinkage, and shall be considered in calculating effective thermal conductivity. Also, pay particular attention to the values assumed for surface emissivities and view factors, as well as the manner used to account for radiation heat transfer in determining the effective thermal conductivities.

Coordinate the thermal review with the structural review (SRP Chapter 3) to ensure that, for components external to the confinement cask, the applicant analyzed situations that may produce the worst-case cask loads. As an illustration, for cask systems that may have multiple shielded casks and/or ones that provide cooling air passages by a single, integral structure, the greatest gradients and loadings caused by thermal expansion may occur with casks in alternative storage or in temporary handling positions, whereas the highest material temperatures probably occur with casks in any position.

Review how the SAR treats heat transfer through the fuel assemblies and, if applicable, the manner in which effective conductivity is determined for each fuel assembly. The fuel may be modeled as a homogenous region using an effective thermal conductivity. The basket wall temperature of the hottest assembly can then be used to determine the peak rod temperature of the hottest assembly using the Wooten-Epstein correlation. Guidance on effective thermal conductivity of the fuel is presented below in the discussion concerning material properties.

Verify that the SAR addresses the thermal interaction among casks in an array by using a view factor less than unity. Generally, this will result in an operating control and limit in SAR Section 12 that imposes a minimum spacing between storage casks.

b. Material Properties

Verify that the material compositions and thermal properties are provided for all components used in the calculational model. Verify that the thermal properties used in the safety analysis are appropriate, and that potential degradation of materials over their service life has been evaluated. The source of the thermal property data should be traced to an authoritative reference (generally not a textbook). The NRC has accepted the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel (B&PV) Code, Division 1, Section II, "Material Specifications," and Section III[5] appendices as a primary source for material properties. Pay particular attention to non-standard materials (e.g., neutron shielding and seals). Temperature and anisotropic dependencies of thermal properties should be considered. In addition, if regional thermal properties are determined from a combination of individual materials, the manner in which these effective properties are calculated should also be described.

If the transverse effective thermal conductivity of the fuel is greater than 0.5 BTU/hr-ft- °F (~0.86 W/m-K) under the conditions described in Effective Thermal Conductivity and Edge Configuration Model for Spent Fuel Assembly[6], the method in which it was determined shall be thoroughly described and supported. If the thermal model is axisymmetric or three-dimensional, the longitudinal thermal conductivity should generally be limited to the conductivity of the cladding (weighted by its fractional area) within the fuel assembly. Gaps between fuel pellets and cracks in the pellets themselves can result in a considerable uncertainty regarding the contribution of the fuel to longitudinal heat transfer. High burnup effects should also be considered in determining the fuel region effective thermal conductivity.

The SAR should also indicate both maximum and minimum temperature criteria for cask materials and components, and the justification and references for these criteria shall be adequately described. Criteria for concrete temperatures are established by American Concrete Institute (ACI) Standard 359[7] for structures, systems, and components within the scope of that code, as well as Appendix A to ACI 349[8].

c. Boundary Conditions

The applicant should identify boundary conditions for normal, off-normal, and fire accident conditions. The required boundary conditions include the decay heat rate from each fuel assembly and the external conditions on the cask surface. The peak power factor for a fuel assembly should be specified and the peak linear power of a fuel assembly should be stated for a given active fuel length. The peak decay heat flux on a basket compartment surface should also be given.

The boundary conditions on the cask surface depend on the environment surrounding the cask. Consequently, the temperature of the environment should be specified for normal and off-normal conditions, as should the incident and absorbed insolance. The mechanisms and models for dissipating the absorbed insolance and decay heat from the surface of the cask to the environment should also be identified and described. The mechanisms for transferring heat from the cask surface during normal and off-normal conditions usually consist of natural (free) convection and thermal radiation. A heat balance on the surface of the cask should be given and the results presented.

The initial temperature distribution of the storage cask system before a fire accident should be established on the basis of the hottest temperature distribution during normal or off-normal storage conditions. The duration and flame temperature of the fire should be specified, as should the flame velocity and emissivity. The flame and cask surface emissivities specified in 10 CFR 71.73(a)(3) (April 1996) for a hypothetical accident test of transportation packages are satisfactory for use with regard to a fire accident involving a storage cask.

