5 THERMAL EVALUATION

5.1 Review Objective

The objective of the U.S. Nuclear Regulatory Commission's (NRC's) thermal review with regard to heat transfer and flow characteristics is to ensure that the storage container and fuel material temperatures of a dry storage system (DSS) or dry storage facility (DSF) will remain within the allowable limits for normal, off-normal, and accident conditions. The review will confirm 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. The review will also confirm that the applicant uses acceptable analytical and testing methods, as applicable, in the safety analysis report (SAR) when evaluating the DSS or DSF thermal design.

Another objective of the thermal review is to ensure that the decay heat removal system is capable of reliable operation so that the temperatures of materials used for structures, systems, and components (SSCs) important to safety, and solidified high-level radioactive waste (HLW) containers remain within the allowable limits under normal, off-normal, and accident conditions. The NRC staff evaluate the wet and dry fuel assembly transfer systems for adequate decay heat removal under normal, off-normal, and accident conditions. In addition to storage container design, the reviewer considers siting and facility design.

The approach to thermal review and evaluation for a specific license builds upon the guidance provided for the certification review of storage containers. The guidance of this chapter unique to specific licenses is necessary because site-specific SARs will contain site-specific features (e.g., ambient temperature and wind speed limits) and other systems (e.g., pools, structures using reinforced concrete). If the DSF uses a storage container that has received a certificate of compliance (CoC), the review will address key assumptions, bounding site characteristics, environmental conditions, and storage container or facility interface requirements identified in the storage container SAR and CoC and compare them with the DSF design and environmental conditions. This review will confirm that the systems in the DSF support the assumptions used in the evaluation of the storage containers.

5.2 Applicability

This chapter applies to the review of applications for specific licenses for an independent spent fuel storage installation (ISFSI) or a monitored retrievable storage facility (MRS) categorized as DSF. It also applies to the review of applications for a DSS CoC for use at a general-license facility. Sections or paragraphs of this chapter that apply only to specific license applications are identified with "**(SL)**." Sections or paragraphs that apply only to DSS CoC applications are identified with "**(CoC)**." A section or paragraph without an identifier applies to both types of license applications.

5.3 Areas of Review

This chapter addresses the following areas of review:

- decay heat removal system
  - general considerations **(SL)**
  - DSSs **(SL)**
  - dry transfer systems **(SL)**

- material and design limits
  - general considerations
  - considerations for specific licenses **(SL)**
- thermal loads and environmental conditions
  - general considerations

  - considerations for specific licenses **(SL)**

- analytical methods, models, and calculations
  - configuration
  - material properties
  - boundary conditions
  - computer codes
  - temperature calculations
  - pressure analysis
  - confirmatory analysis
- surveillance requirements

5.4 Regulatory Requirements and Acceptance Criteria

This section summarizes those parts of Title 10 of the *Code of Federal Regulations* (10 CFR) Part 72, "Licensing Requirements for the Independent Storage of Spent Nuclear Fuel, High-Level Radioactive Waste, and Reactor-Related Greater than Class C Waste," that are relevant to the review areas this chapter addresses. The NRC staff reviewer should refer to the exact language in the regulations. Tables 5-1a and 5-1b match the relevant regulatory requirements to the areas of review covered in this chapter.

Table 5-1a Relationship of Regulations and Areas of Review for a DSF (SL)

Areas of Review	**10 CFR Part 72 Regulations**					
	72.26	72.44	72.92	72.120	72.122	72.128
Decay Heat Removal Systems					(h)	(a)(4)
Material and Design Limits				(a)(d)		(a)
Thermal Loads and Environmental Conditions			(a)		(b)	
Analytical Methods, Models, and Calculations					•	(a)
Surveillance Requirements	•	(c)			(f), h(4), (i), (j)	

Table 5-1b Relationship of Regulations and Areas of Review for a DSS (CoC)

Areas of Review	10 CFR Part 72 Regulations
	72.236
Decay Heat Removal Systems	(f)(h)
Material and Design Limits	(a)(b)
Thermal Loads and Environmental Conditions	(b)
Analytical Methods, Models, and Calculations	(g)(l)(m)
Surveillance Requirements	(b)(g)

5.4.1 Decay Heat Removal System

The spent fuel cladding must be protected during storage against degradation that leads to gross fuel rupture (10 CFR 72.122(h)). Decay heat removal systems shall have testability and reliability consistent with their importance to safety (10 CFR 72.128(a)(4)). The spent fuel storage cask must be designed to provide adequate heat removal capacity without active cooling systems (10 CFR 72.236(f)). The spent fuel storage cask must be compatible with wet or dry spent fuel loading and unloading facilities (10 CFR 72.236(h)).

The applicant should provide a detailed description of the proposed storage container heat removal system and its passive cooling characteristics. The SAR should clearly identify all major components and thoroughly explain their contribution to the removal of heat from the fuel. The SAR should also discuss the mechanism of heat removal (i.e., conduction, convection, radiation) for each component.

The applicant should provide evidence that the decay heat removal system will operate reliably under normal and loading conditions. The applicant should provide evidence that under off-normal and accident conditions, the decay heat removal system will not exceed allowable thermal limits and that the applicant will take adequate actions to bring the decay heat removal system to normal cooling.

The SAR should also describe all instrumentation used to monitor storage container thermal performance.

5.4.2 Material and Design Limits

An application to store spent fuel or reactor-related greater-than-Class-C (GTCC) waste in an ISFSI or to store spent fuel, HLW, or reactor-related GTCC waste in an MRS must include the design criteria for the proposed storage installation (10 CFR 72.120(a)). The ISFSI or MRS must be designed, made of materials, and constructed to ensure that there will be no significant chemical, galvanic, or other reactions between or among the storage system components, spent fuel, reactor-related GTCC waste, and/or high level waste including possible reaction with water during wet loading and unloading operations or during storage in a water-pool type ISFSI or MRS. The behavior of materials under irradiation and thermal conditions must be taken into account (10 CFR 72.120(d)). SSCs important to safety shall be maintained within their minimum and maximum temperature criteria for normal, off-normal, and accident conditions so as to support the performance of the intended safety function (10 CFR 72.128(a)). Specifications must be provided for the spent fuel to be stored in the spent fuel storage cask, such as, but not limited to, type of spent fuel (i.e., boiling-water reactor, pressurized-water reactor, or both), maximum allowable enrichment of the fuel before any irradiation, burn-up (i.e., megawatt days per metric ton of uranium (MTU)), minimum acceptable cooling time of the spent fuel before storage in the spent fuel storage cask, maximum heat designed to be dissipated, maximum spent fuel loading limit, condition of the spent fuel (i.e., intact assembly or consolidated fuel rods), the inerting atmosphere requirements (10 CFR 72.236(a)). Design bases and design criteria must be provided for SSCs important to safety (10 CFR 72.236(b)).

Storage container components and fuel materials should be maintained between their minimum and maximum temperature limits for normal, loading, off-normal, and accident conditions to enable all components to perform their intended safety function.

To guarantee the integrity of zirconium-based alloy cladding, the maximum calculated fuel-cladding temperature should not exceed 400 degrees Celsius (°C) (752 degrees Fahrenheit (°F)) for normal conditions of storage and short-term loading operations, including cask drying and backfilling. A higher temperature limit may only be used for low burnup spent nuclear fuel (SNF) (less than 45 gigawatt days MTU), as long as the applicant can demonstrate that the best estimate cladding hoop stress is equal to or less than 90 megapascals (MPa) (13.1 thousand pounds per square inch (ksi)) for the proposed temperature limit. During loading operations, repeated thermal cycling should be limited to less than 10 cycles when the cladding temperature difference exceeds 65 °C (149 °F). For off-normal and accident conditions, the maximum zirconium-based cladding temperature should not exceed 570 °C (1,058 °F).

To guarantee the integrity of stainless-steel cladding, the maximum calculated fuel cladding temperature should not exceed 570 °C (1,058 °F) for off-normal and accident conditions. The maximum calculated fuel cladding temperature should not exceed 400 °C (752 °F) for normal conditions of storage and short-term loading operations, including storage container drying and backfilling.

The applicant should clearly identify the operational temperature limits for all component materials important to safety under normal, loading, unloading, off-normal, and accident conditions. The applicant should provide a reliable basis for all the temperature limits.

The maximum internal pressure of the fuel container 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 initial fill gas and 30 percent of the fission product gases generated within the fuel rods during operation.

The applicant should clearly identify the design pressure limits for the fuel container under normal, off-normal, and accident conditions.

5.4.3 Thermal Loads and Environmental Conditions

The applicant must identify and justify the design-basis thermal load and the insolation and ambient temperature assumptions used as boundary conditions for the normal, loading, off-normal, and accident scenarios (10 CFR 72.92(a)). The heat removal system must accommodate the decay heat of the SNF or HLW and the site normal, off-normal, and accident thermal conditions (10 CFR 72.122(b)). Design bases and design criteria must be provided for structures, systems, and components important to safety (10 CFR 72.236(b)). Further guidance to review the thermal impact of environmental conditions (e.g., ambient temperature, wind, elevation) on a DSS or DSF is provided in NUREG-2174, "Impact of Variation in Environmental Conditions on the Thermal Performance of Dry Storage Cask, Final Report," issued March 2016.

5.4.4 Analytical Methods, Models, and Calculations

SSCs important to safety must be designed to show compliance with 10 CFR 72.122, "Overall requirements." Spent fuel and high-level radioactive waste storage and handling systems. Spent fuel storage, high-level radioactive waste storage, reactor-related GTCC waste storage and other systems that might contain or handle radioactive materials associated with spent fuel, high-level radioactive waste, or reactor-related GTCC waste, must be designed to ensure adequate safety under normal and accident conditions (10 CFR 128(a)). The spent fuel storage cask must be designed to store the spent fuel safely for the term proposed in the application, and permit maintenance as required (10 CFR 72.236(g)). The spent fuel storage cask and its systems important to safety must be evaluated, by appropriate tests or by other means acceptable to the NRC, to demonstrate that they will reasonably maintain confinement of radioactive material under normal, off-normal, and credible accident conditions (10 CFR 72.236(l)). To the extent practicable in the design of spent fuel storage casks, consideration should be given to compatibility with removal of the stored spent fuel from a reactor site, transportation, and ultimate disposition by the Department of Energy (10 CFR 72.236(m)).

The applicant should present a thermal analysis that clearly demonstrates the storage system's ability to manage design heat loads and have the various materials and components remain within temperature limits. The analysis should be conducted for normal, loading (including storage container drying and backfilling), draindown and reflood (as applicable), off-normal, and accident conditions. Resulting temperature profile and internal pressure information are necessary to support the structural analysis and the confinement analysis in the SAR.

The applicant should specify the analytical methods used in the thermal evaluations, including any computational modeling software (i.e., finite element analysis or computational fluid dynamics (CFD) computer analysis codes) and should discuss the basis for the parameters and options selected for the analysis. All models should be clearly described. Material thermal properties for all storage container components should be provided and justified. Temperature-dependent thermal properties provided in the application should cover the expected operational range. The applicant should discuss, quantify, and report in the SAR any conservatism associated with the proposed thermal models. The level of detail of the discussion should be comparable with sections of the SAR that describe the analytical thermal models. For cases with small thermal margin, the SAR should include a table of results showing how the associated conservatisms affect the safety parameters (e.g., calculated peak cladding temperature, confinement seal temperatures). The table of results should be supported with fully documented analytical models and calculations. In order to justify a small thermal margin, the identified model conservatisms should demonstrate a positive increase in the predicted margin.

The computer codes used in the thermal evaluation should be well verified and validated. The applicant can include the code verification and validation in the application or in a separate calculation package along with applicable references. The applicant should provide acceptable basis (e.g., benchmark efforts that mimic heat transfer and flow characteristics for the proposed design and that includes well defined boundary conditions and high-quality data for validation purposes, published results that include the range of applicability of the computer codes and highlight the specific features relevant to storage container design) for the accuracy of the selected computer code or codes and justification for the code's use in the proposed evaluation. The applicant should provide a discussion of the resulting level of convergence and conservatism achieved as a function of the modeling options (e.g., meshing, time-differencing). The applicant should provide solution verification results by calculating the grid convergence index (GCI). Guidance to calculate the GCI is provided in NUREG-2152, "Computational Fluid Dynamics Best

Practice Guidelines for Dry Cask Applications, Final Report," issued March 2013 (ADAMS Accession No. ML13086A202) and American Society of Mechanical Engineers (ASME) "Standard for Verification and Validation in Computational Fluid Dynamics and Heat Transfer."

To facilitate confirmatory analyses, the applicant should provide detailed drawings of the proposed design and electronic copies of the most significant input and output files. Further guidance on the review of analytical methods, models, and calculations provided to the staff for review is provided in Appendix 4A, "Computational Modeling Software Technical Review Guidance," to this standard review plan (SRP) and NUREG-2152.

5.4.5 Surveillance Requirements

Section 5.5.1, "Decay Heat Removal Systems," and Chapter 17, "Technical Specifications Evaluation," of this SRP provide information relevant to the review of surveillance requirements for a specific license.

Each application under this part shall include proposed technical specifications in accordance with the requirements in 10 CFR 72.44 and a summary statement of the bases and justifications for these technical specifications (10 CFR 72.26). The applicant must describe the program of surveillance to ensure satisfactory in-service performance of items and activities important to safety (10 CFR 72.122(f), 72.122(h)(4), 72.122(i), 72.122(j), 72.236(b), and 72.236(g)). The SAR should present the surveillance program for temperatures and pressures, as applicable, for SSCs important to safety, including those described in Chapter 12, "Conduct of Operations Evaluation," and Chapter 17 of this SRP.

5.5 Review Procedures

Review design features and acceptance criteria, given in the chapters of the SAR on general information and principal design criteria, for additional insight about the thermal models that are being presented. Review the appropriateness of the proposed heat loads and environmental conditions. Assess modeling details such as assumptions, simulation options, simplifications, and accuracy of results. The DSS or DSF is to be analyzed under normal, loading, off-normal, and accident scenarios. Review the resulting temperature distributions and internal pressures calculated in the SAR to verify compliance with design criteria and regulatory requirements.

One aspect of the DSS or DSF thermal evaluation is confirmation that the fuel cladding temperature will remain below a specified allowable limit to prevent degradation during storage. Another aspect of the DSS or DSF thermal evaluation is confirmation that materials used for SSCs important to safety and solidified HLW containers remain within the allowable limits.

Thermal performance of the storage container under off-normal and accident conditions is also evaluated in accordance with Chapter 16, "Accident Analysis Evaluation," of this SRP, as appropriate, in the overall accident analyses presented in the SAR.

Figures 5-1a and 5-1b show the interrelationships between the thermal evaluation review and the other areas of review described in this SRP for specific license and CoC applications, respectively.