The applicant should identify and describe the mechanisms and models for coupling the fire energy to the cask surface. These mechanisms include forced convection in relation to the flame velocity (5-15 m/s) as well as thermal radiation. In addition, the applicant should justify convection coefficients during the fire. Natural convection coefficients are not appropriate, as such coefficients imply downward gas flow adjacent to relatively cool cask walls. In general, buoyant upward flow will dominate.

Following the fire, the cask is subject to insolation and content decay heat while being cooled by natural convection and thermal radiation to the environment. The applicant should identify the post-fire conditions of the cask, including any changes in surface conditions and/or geometry that may affect radiation and convection heat losses. In addition, the applicant should identify and describe the models for the post-fire processes.

5. Thermal Analysis

a. Computer Programs

Determine which computer codes were used in the thermal evaluation. The applicant should use well-verified and validated computer code used to perform the thermal evaluation. The two codes most frequently encountered in SARs are ANSYS[9] and HEATING[10]. Both are capable of general 3-D steady state and transient calculations. Assess that the number of dimensions and temporal treatment are appropriate for the calculations being performed.

At least two codes, SCANS[11] and CASKS[12], have been developed to perform simple, approximate confirmatory analyses. These codes are not acceptable for use in an SAR for thermal design and analysis.

In addition, since these codes address temperatures of only the cask body, they cannot be used as the sole confirmatory tool for the thermal review.

The SAR documentation should include input and output file listings for the thermal evaluations. Reviewers should be familiar with the codes used in the SAR documentation. If the applicant proposes to use codes not previously accepted by NRC, development of reviewer familiarity with those codes is considered to be a necessary part of the review process. The applicant should also describe, in the SAR, the code and justification for use in the thermal evaluation. Verify that the information from the thermal model is properly input into the code. Verify that the output has been properly interpreted and applied in the thermal and structural analyses. The scope of confirmatory calculations is partly dependent on the quality of the output data and its use.

b. Temperature Calculations

The SAR should include a table that lists the maximum and minimum temperatures of all components important to safety under normal, off-normal, and accident conditions. This table should specify the operating temperature range for each component. Verify that temperatures have been calculated for key components and that they do not exceed the allowable range for each. Justification shall be provided in the SAR for any material important to safety that exceeds acceptable temperature ranges. If compliance with minimum temperature criteria relies on a specific minimum heat load from the fuel, such heat load shall be quantified and included as an operating control and a technical specification criterion in SAR Section 12.

Pay particular attention to the maximum temperature of the cladding. Currently, the staff accepts temperature criteria established on the basis of the DCCG[13]. Comparable criteria are also defined in PNL-6189[14], even though the maximum temperatures are established on the basis of a different failure mechanism (creep). Experience with previous SARs has shown that most of the review effort is generally devoted to confirming that these temperature criteria are satisfied.

Some storage systems rely upon natural circulation of air through internal passages to remove heat from the stored confinement cask. For storage systems with internal air flow passages, blockage of inlet and/or outlet flow is an accident situation that should be evaluated. Total blockage of all inlets and outlets may result in fuel heatup, which has been assumed to approach adiabatic conditions. To ensure that blockages do not go undetected for significant periods, the NRC has required objective evidence that inlet and outlet flows are not obstructed. Consequently, for these type of storage systems, the NRC has accepted periodic visual inspection of the vents coupled with temperature measurements to verify proper thermal performance and detect flow blockages. The inspections should take place within an interval that will allow sufficient time for corrective actions to be taken before the accident temperature is reached. The inspection interval should be more frequent than the time interval required for the fuel to heatup to the established accident temperature criteria, assuming a total blockage of all inlets and outlets.

Review of the heatup calculations should especially address any assumptions regarding limiting components and quasi-steady state responses. The initial ambient temperature for the heatup calculations should bound the maximum "normal condition" temperature. The resulting heatup time history should be included in the SAR documentation, and should support the proposed inspection and monitoring intervals. The information is also useful in developing contingency operation procedures, since it indicates the available time in which to take corrective actions before the fuel accident temperature criteria may be exceeded.

The most extreme thermal conditions may result from credible ambient temperatures, temperature-time histories, an adjacent fire, or any off-normal or design-basis event (DBE) resulting in blockage of ventilation passages. The worst-case structural loads may occur at temperatures lower than those of design-basis accidents or natural phenomena, since load combination expressions effectively require greater safety factors for normal and off-normal analyses than for design-basis (accident) events and conditions. For storage systems without internal air flow passages, the worst-case accident thermal conditions typically have been fire.

Burning of fuel and other combustibles associated with vehicles involved in transfer operations should, at a minimum, be presumed to be a DBE with the cask in the most exposed situation during transfer or loading into storage. Fire parameters included in 10 CFR 71.73 have been accepted for characterizing the heat transfer during the in-storage fire. However, a bounding analysis that limits the fuel source thus limits the length of the fire (e.g., by limiting the source to the fuel in the transporter) has also been

accepted. If the SAR does not address fire, or if the site-specific fire parameters exceed those of the SAR, the site-specific application will need to include analysis of the worst-case credible fire.

Some structures, systems, and components may experience the most severe conditions if exposure to high temperatures is followed by dousing (as by rain or fire water). A small amount of exterior concrete spalling may result from a fire, the application of fire suppression water, rain on heated surfaces or other high-temperature condition. The damage from these events is readily detectable, and appropriate recovery or corrective measures may be presumed. Therefore, the loss of such a small amount of shielding material is not expected to cause a storage system to exceed the regulatory requirements in 10 CFR 72.106 and, therefore, need not be estimated or evaluated in the SAR. The NRC accepts that concrete temperatures may exceed the temperature criteria of ACI 349 for accidents if the temperatures result from a fire. In that case, corrective action may be required for continued safe storage.

The methods that are acceptable for analyzing and reviewing the consequences of a fire depend upon the duration of the fire and the margin between the predicted temperatures and the actual thermal limits of the components. For a fire of very short duration (i.e., less than 10 percent of the thermal time constant of the cask body), the NRC finds it acceptable to calculate the fuel temperature increase by assuming that the cask inner wall is adiabatic. The fuel temperature increase should then be determined by dividing the decay energy released during the fire by the thermal capacity of the basket-fuel assembly combination. For a fire of somewhat longer duration, it is acceptable to evaluate the cask body with no credit for the thermal capacity of the fuel assemblies and basket. This model assumes that the fuel temperature increase relates to the decay heat conducted or radiated from the fuel assemblies to the maximum temperature of the cask inner wall. A fire of sufficient duration, or one in which material temperatures are close to the criteria of their acceptable operational range, will require a detailed model of the cask and its contents. Cask system components (e.g., the neutron shield) may be assumed to be intact at the start of the fire, unless the fire is a secondary effect resulting from another credible event that may have physically affected the cask system (e.g., an aircraft impact).

Some storage systems may use a transfer cask to move the loaded confinement cask to the independent spent fuel storage installation (ISFSI) storage site. When the confinement cask is within the transfer cask, cooling is typically less than for normal operation. Fuel cladding temperatures would therefore be expected to be higher than for normal storage conditions. This is generally acceptable as long as the short-term accident temperature of 570 °C (1058 °F) is not exceeded.

Examine the temperature distribution calculations for the fuel container inside the transfer cask. Verify that heat transfer through gap regions has been treated in a conservative manner, and that material properties and dimensions of the transfer cask are consistent with the design data defined in the SAR documentation. The initial ambient temperature should be the maximum "normal condition" temperature. Cask preparation for storage or unloading operations may include situations in which the confinement cask is evacuated while it is in the transfer cask. For such conditions, determine that the maximum fuel cladding temperature has been calculated in an acceptable manner. The short-term accident temperature of 570 °C (1058 °F) for zircalloy fuel cladding has been accepted as a suitable criterion for fuel transfer operations, with restrictions (see the earlier discussion of spent fuel cladding review procedures). If the calculation is based on heatup over a limited time, verify that limiting conditions for the operations have been imposed to ensure that the temperature will remain acceptable during the process, and that normal cooling will begin before the temperature criterion is exceeded.

If a cask tipover is a credible accident, verify that the applicant has evaluated the effect on cask and fuel temperatures in the new configuration. An analysis may be warranted when a significant portion of heat removal capability is attributed to internal convection if a change in orientation of that cask may have a significant effect.