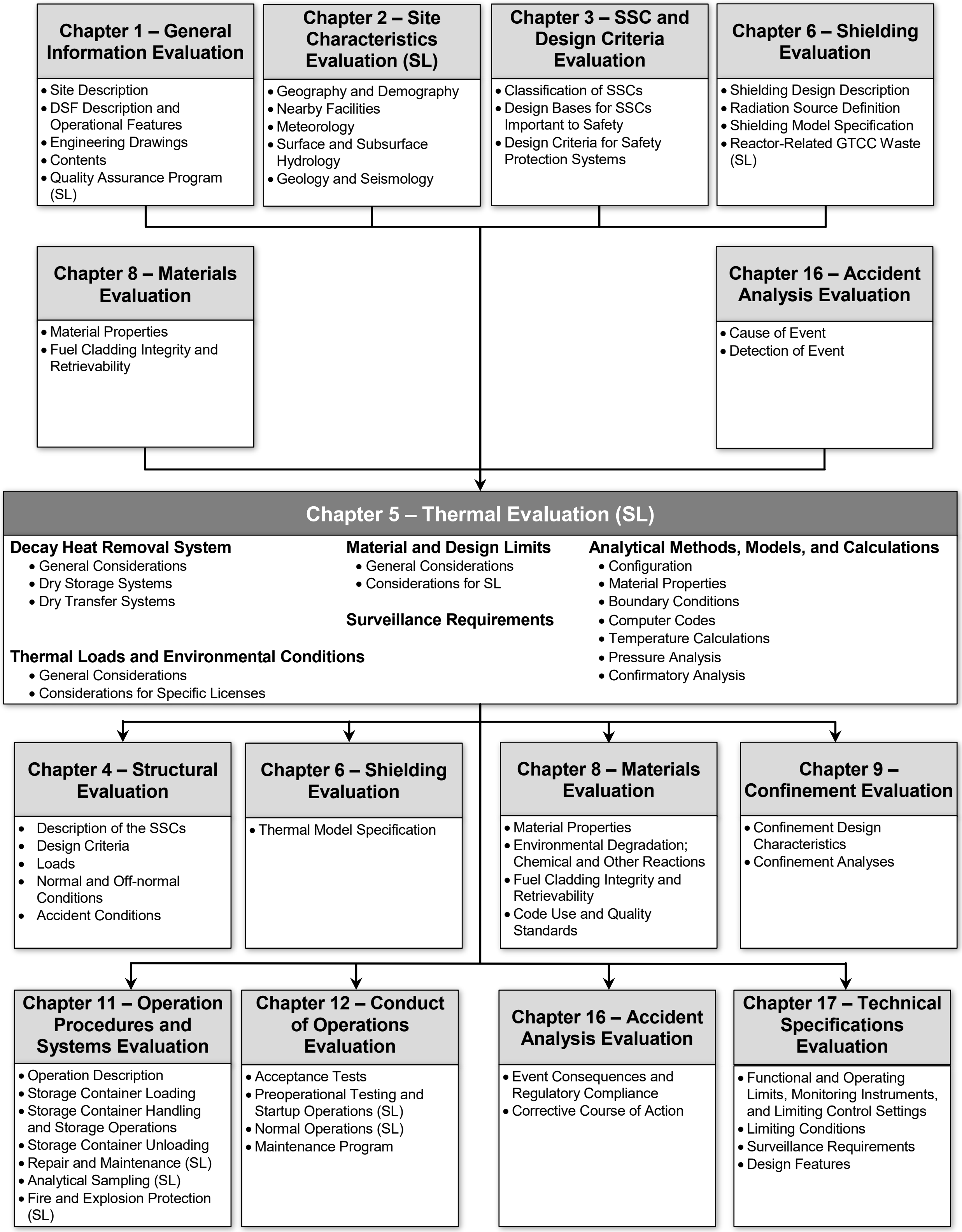

Figure 5-1a Overview of Thermal Evaluation of Specific License Applications for a DSF (SL)

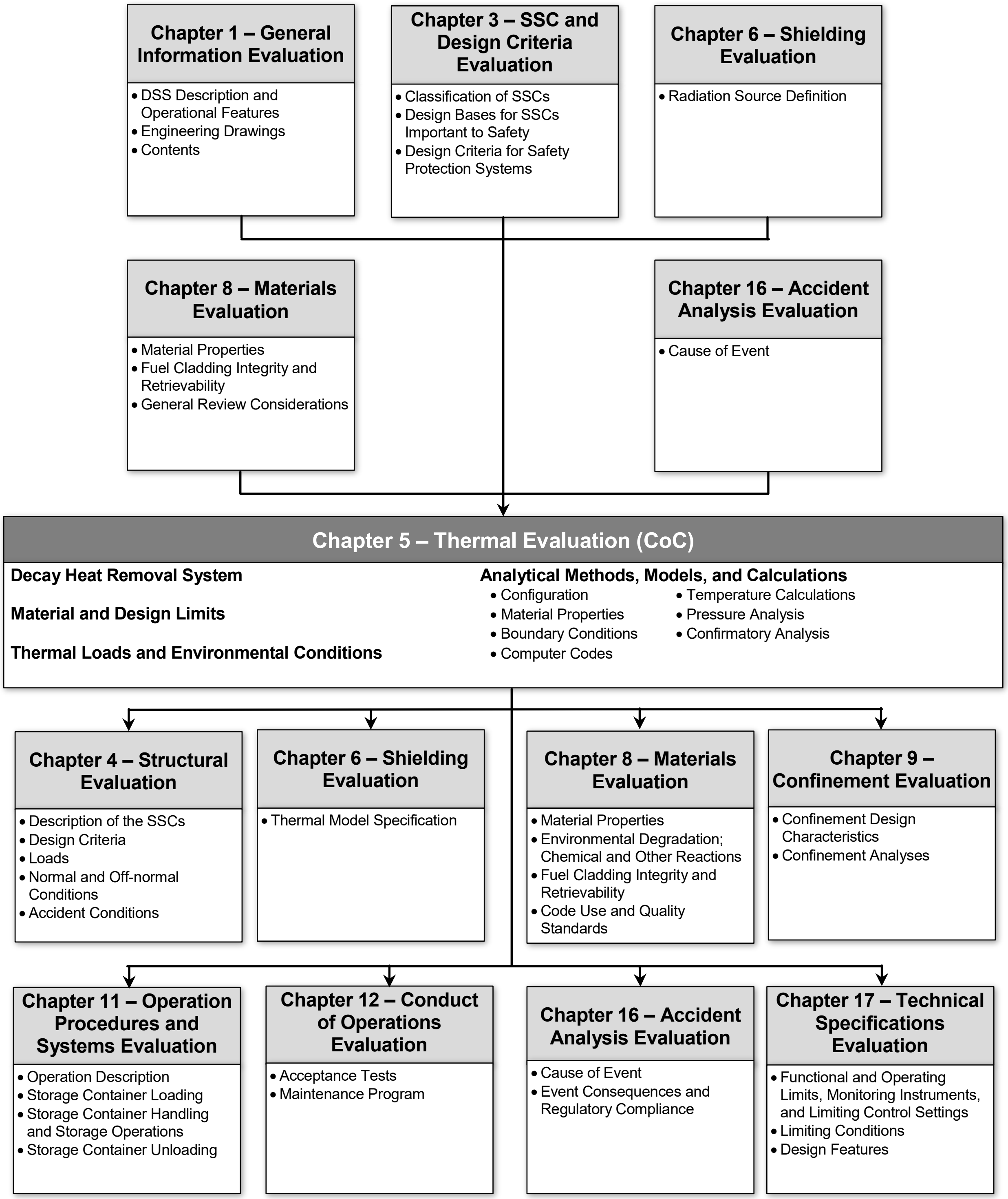

Figure 5-1b Overview of Thermal Evaluation of Applications for a DSS (CoC)

5.5.1 Decay Heat Removal Systems

Review the description of the DSS and DSF presented in the SAR chapter on general information, as supplemented by the additional information provided in the SAR on thermal evaluation. Ensure these two sources of information are consistent and supplementary. In addition to the material specifications, the dimensions of the storage container components and SNF assemblies are to be clearly indicated. Ensure all drawings, figures, and tables are sufficiently detailed to support an indepth staff evaluation.

Confirm that the applicant describes the significant thermal design features and operating characteristics of all pertinent DSS or DSF components and subsystems. Design features typically include, but are not limited to, the storage container body, thermal fins, shielding materials, fuel baskets, heat transfer disks, confinement seals, drain and vent ports, and external pressure relief devices (for the case of transfer casks). Verify that the thermal design features will adequately perform their intended safety functions during normal, loading, off-normal, and accident conditions. All thermal design features should be passive. Applicants have requested temporary supplemental cooling (circulating water or air flow) of storage container systems during loading operations or as a technical specifications action statement during transfer operations. Review such requests to ensure that they meet the original intent of the regulations—that storage container systems remain passively cooled during normal operations.

Ensure that the applicant has described any instrumentation used to monitor storage container heat removal capability in sufficient detail to support an indepth staff evaluation. Ensure that the monitoring instrumentation components have a safety classification (presented in the SAR chapter on principal design criteria) commensurate with their function and is fully justified. Verify that the SAR chapter on technical specifications and operational controls and limits clearly indicates applicable operating controls and criteria, such as temperature or pressure criteria and surveillance requirements. These should also be discussed in the safety evaluation report (SER) and included in the CoC or specific license, as appropriate.

5.5.1.1 *General Considerations* ***(SL)***

ISFSI or MRS decay heat removal systems must accommodate the decay heat of the SNF or HLW and the site normal, off-normal, and accident environmental conditions (10 CFR 72.122(b)). Verify that the SAR for the ISFSI or MRS clearly establishes that the storage system will function within the allowable thermal limits under normal, off-normal, and accident conditions. Review the specification for the design-basis fuel assembly decay heat presented in the SAR's discussion of principal design criteria and the corresponding sections of the storage container(s) SAR(s) if the storage container has received an NRC CoC. Coordinate the review with the shielding reviewer to ensure that this decay heat is consistent with the specified enrichments, burnups, and cooling times. Consider relevant generic communications (e.g., NRC information notices, regulatory guides) as part of the review.

Ensure that the decay heat removal systems have testability and reliability consistent with their importance to safety (10 CFR 72.128(a)(4)). Ensure that, during storage, the SNF cladding is protected against degradation that could lead to gross fuel rupture and is otherwise confined such that degradation of the fuel during storage will not pose operational problems with respect to its removal from storage (10 CFR 72.122(h)(1)). For each type of fuel assembly proposed for storage, confirm that the systems ensure a very low probability (e.g., 0.5 percent), per fuel rod, of cladding breach during long-term (e.g., 40-year) storage (10 CFR 72.122(h), (Levy et al. 1987).

This can be accomplished by confirming that fuel cladding temperatures will remain below recommended limits, as specified in Section 5.4.2, "Materials and Design Limits," of this SRP.

Review the thermal analysis, material temperature limits, and key assumptions of the analysis to ensure that the DSS or DSF design and environmental conditions are within the envelope of the DSS original analysis and the associated technical specifications. Confirm that the design criteria include maximum heat output of the radioactive materials (including control components or other assembly hardware such as shrouds); temperature levels for the ambient air under normal, off-normal, and accident conditions; and associated insolation. Confirm that the SAR identifies the conditions (off-normal or accident) that may result in high temperature gradients and pressures. The conditions may be time-varying and may be controllable or subject to limits (e.g., temperature, pressure, time).

Coordinate with the structural review under Chapter 4, "Structural Evaluation," of this SRP to ensure that the temperatures and pressures for all other SSCs important to safety, presented in the SAR, correspond to the same temperatures and pressures given in the thermal loads analysis in Chapter 4.

5.5.1.2 *Dry Storage Systems* ***(SL)***

Verify that the technical specifications include limiting conditions for operation and surveillance requirements to ensure that the temperature will remain within acceptable limits during dry storage and that normal cooling will begin before the temperature criterion is exceeded if the fuel cladding temperature calculation is based on heatup over a limited time period.

5.5.1.3 *Dry Transfer Systems* ***(SL)***

If the fuel cladding temperature calculation is based on heatup over a limited time period, verify that the technical specifications impose limiting conditions for the operation and surveillance requirements that ensure that the temperature will remain within acceptable limits during the process and that normal cooling will begin before the temperature criterion is exceeded.

5.5.2 Material and Design Limits

5.5.2.1 *General Considerations*

One aspect of the thermal evaluation is the confirmation that the fuel cladding temperature will prevent cladding damage or potential failure during storage. Ensure that the application complies with the criteria for cladding integrity (see Section 5.4.2 of this SRP) or provides adequate justification for any deviation from these criteria.

Ensure that the application reflects one of the following criteria: (1) the maximum calculated temperatures for normal conditions of storage and for fuel loading operations do not exceed 400 °C (752 °F), or (2) for low burnup fuel, the maximum calculated temperatures for normal conditions of storage and fuel loading operations do not exceed 570 °C (1,058 °F) and that the materials reviewer has verified that the best estimate cladding hoop stress is less than 90 MPa (13.1 ksi) for the maximum allowable temperature the applicant specified.

If the applicant uses the second approach, confirm that the materials reviewer has verified that the cladding hoop stresses are less than 90 MPa (13.1 ksi) for each fuel assembly type (e.g., 14 x 14, 17 x 17, 9 x 9) proposed for storage. Confirm that the materials reviewer evaluated cladding oxide thickness used to compute hoop stress. Because the hoop stress is dependent on the rod internal pressure, cladding geometry, and the temperature of the gases inside the rod, coordinate with the materials reviewer to verify that the applicant calculated the best estimate hoop stress corresponding to the rod internal pressure of the highest burnup fuel assemblies of the specific type of assembly.

To limit the amount of SNF that could be released from the cladding under off-normal or accident conditions, ensure that the application reflects the maximum calculated cladding temperatures is maintained below 570 °C (1,058 °F). Verify that the application clearly identifies the temperature restrictions (upper and lower allowable limits) on all components important to safety (e.g., confinement, shielding, subcriticality, heat removal) during normal, loading, off-normal, and accident scenarios and that the predicted thermal behavior of the entire DSS or DSF is indeed within the specified allowable limits. Confirm with the materials reviewer the acceptability of all proposed temperature limits.

Ensure that the maximum internal pressure of the fuel container remain within its design limits for normal, off-normal, and accident conditions assuming rupture of 1 percent, 10 percent, and 100 percent of the fuel rods, respectively. Confirm with the structural reviewer the acceptability of the proposed design pressure limits.

Ensure that any operating scenario (loading or unloading) that results in a time-dependent limiting condition (e.g., number of hours allowed for vacuum drying before fuel cladding temperature reaches its allowable limit) is also addressed in Chapter 17, “Technical Specifications Evaluation,” of this SRP and is included as a limiting condition for operation (e.g., technical specifications) in the CoC or specific license, as appropriate.

Consider the issue of storage container heatup during loading operations. If there is a loading issue, the storage container has to reach equilibrium again before reattempting loading to ensure that temperatures are not exceeded. For example, applicants may change a fill gas (i.e., helium to nitrogen) for vacuum drying. Vacuum drying may take multiple cycles, and the temperatures of the contents may therefore not fall below the contents’ initial temperature, leading to higher temperatures during subsequent cycles occurring at an earlier time during the vacuum drying process. Confirm that the applicant has provided adequate analysis and assumptions (i.e., adequate initial and boundary conditions) for subsequent drying cycles to cover loading-issue scenarios.

NRC Information Notice 2011-10, “Thermal Issues Identified During Loading of Spent Fuel Storage Casks,” dated May 2, 2011, and its supplement, Information Notice 2014-08, “Need for Continuous Monitoring of Active Systems in Loaded Spent Fuel Storage Canisters (Including Vacuum Drying Process),” dated May 16, 2014, also contain relevant information.

5.5.2.2 *Considerations for Specific Licenses* ***(SL)***

Verify that the SAR identifies and justifies temperature restrictions on other SSCs important to safety, including materials that are integral to confinement (e.g., storage container mechanical seals), shielding, and subcriticality functions. Verify that the applicant included the temperature limit criteria and the basis for the limits selected.

Considerations for determining temperature limits for the material of construction and the stored radioactive material can include the following, but are not limited to:

- the temperature at which the structural strength of the material is affected and the time-temperature relation required to cause the effect
- the retrievability of the radioactive material
- the temperature at which chemical or galvanic reactions that affect shielding, subcriticality assurance, or structural integrity may take place (at a significant rate)
- the temperature at which the black body characteristics of the material used for modeling may be affected
- the allowance to provide for uncertainties in the temperatures that may occur
- the temperatures that may be reached in normal, off-normal, and accident conditions and events
- the potential combinations of temperature and environment (such as may produce significant reaction with borated water)
- the outgassing of materials that produce significant amounts of either radioactive or nonradioactive gases
- the state changes of materials

Information on thermal properties may be needed for materials that are analyzed for loads on SSCs. Confirm that the source of data on thermal properties is an acceptable reference, such as the appendices to the ASME Boiler and Pressure Vessel Code, Section II, “Material,” and Section III, “Rules for Construction of Nuclear Facility Components.” Applicants may need to use other sources for nonstandard (or vendor-specific) materials such as neutron absorbers and storage container seals. Coordinate with the materials reviewer to verify the acceptability of these materials.