Using the accident condition temperatures, verify that the applicant has correctly determined the post-accident pressure of the gas in the cask cavity. The pressure should be determined on the basis of the assumption that 100 percent of the fuel rods have failed. The resulting load on the cask confinement boundary should be used in the structural analysis with the appropriate load combinations for accident conditions.

c. Pressure Analysis

Verify that the containment pressure of the cask is within its design limits for normal and accident conditions. Pressure calculations should be performed using the ideal gas law (i.e., $PV = nRT$) and

summing the partial pressures of each of the gas constituents in the cask cavity. The SAR should identify the method and all assumptions used in the pressure analysis. The SAR should also identify and justify the method used to determine the fission gas inventory. Reviewers should also assess the applicant's calculation packages.

In addition, it is necessary to consider the temperature distribution of all components within the cask cavity and the cavity walls in calculating the gas pressure in the cavity. For fire analysis, the SAR should identify the maximum gas temperature reached during the post-fire transient phase, explain the method used to determine the average gas temperature, and specify the time in the transient at which the peak gas temperature is attained.

This pressure also depends on the free volume in the cask cavity, the amount (moles) of cover gas (helium) in the cavity, and the amount of gases released from ruptured fuel pins. The free volume calculation should be reviewed to determine if all components internal to the cask cavity (e.g., fuel assemblies, basket, structural supports, spacer disks, reactor control components) have been properly considered. Free volume calculations should account for thermal expansion of the cask internal components and the fuel when subjected to accident temperatures.

The NRC accepts that normal-conditions occur with less than 1 percent of the fuel rods failed, off-normal-conditions occur with up to 10 percent of the fuel rods ruptured, and 100% of the fuel rods will have ruptured following a design-basis accident event. The NRC also accepts that a minimum of 100 percent of the fill gas and 30 percent of the significant radioactive gases (e.g., H^3, Kr, and Xe) within a ruptured fuel rod is available for release into the cask cavity. Verify that design criteria pressures stated in SAR Section 2 are consistent with the calculated maximum pressures. Verify that the pressure testing specified in SAR Section 9 is consistent with the calculated pressures.

d. Confirmatory Analysis

Reviewers should perform a confirmatory analysis of the thermal performance of the cask structures, systems, and components identified as important to safety. Review the SAR to ensure that the applicant made the correct assumptions and provided the correct input, and that the output is consistent with established physical (thermal) behavior. These results should specifically include steady-state temperature distributions; local heat balances; temperatures reached and temperature distributions within any reinforced concrete structures, systems, and components; and cask cavity pressures for the bounding ambient temperatures.

To provide the most reliable confirmation, confirmatory analysis should, to the degree possible, use a different thermal method than the code used by the applicant. Similar confirmation of transient temperatures (e.g., during a fire) should be performed, as applicable to the SAR analysis.

The minimum confirmatory review should include verifying that key design parameters have been appropriately determined and correctly expressed as input into the computer program(s) used for the thermal analysis. Key parameters include proper dimensions, material properties (including surface emissivities and view factors for radiation), and definition of heat sources. A heat balance at the outer surface of the cask should be performed to verify that the heat from the spent fuel and insolance, balance that removed by convection and radiation. Correlations for the heat transfer coefficient should then be assessed to confirm that they are appropriate for the existing storage conditions. The temperature of the cask's inner surface should be estimated by calculating the temperature distribution across the cask body with simple heat balance approximations. Finally, the difference between the cask's inner surface temperature and the maximum cladding temperature should be compared with that of similar casks and baskets reviewed in previous SARs.

If a more detailed confirmatory review is required, a portion of the cask or basket may be modeled and evaluated to ensure that the SAR results are realistic and conservative. An extensive confirmatory analysis is necessary if major errors are suspected, if the applicant's margin in a complex analysis is small, or if little conservatism exists in the SAR modeling approach. As an alternative, the applicant may be required to perform design-verification testing of an as-built cask system to confirm the thermal analyses presented in the SAR. Such testing may include verifying gap conductance values assumed in modeling thermal resistance. The test conditions, configuration, and type and location of instrumentation used, if any, should be sufficiently described in SAR Section 9.

The NRC accepts simplifying assumptions for the effects of reinforcing steel in determining the thermal performance and temperature distributions of reinforced concrete. Use of a homogeneous material, instead of modeling the concrete and reinforcing steel as separate elements, is acceptable if the substitute hypothetical material has appropriately adjusted the thermal properties, and the reinforcing steel is covered with concrete in accordance with the applicable structural code. More specific analysis may be required for thermal performance and/or temperature distributions of reinforced concrete designs with features that allow significant thermal transfer below the concrete surface (such as internal studs welded to an exposed steel plate).