5.5.3 Thermal Loads and Environmental Conditions

5.5.3.1 *General Considerations*

Review the specification for the design-basis fuel decay heat presented in the chapter of the SAR on principal design criteria and coordinate with the shielding reviewer to ensure that this decay heat is consistent with the specified fuel types, burnups, enrichments, and cooling times, if included. However, some applications may provide a bounding decay heat load (kilowatt per assembly) without specifying details about the SNF (e.g., design, enrichment, cooling time). In these cases, ensure that the SER clearly specifies that the decay heat values are evaluated on the basis that NRC inspectors will verify compliance with the CoC. This verification includes reviewing the approach to determine the per-assembly decay heat and any uncertainties associated with the approach. If necessary, inspectors will coordinate with technical reviewers to determine adequacy of site-specific decay heat values and method of evaluation.

Verify that the applicant also discusses the axial distribution for the decay heat sources, with clear justification for a bounding approach. Expect a somewhat flat-at-the center axial distribution with a peak-to-average value in the range of 1.1 to 1.2, tapering to lower values toward both ends.

In general, the NRC staff accepts insolation values presented in 10 CFR Part 71, "Packaging and Transportation of Radioactive Material," for 10 CFR Part 72 applications. Because of the large thermal inertia of a DSS, the insolation values listed in 10 CFR 71.71, "Normal conditions of transport," may be averaged over a 24-hour day assuming steady-state conditions. Verify that insolation values specified in the thermal model are consistent with the values listed in 10 CFR 71.71. Ensure that any deviation from these values is fully justified. Confirm that the insolation values specified in the thermal model are consistent with the types of surfaces listed in 10 CFR 71.71. Verify that the applicant performed a heat balance and that the result is consistent with all heat sources specified in the thermal model.

Verify that the ambient temperatures used for normal, off-normal, and accident condition evaluations do indeed bound the available historical temperature data for any suggested storage site (current or future). Refer to the National Oceanic Atmospheric Administration National Climatic Data Center for temperature statistics for many American cities and regions (http://www.ncdc.noaa.gov/oa/ncdc.html). Further guidance to review the thermal impact of environmental conditions (e.g., ambient temperature, wind, elevation) on DSS is provided in NUREG-2174.

Ensure the loading and unloading evaluations are based on the SNF pool's technical specifications maximum temperature limit (typically 46 °C (115 °F)).

5.5.3.2 *Considerations for Specific Licenses* ***(SL)***

Determine whether the applicant has demonstrated that reactor-related GTCC waste containers, co-located with SNF storage containers at an ISFSI or MRS, or co-located with HLW containers at an MRS, are located such that normal, off-normal, and design-basis accident conditions will not adversely impact the heat removal capability of the SNF storage containers. In general, the thermal design of reactor-related GTCC waste containers is very similar to that of SNF canisters. However, because SNF decay heat is higher than reactor-related GTCC waste, SNF canisters bound GTCC containers.

5.5.4 Analytical Methods, Models, and Calculations

For storage container system components in which material properties and performance vary with temperature, review the modeling assumptions used in determining temperature maxima, minima, gradients, and differences for the storage container system. 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. Compare the calculated temperatures in the various storage container system components to the limiting temperature criteria for the appropriate materials. Ferritic materials are subject to failure by brittle fracture at low temperatures. Verify the assumed low temperatures for storage container system handling operations for consistency with material properties. Ambient temperature restrictions may be appropriate for storage container handling operations. Ensure that any limiting conditions regarding ambient temperatures are addressed in the chapters of the SAR and SER on technical specifications and operating controls and limits. The CoC or site license should include ambient temperatures as a limiting condition for operation (e.g., technical specifications), as appropriate.

Analysis for accident conditions temperatures should not be considered to envelop the analysis of normal or off-normal temperatures. The acceptance criteria for normal and off-normal temperature demands for structural capacity will differ. Therefore, ensure that the application includes an analysis for normal, off-normal, and accident conditions. In addition, ensure the applicant evaluated the duration over which accident temperature conditions may exist.

5.5.4.1 *Configuration*

Verify that the applicant clearly described any model used in the thermal evaluation. Separate models and submodels may be used for the evaluation of different conditions (normal storage, loading, off-normal situations, and accidents). Verify that the applicant provided adequate justification when using separate models and submodels to evaluate different conditions (for example, a simplified model may be used to evaluate fire accident conditions; in which case, verify that the application provides adequate justification and shows that the results are conservative). Coordinate with the structural review as necessary to evaluate any damage that may result from accidents or natural phenomena events. All models should be shown as conservative (i.e., thermal results should include adequate margin against allowable limits).

Review the sketches or figures of all models to ensure their proper use in the thermal calculations and verify that the dimensions and materials are consistent with those in the drawings of the actual storage container, as presented in the chapter of the SAR on general information. If possible, review the computer input files to verify consistency with the model sketches and engineering drawings. The application should identify any differences between the actual storage container configuration and the model, and the model should be shown to be conservative.

Pay particular attention to gaps between storage container components. Consider tolerances so that the thermal resistance of each gap is treated conservatively. Confirm that the application describes and justifies gases (e.g., air, helium) assumed to be present in the gap. If a specific gas other than air in the cavity of the storage container or gaps between storage container components is relied upon for heat removal, verify that the applicant shows that the gas is retained and that the gas is not diluted by other gases with lower thermal conductivity during the entire storage period. For storage container components that are important to heat removal, ensure that the application adequately describes and justifies manufacturing techniques for joining components, surface roughness, contact pressures, and gap conductance values. For example, poured lead may shrink when cooled or gaps may exist if lead shielding is pounded in place as part of manufacturing.

Verify that decay heat generated in the SNF is limited to the active fuel region of the assemblies. Ensure that the decay heat model specifically accounts for peaking in the central region or provides another conservative approach. Ensure also that the heat from any other stored component (e.g., control rods), if applicable, is distributed appropriately. In addition, ensure that the position of heat sources relative to other storage container components is identified.

Confirm that the application addresses the thermal interaction among storage containers in an array by calculating the appropriate view factor. Generally, this will result in an operating control and limit in the SAR chapter on technical specifications and operating controls and limits that impose a minimum spacing between storage containers.

Coordinate with the structural reviewer to ensure that the applicant has analyzed situations that may produce the worst-case storage container loads. The greatest gradients and loadings caused by thermal expansion may occur with storage containers in alternative storage or in temporary handling positions.

Review the heat transfer processes used in the analysis. Conduction and radiation are typically defined as the primary heat transfer mechanisms within the storage container itself. In narrow regions of any orientation, little or no convective heat transfer will occur, and only conduction through the gas-filled void spaces is assumed. Larger gas volume regions can experience a significant level of convective heat transfer. Therefore, verify that the applicant has demonstrated the existence of convection in the larger gas regions and has quantified the contribution of convection heat transfer to the overall removal of heat from the package. Ensure that natural convection in enclosed cavities was validated through applicable CFD calculations or physical experiments.

5.5.4.1.1 General Guidance on CFD Analyses

Because the computational resources necessary to fully resolve flow between individual fuel pins in a storage container model with numerous fuel assemblies would be enormous, one acceptable approach would be to treat fuel assemblies as a porous media for applications seeking to credit heat removal from fuel via internal convection. Verify that any CFD approach uses realistic or bounding flow friction factors in the porous media representation of the fuel, and that friction factors are obtained for each of the limiting fuel assembly types sought as approved contents for the storage container.

An acceptable approach to calculate the friction factors would be to perform a CFD analysis for each type of fuel assembly for the expected operating conditions (pressure and average gas temperature). Verify that the application reflects that wall shear stresses were obtained separately for bare fuel rods and for fuel rods and associated grid straps. Confirm that the applicant calculated the friction factor based on the wall shear stress method. Additional details to obtain flow friction factors are provided in NUREG-2208, “Validation of Computational Fluid Dynamics Methods Using Prototypic Light Water Reactor Spent Fuel Assembly Thermal-Hydraulic Data,” issued March 2017 (ADAMS Accession No. ML17062A567).

Evaluate the method used to obtain the friction factors and ensure that the obtained values are realistic or bounding for the intended fuel assembly types. Also, since the friction factor is generally very sensitive to the geometric information (dimensions) and fuel assembly configuration, verify this information by reviewing the fuel assembly design drawings provided by the applicant.

For ventilated SNF storage systems (a canister containing the fuel within an outer overpack fitted with air vents), the mesh spacing (computational cell size) and density between an overpack liner and canister outer shell wall play an important role when selecting a turbulence model for the air flow through this annular gap, as described below.

The near-wall modeling significantly impacts the fidelity of numerical solutions, inasmuch as walls are the main source of flow mean vorticity and turbulence. After all, it is in the near-wall region that the solution variables have large gradients, and the transport of momentum and other scalar variables occurs more vigorously. Therefore, accurate representation of the flow in the near-wall region determines a successful prediction of wall-bounded turbulent flows. When dealing with wall effects on the flow, usually two modeling options are available to the analyst. The first one is the use of the semi-empirical formulas called “standard wall functions,” which are used to bridge the viscosity-affected region between the wall and the fully turbulent core region. Generally, a uniform mesh would be used when these wall functions are invoked. The use of wall functions obviates the need to modify the turbulence models to account for the presence of the wall. This modeling approach is usually applicable to flows with high Reynolds numbers. In the second approach, the viscosity-affected region is resolved with a mesh all the way to the wall, including the viscous sublayer. This type of approach is referred to as "near wall modeling." The dimensionless distance between the wall and the cell center near the wall (y+) for the mesh used for this case should generally be around 1. The documentation for the CFD program used in the application should provide guidance on how to apply any of these modeling approaches. Verify that the application fully justifies and validates any modeling approach taken.

To properly characterize the flow (e.g., internal, external, annular), Reynolds number estimates should be made using velocities from initial runs for the cooling air in the annulus and helium fill inside the canister. Reynolds numbers above 3000 based on the channel hydraulic diameter are above the critical Reynolds number of 2300 for internal flows, characterizing the flow in the transitional range between the laminar and turbulent zones. Because these are buoyancy-driven flows, both the Grashof (Gr) number, based on the hydraulic diameter of the channel, and the modified Grashof number, defined as Graetz number (Gz = Gr * W/H), where W and H are the width and height of the air channel, respectively, should also be calculated to properly characterize the annular flow. On the other hand, buoyancy-driven helium flow, cooling the inside of the canister, generally would be laminar based on both the Grashof and the Reynolds numbers because of higher kinematic viscosities and low achieved velocities within the canister. Confirm that the application provides solution verification results by calculating the GCI. Guidance to calculate the GCI is provided in NUREG-2152 and ASME's "Standard for Verification and Validation in Computational Fluid Dynamics and Heat Transfer" (ASME V&V 20).

Verify that the GCI calculation follows the assumptions used to develop the GCI method, as described in NUREG-2152 and ASME V&V 20. These are summarized below:

- Grid refinement or coarsening is performed systematically in all directions; that is, the refinement or coarsening should be structured even if the grid is unstructured.

- The observed order of accuracy should not vary greatly from the theoretical order of accuracy (i.e., the order of accuracy of the numerical method used in the analysis).

- A minimum of four grids is required to demonstrate that the observed order of accuracy is constant for a simulation series.

- A three-grid solution for the observed order of accuracy may be adequate if the values of the target variable (for example, peak cladding temperature, total heat transfer rate, or mass flow rate) predicted on the three grids are in the asymptotic region for the simulation series.

- Methods to test for asymptotic behavior of the target variable predicted values are provided in ASME V&V 20.

- The factor of safety (F_s) value is 1.25 if the target values on the three grids are in the asymptotic region and the observed order of accuracy does not vary greatly from the theoretical order of accuracy. Otherwise an F_s of 3.0 is used.

- The GCI is calculated using the observed order of accuracy if it is smaller than the theoretical value. Otherwise the theoretical order of accuracy is used.

Confirm that the application also addresses actual SNF properties and uncertainties (e.g., friction factors, crud and oxide buildup, eccentricities, nonuniform axial and radial decay heat profiles). Verify that the applicant avoided using an effective thermal conductivity for the cover gas (e.g., helium) in lieu of a specific convection model.

If applicable, confirm that the application includes an evaluation of the added heat from components stored with the SNF assemblies (e.g., control rods, fuel channels). This would ultimately affect the maximum predicted cladding temperature.

NUREG-2152 provides further guidance for the review of CFD applications. NUREG-2152 also provides additional guidance to perform CFD confirmatory analysis for dry storage container thermal evaluations.

5.5.4.1.2 General Guidance on Application of Effective Conductivity Models

In addition to a CFD method using porous media model, fuel assemblies may be modeled as a homogenous region using an effective thermal conductivity model. Review the manner in which effective conductivity is determined for each fuel assembly (see Section 5.5.4.2 below).

Use of effective thermal conductivity coefficients for regions within the confinement storage container 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, CFD submodels, or other appropriate sources 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 within thermal fins. Voids or gaps typically exist as a result of either tolerances or shrinkage and should be considered in calculating effective thermal conductivity. Also, confirm that the applicant paid 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.

5.5.4.2 *Material Properties*

Coordinate with the materials reviewer to verify that the material specifications and thermal properties are provided for all components used in the analytic model, the thermal properties used in the safety analysis are appropriate, and potential degradation of materials over their service life has been evaluated. Confirm that the applicant considered temperature and anisotropic dependencies of thermal properties. If regional thermal properties are determined from a combination of individual materials, ensure the manner in which these effective properties are calculated is fully described and justified.

If the thermal model is axisymmetric or three dimensional, check that the longitudinal thermal conductivity is generally 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. Verify that the applicant considered high-burnup effects in determining the fuel region effective thermal conductivity.

5.5.4.3 *Boundary Conditions*

Verify that the applicant identified boundary conditions for normal, loading, off-normal, and accident conditions. The required boundary conditions include the total decay heat from each fuel assembly and the external conditions on the storage container surface. Ensure that the peak power factor for a fuel assembly is specified and the peak linear power ("peaking factor") of a fuel assembly is stated for a given active fuel length.

The boundary conditions on the storage container surface depend on the environment surrounding the storage container. Consequently, confirm that the application specifies the temperature of the environment for all simulated conditions, as well as the incident and absorbed insolation. Verify that the application identifies and describes the mechanisms and models for dissipating the absorbed insolation and decay heat from the surface of the storage container to the environment. The mechanisms for transferring heat from the storage container surface usually consist of natural (free) convection and thermal radiation. Confirm that the SAR presents the results of a heat balance on the surface of the storage container.

Ensure that the application establishes the initial temperature distribution of the storage container system before a fire accident based on the hottest temperature distribution during normal or off-normal storage conditions. Confirm that the application specifies the duration and flame temperature of the fire, as well as gas velocities and flame emissivity. The NRC considers the flame and storage container surface emissivities specified in 10 CFR 71.73(c)(4) for a hypothetical accident test of transportation packages as satisfactory for use with regard to a fire accident involving a storage container.

Confirm that the application identifies and describes the mechanisms and models for coupling the fire energy to the storage container surface. These mechanisms include forced convection in relation to the flame velocity (5 to 15 meters per second (16 to 49 feet per second)) as well as thermal radiation. In addition, confirm that the application justifies the convection coefficients during the fire. Verify that the application also considers the orientation of the storage container.

Following the fire, the storage container is subject to insolation and content decay heat while cooling by natural convection and thermal radiation to the environment. Confirm that the application identifies the postfire conditions of the storage container, including any changes in surface conditions or geometry (or both) that may affect radiation and convection heat losses. Confirm that the application also identifies and describes the models used for the analysis of the postfire processes.