6. Supplemental Information

Supplemental information may include copies of applicable references (if not generally available to reviewers), computer code descriptions, input and output files, and any other information that the applicant deems necessary. Likewise, reviewers should request any additional information needed to complete the evaluation process.

VI. Evaluation Findings

Review the 10 CFR Part 72 acceptance criteria and provide a summary statement for each. These statements should be similar to the following model:

> Structures, systems, and components (SSCs) important to safety are described in sufficient detail in Sections _____ of the SAR to enable an evaluation of their thermal effectiveness. Cask SSCs important to safety remain within their operating temperature ranges.
>
> The [cask designation] is designed with a heat-removal capability having verifiability and reliability consistent with its importance to safety. The cask is designed to provide adequate heat removal capacity without active cooling systems.
>
> The spent fuel cladding is protected against degradation leading to gross ruptures by maintaining the cladding temperature for _____ -year cooled fuel below ______ °C in an [applicable gas] environment. Protection of the cladding against degradation is expected to allow ready retrieval of spent fuel for further processing or disposal.
>
> The staff concludes that the thermal design of the [cask designation] is in compliance with 10 CFR Part 72, and that the applicable design and acceptance criteria have been satisfied. The evaluation of the thermal design provides reasonable assurance that the [cask designation] will allow safe storage of spent fuel for a licensed (certified) life of _____ years. This finding is reached on the basis of a review that considered the regulation itself, appropriate regulatory guides, applicable codes and standards, and accepted engineering practices.

VII. References

1. A.B. Johnson and E.R. Gilbert, Pacific Nuclear Laboratories, "Technical Basis for Storage of Zircalloy-Clad Spent Fuel in Inert Gases," PNL-4835, September 1983.

2. Cunningham, M.E. , *et al* "Control of Degradation of Spent LWR Fuel During Dry Storage in and Inert Atmosphere" PNL-6364, PNL September 1987

3. U.S. Nuclear Regulatory Commission, "Spent Fuel Heat Generation in an Independent Spent Fuel Storage Installation," Regulatory Guide 3.54, September 1974.

4. *U.S. Code of Federal Regulations*, "Packaging and Transportation of Radioactive Material," Part 71, Title 10, "Energy."

5. American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel (B&PV) Code, Division 1, Section II, "Material Specification,"

6. R.D. Manteufel and N.E. Todreas, "Effective Thermal Conductivity and Edge Configuration Model for Spent Fuel Assembly," *Nuclear Technology*, Vol. 105, pp. 421–440, March 1994.

7. American Concrete Institute/American Society of Mechanical Engineers Joint Technical Committee, ACI 359 (ASME B&PV Code, Section III, Division IIA)

8. American Concrete Institute, “Code Requirements for Nuclear Safety-Related Concrete Structures,” ACI 349.

9. Swanson Analysis Systems, Inc., "ANSYS Computer Code for Large-Scale General-Purpose Engineering Analysis," Houston, Texas

10. K.W. Childs, Oak Ridge National Laboratory, "Heating 7.2 User’s Manual," NUREG/CR-0200, Vol. 2, Rev. 4, April 1995.

11. G.C. Mok, *et al*., Lawrence Livermore National Laboratory, "SCANS [Shipping Cask Analysis System] — A Microcomputer-Based Analysis System for Shipping Cask Design Review," NUREG/CR-4554, 1989.

12. T.F. Chen, *et al*., Lawrence Livermore National Laboratory, "CASKS [Computer Analysis of Storage Casks]: A Microcomputer-Based Analysis System for Storage Cask Design Review," NUREG/CR-6242, February 1995.

13. M.W. Schwartz and M.C. Witte, Lawrence Livermore National Laboratory, "Spent Fuel Cladding Integrity During Dry Storage," UCID-21181, September 1987.

14. I.S. Levy, *et al*., Pacific Northwest Laboratory, "Recommended Temperature Limits for Dry Storage of Spent Light-Water Zircalloy Clad Fuel Rods in Inert Gas," PNL-6189, May 1987.