5.5.4.4 *Computer Codes*

Verify that the applicant has provided information on any computer-based modeling as described in Appendix 4A to Chapter 4 of this SRP, and review the thermal analysis submitted by the applicant in accordance with the appendix.

5.5.4.5 *Temperature Calculations*

Confirm that the application includes a table that lists the maximum and minimum temperatures of all components important to safety under normal, loading, 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. Ensure that the application provides justification 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, the SAR should quantify and include such a heat load as an operating control and a technical specifications criterion.

Pay particular attention to the maximum temperature of the cladding, discussed in Sections 5.4.2 and 5.5.2, “Material and Design Limits,” of this chapter.

Some storage systems rely upon natural circulation of air through internal passages to remove heat from the stored confinement canister. For storage systems with internal air flow passages, blockage of inlet flow or outlet flow (or both) 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 types 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 heat up to the established accident temperature criteria, assuming a total blockage of all inlets and outlets. Verify that the technical specifications include limiting conditions for operation and surveillance requirements to ensure that the temperature will remain within acceptable limits during dry storage and that normal cooling will begin before the temperature criterion is exceeded.

Confirm that the adiabatic heatup calculations specifically 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. Ensure that the SAR includes the resulting heatup time history, which should support the proposed inspection and monitoring intervals. This information is also useful in developing contingency operation procedures because it indicates the available time in which to take corrective actions before the fuel accident temperature criteria may be exceeded. Verify that the technical specifications include limiting conditions for operation and surveillance requirements to ensure that the temperature will remain within acceptable limits during dry storage and that normal cooling will begin before the temperature criterion is exceeded.

Some storage systems may use a transfer cask to move the loaded confinement canister from the fuel-handling building to the DSF site. When the canister is within the transfer cask, the rate of cooling is typically less than for normal operation. Therefore, fuel cladding temperatures are expected to be higher than for normal storage conditions.

Review the temperature distribution calculations for the canister inside the transfer cask and 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. Storage container preparation for storage or unloading operations may include situations in which the canister is evacuated while it is in the transfer cask. If the fuel cladding temperature calculation is based on heatup over a limited time period for storage container drying operations, verify that the technical specifications impose limiting conditions for the operations. 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.

During wet-fuel transfer operations, the liquid in the fuel canister should not be permitted to boil. This practice avoids uncontrolled pressures on the canister and the connected dewatering, purging, and recharging system(s); unacceptable discharge of liquids that may be providing radiation shielding; and a potentially unacceptable reduction in the safety margin. Ensure that, to prevent any of the above conditions, both the SAR and corresponding operating procedures identify an adequate subcooling margin to prevent boiling. This margin may be storage container specific, depending on the design of the fuel basket and key assumptions used in the criticality analysis. Ensure that the applicant performs the heatup and time-to-boil calculations and assesses whether any technical specifications or limiting conditions for operation are needed. Heatup calculations should be established on the basis of the SNF pool's technical specifications maximum temperature limit (typically 46 °C (115 °F)).

For unloading operations, ensure that the applicant evaluates temperature and pressure calculations supporting procedural steps presented in the SAR chapter on operating procedures for storage container cooldown and reflooding of the storage container internals. To ensure that the storage container does not overpressurize and that the fuel assemblies are not subjected to excess thermal stresses, confirm that the applicant's analysis specifies and justifies the appropriate temperature and flow rate of the quench fluid, assuming maximum fuel cladding temperatures in the unloading configuration. Verify that the chapter of the SAR on accident analyses also indicates that this analysis was considered in the development of thermal models for the unloading procedures, and that the technical specifications include it, as appropriate. Provide thermal profiles to the materials reviewer so that the latter can determine if the applicant has adequately addressed the issue of fuel rod response to a reflood incident as described in Chapter 8, "Materials Evaluation," of this SRP.

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 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 any design-basis event. Typically, fire has been the worst-case accident thermal condition for storage systems without internal air flow passages.

The burning of fuel and other combustibles associated with vehicles involved in transfer operations should, at a minimum, be presumed to be a design-basis event, with the storage container in the most exposed situation during transfer or loading into storage. The NRC staff has accepted fire parameters included in 10 CFR 71.73, "Hypothetical Accident Conditions," for characterizing the heat transfer during the in-storage fire. However, the staff has also accepted a bounding analysis that limits the fuel source and thus limits the duration of the fire (e.g., by limiting the source to the fuel in the transporter).

Some SSCs may experience the most severe conditions if exposure to high temperatures is followed by dousing with water (such as rain or fire-suppression activities). 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, "Controlled area of an ISFSI or MRS," and need not be estimated or evaluated in the SAR. The NRC accepts that concrete temperatures may exceed the temperature criteria of American Concrete Institute 349, "Code Requirements for

Nuclear Safety-Related Concrete Structures and Commentary," 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. 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 storage container and its contents. Storage container system components (e.g., the neutron shield) may be assumed to be intact at the start of the fire.

If a storage container tipover is a credible accident, verify that the applicant has evaluated the effect on storage container 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 storage container may have a significant effect.

5.5.4.6 *Pressure Analysis*

Pressure calculations should be performed using the ideal gas law (i.e., PV = nRT, where P is pressure, V is volume, n is the number of moles of a gas, R is the ideal gas constant, and T is the absolute temperature) and summing the partial pressures of each of the gas constituents in the storage container cavity. Confirm that the application identifies the method and all assumptions used in the pressure analysis, including the determination of the fission gas inventory.

It is necessary to consider the temperature distribution of all components within the storage container cavity and the cavity walls in calculating the gas pressure in the cavity. For the fire accident analysis, confirm that the application identifies the maximum gas temperature reached during the postfire accident phase, explains the method used to determine the average gas temperature, and specifies the time in the accident at which the peak gas temperature is attained.

This pressure also depends on the free volume in the storage container cavity, the amount (moles) of cover gas (helium) in the cavity, and the amount of gases released from ruptured fuel pins. Review the free volume calculation to determine if all components internal to the storage container cavity (e.g., fuel assemblies, basket, structural supports, spacer disks, reactor control components) have been properly considered.

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 percent of the fuel rods will have ruptured following a design-basis 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., tritium, krypton, and xenon) within a ruptured fuel rod is available for release into the storage container cavity.

Under the conditions where any of the storage container component temperatures are close (within 5 percent) to their limiting values during an accident, or the maximum normal operating pressure is within 10 percent of its design-basis pressure, or any other special conditions, ensure that the applicant considers, by analysis, the potential impact of the fission gas in the canister (from the effect of its thermal conductivity) on the storage container component temperature limits and the storage container internal pressurization.

Coordinate with the structural reviewer to verify that the confinement pressure of the storage container is within its design limits for normal, off-normal, and accident conditions.

5.5.4.7 *Confirmatory Analysis*

Reviewers may need to perform a confirmatory analysis of the thermal performance of the storage container SSCs identified as important to safety. Confirmatory analyses are recommended if margins between the calculated temperatures and prescribed component temperature limits are small, the applicant has submitted particularly complex thermal analyses, or the applicant is submitting a new thermal methodology or analysis approach.

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 SSCs, and storage container cavity pressures for the bounding ambient temperatures.

To provide the most reliable confirmation, confirmatory analysis should, to the degree possible, use a different thermal analysis method than that used by the applicant. The code used for the confirmatory analysis may be the same as or different from that used by the applicant. Regardless, a review of the applicant's analytical approach and analysis models should be considered part of the overall confirmatory analysis. If necessary, include a confirmatory analysis of accident temperatures (e.g., during a fire), as applicable to the SAR analysis.

If a full confirmatory analysis is not deemed necessary, perform a minimum confirmatory review to verify that the applicant appropriately determined key design parameters and correctly expressed them 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. Perform a heat balance at the outer surface of the storage container to verify that the heat from the SNF and insolation balance that removed by convection and radiation. Then assess correlations for the heat transfer coefficient to confirm that they are appropriate for the existing storage conditions. The temperature of the storage container's inner surface should be estimated by calculating the temperature distribution across the storage container body with simple heat balance approximations. Finally, compare the difference between the storage container's inner surface temperature and the maximum cladding temperature with that of similar storage containers and baskets reviewed in previous SARs.

As discussed above, a more detailed confirmatory analysis may be required and could include a model of a portion of the storage container or basket to ensure that the SAR results are realistic and conservative. A more extensive confirmatory analysis may involve the full geometry of the storage container, with relevant component details, to determine temperature distributions in the storage container system.

Appendix 4A to Chapter 4 of this SRP provides additional guidance on reviewing analytical models and conducting confirmatory analyses. NUREG-2152 also provides practical advice for reviewing CFD and heat transfer methods used in vendor applications and for achieving high-quality simulations (confirmatory analysis) of a storage container. To assist in the confirmatory analysis, the report includes procedures, analysis methods, and acceptable assumptions.

As an alternative to a confirmatory analysis, the applicant may be required to perform design-verification testing of an as-built storage container or properly scaled mockup system (when applicable) 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 the SAR chapter on acceptance criteria and maintenance. Design-verification testing results should be provided in the SAR for storage container certification.

5.5.5 Surveillance Requirements

Active supplemental cooling is permitted in the cases where a limiting condition for operation is not met and an action statement of active supplemental cooling is required in the technical specification surveillance requirements. Verify that the SAR includes technical specifications relating to heat-removal capability. The applicant may have proposed these in compliance with 10 CFR 72.26, "Contents of application: Technical specifications," or they may result from the review and evaluation of submittals relating to those areas. The following is an example of a technical specification related to thermal evaluations that the NRC staff has accepted in previous applications:

> Surveillance requirement: Periodic surveillance will be performed to ensure that there is no blockage of cooling air flow in the heat removal system. This surveillance [typically based on the minimum time for stored material cladding or other material important to safety (e.g., shielding) to reach a threshold temperature in the event of a complete blockage occurring immediately following the prior surveillance and the minimum time to repair or correct the blockage condition] shall be no less frequent than _______ [insert time interval].

Other areas that are often included as part of the technical specifications include, but are not limited to, blockage of inlet ducts, burial under debris, jacket water loss, moisture removal operation (e.g., vacuum drying), multipurpose canister in a transfer cask, fuel-loading operation, fuel-unloading operation, and other short-term operations.

5.6 Evaluation Findings

The NRC reviewer should prepare evaluation findings on satisfaction of the regulatory requirements in Section 5.4 of this SRP. If the documentation submitted with the application fully supports positive findings for each of the regulatory requirements, the statements of findings should be similar to the following:

Certificate of Compliance (**CoC**)

F5.1 SSCs important to safety are described in sufficient detail in the SAR to enable an evaluation of their thermal effectiveness in accordance with 10 CFR 72.236(f) and 10 CFR 72.236(h). Storage container SSCs important to safety remain within their operating temperature ranges in accordance with 10 CFR 72.236(a) and 10 CFR 72.236(b).

F5.2 The [storage container designation] is designed with a heat-removal capability, verifiably and reliably consistent with its importance to safety. The storage container is designed to provide adequate heat removal capacity without active cooling systems in accordance with 10 CFR 72.236(f).

F5.3 The SNF cladding is protected against degradation leading to gross ruptures under normal conditions by maintaining the cladding temperature for [X] years below [X] °C ([X] °F) in an [applicable gas] environment. Protection of the cladding against degradation is expected to allow ready retrieval of the SNF for further processing or disposal in accordance with 10 CFR 72.236(g), 10 CFR 72.236(l), and 10 CFR 72.236(m).

F5.4 The SNF cladding is protected against degradation leading to gross ruptures under off-normal and accident conditions by maintaining the cladding temperature below [X] °C ([X] °F) 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 in accordance with 10 CFR 72.236(g), 10 CFR 72.236(l), and 10 CFR 72.236(m).

The reviewer should provide a summary statement similar to the following:

The staff concludes that the thermal design of the [storage container 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 [storage container designation] will allow safe storage of SNF for a licensed (certified) life of [X] years. This conclusion is reached on the basis of a review that considered the regulation itself, appropriate regulatory guides, applicable codes and standards, and accepted engineering practices.

Specific License (**SL**)

F5.5 SSCs important to safety are described in sufficient detail in the SAR to enable an evaluation of their heat removal effectiveness in accordance with 10 CFR 72.122(b), 10 CFR 72.122(f), 10 CFR 72.122(i), 10 CFR 72.122(j), 10 CFR 72.122(h) and 10 CFR 72.128(a)(4). Storage container structures, systems, and components important to safety remain within their operating temperature ranges in accordance with 10 CFR 72.92(a), 10 CFR 72.120(a), 10 CFR 120(d), and 10 CFR 72.128(a).

F5.6 [If applicable] The [dry storage system designation] is designed with a heat-removal capability, testable and reliably consistent with its importance to safety in accordance with 10 CFR 72.26, 10 CFR 72.44(c), and 10 CFR 72.128(a)(4).

F5.7 [If applicable] The SNF cladding is protected against degradation leading to gross ruptures under normal conditions by maintaining the cladding temperature for [X] years below [X] °C ([X] °F) in an [applicable gas] environment. Protection of the cladding against degradation will allow ready retrieval of the SNF assembly for further processing or disposal in accordance with 10 CFR 72.122(h).

F5.8 The SNF cladding is protected against degradation leading to gross ruptures under off-normal and accident conditions by maintaining the cladding temperature below [X] °C ([X] °F) in an [applicable gas] environment. Protection of the cladding against degradation is expected to allow ready retrieval of the SNF for further processing or disposal in accordance with 10 CFR 72.122(h).

The staff concludes that the thermal design of [DSF designation] is in compliance with 10 CFR Part 72 and that the applicable design and acceptance criteria as identified in the SAR have been satisfied. The evaluation of the thermal design provides reasonable assurance that [DSF designation] will allow safe storage of SNF. This conclusion is reached on the basis of a review that considered 10 CFR Part 72, appropriate regulatory guides, applicable codes and standards, and accepted engineering practices.

5.7 References

10 CFR Part 71, "Packaging and Transportation of Radioactive Material."

10 CFR Part 72, "Licensing Requirements for the Independent Storage of Spent Nuclear Fuel, High-Level Radioactive Waste, and Reactor-Related Greater than Class C Waste."

American Concrete Institute 349, "Code Requirements for Nuclear Safety-Related Concrete Structures and Commentary."

American Society of Mechanical Engineers (ASME), "Standard for Verification and Validation in Computational Fluid Dynamics and Heat Transfer," (ASME V&V 20)

ASME, Boiler and Pressure Vessel (B&PV) Code, 2007 – Addenda 2008:
Section II, "Materials,"
Section III, "Rules for Construction of Nuclear Facility Components," Division 1, "Metallic Components."

NRC Information Notice 2011-10, "Thermal Issues Identified During Loading of Spent Fuel Storage Casks," May 2, 2011 (ADAMS Accession No. ML111090200).

NRC Information Notice 2014-08, "Need for Continuous Monitoring of Active Systems in Loaded Spent Fuel Storage Canisters (Including Vacuum Drying Process)," May 16, 2014 (ADAMS Accession No. ML14121A089).

Levy, I.S., B.A. Chin, E.P. Simonen, and A.B. Johnson, Jr., "Recommended Temperature Limits for Dry Storage of Spent Light Water Zircaloy-Clad Fuel Rods in Inert Gas," PNL-6189, Pacific (Northwest) National Laboratory, May 1987.

NUREG-2152, "Computational Fluid Dynamics Best Practice Guidelines for Dry Cask Applications: Final Report," March 2013 (ADAMS Accession No. ML13086A202).

NUREG-2174, "Impact of Variation in Environmental Conditions on the Thermal Performance of Dry Storage Cask, Final Report," March 2016 (ADAMS Accession No. ML16081A181).

NUREG-2208, "Validation of Computational Fluid Dynamics Methods Using Prototypic Light Water Reactor Spent Fuel Assembly Thermal-Hydraulic Data," March 2017 (ADAMS Accession No. ML17062A567).