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Developing an Analytical Framework for Cumulative Effects

Spent Fuel and Waste Disposition

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SUMMARY

The extended dry storage scenario for spent nuclear fuel (SNF) in the United States introduces the possibility of more than one transportation campaign to move the SNF from its point of origin to one or more interim storage facilities before it reaches its final destination. While the structural integrity of SNF and its storage and transportation systems are often evaluated under single event loading conditions, the reality is that a single SNF system will experience multiple structural loading events during its life cycle, the number and severity of which will depend on its individual circumstances. SNF systems will also be subjected to environmental exposure that will affect their temperature and the potential for cracks to develop in the SNF canister walls. Considered separately, many different events and scenarios might be strong enough to challenge the integrity of SNF cladding and the storage and transportation canisters that contain SNF. But considered together, over the full life cycle of an SNF system, there is the possibility that individual low-magnitude events could cause enough incremental damage to components of the SNF system to challenge its structural integrity if the time span is long enough or if the life cycle includes a sufficient number of loading events. The concern is that the cumulative effect of relatively small mechanical loads, thermal stresses, or cracking can add up to conditions that could compromise SNF or its containment structures. This report is a first step in establishing an analysis framework for evaluating these cumulative effects.

The cumulative effects of structural loads is the focus of this analysis. The phenomena being considered are structural failure, fatigue failure, and cracking failure. Structural failure is a key design and safety consideration, so failure of critical containment boundaries from a single event is not expected under normal conditions of operation, but the regulations do not require SNF and SNF assembly components to remain intact. Fatigue failure is important to evaluate because the time scale for its occurrence is uncertain. Cracking is an important phenomenon because chloride-induced stress corrosion cracking has been identified as a potential failure mode. The presence of unanticipated cracks can challenge the integrity of containment boundaries under design-basis conditions. Cracking evaluations are always a part of safety-basis analyses, but they are typically focused on weld defects that are introduced during fabrication. The cracks considered in this cumulative effects analysis could be fabrication defects or they could develop as a result of environmental exposure over a long time period in dry storage.

The initial scope of the SNF cumulative effects problem is proposed to consider time spans of 50, 100, 150, 200, 250, and 300 years, at up to five interim storage locations. These parameters define the SNF life cycle enough to enable initial analysis. The scope will be refined based on the initial analysis results. For example, 50 years might be too short of a time to consider or there might not be a significant difference between four and five interim storage locations. The goal in this first iteration is to explore the problem space and determine which variables are most important to cumulative effects. Note that the initial scope of the problem proposes 300 years of dry storage and 5 interim storage sites as the upper limits of the analysis. These values were chosen to bound the anticipated range of values and allow the calculation of long-term trends. This scope will be re-evaluated and updated after the first set of results are calculated.

One important feature of the cumulative effects analysis is that the distribution of stress, strain, and other important structural results is at least as important as the instantaneous peak values. Because we are considering the cumulative effects of multiple separate events the peak location might change with each event. It could be very conservative to assume that the peak value of all the contributing events happens to occur at the same location. Typical 3D models already have this information and the challenge is to keep track of results by location.

Another important feature of the cumulative effects analysis is the incorporation of experimental results into the structural analysis. The Spent Fuel and Waste Science and Technology (SFWST) program has been conducting experiments to measure mechanical loads in transportation, handling, and cask drop scenarios, and has been sponsoring material science research on SNF under the sibling pin test program.

The SFWST program is learning a lot about SNF systems and the normal operational loading environment. The cumulative effects analysis task will apply the information acquired from the SFWST experimental tasks to complete the analyses. For example, the sibling pin test program is determining the failure criteria for high burnup SNF cladding so the cumulative effects analysis should include this new information.

A conceptual sketch of the cumulative effects analysis framework is shown in Figure S.1. Single-scenario models are the typical kinds of finite element analysis or computational fluid dynamic models that are performed at Pacific Northwest National Laboratory (PNNL). The SNF life cycle includes many of these single events. For example, a life cycle might include two transportation legs, four handling events, and two strong earthquakes over a period of 150 years. If none of the events are strong enough to cause any lasting effects, then that is a significant finding. It is assumed that some amount of fatigue life consumption, crack propagation, permanent deformation, or other phenomena that affect structural analyses could occur during these life cycles, so the single-scenario models might need to be updated as the system changes (accumulates damage) over time. PNNL will complete examples of this life cycle evaluation in future years per programmatic priorities and as funding allows.

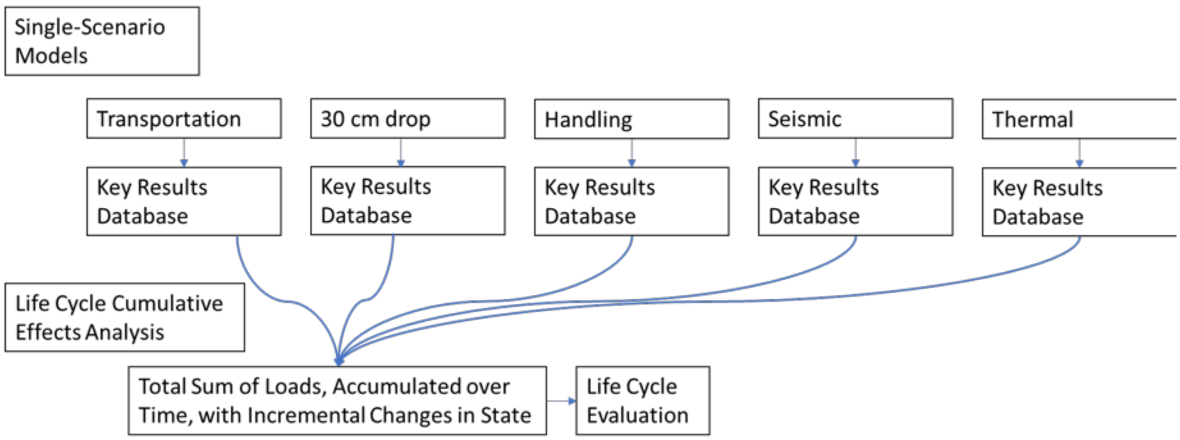

Figure S.1. Conceptual sketch of the cumulative effects analysis framework.

During fiscal year 2020, PNNL completed initial thermal stress analysis that suggests that thermal stress in a canister could be a significant fraction of the total canister wall stress state. This is important for crack propagation during dry storage and is potentially a source of material fatigue during seasonal changes in ambient temperature. PNNL also considered the modeling need to predict the growth of cracks during transient dynamic events and plans to pursue thermal stress analysis and crack propagation model development in future work.

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ACRONYMS

AAR	Association of American Railroads
ASME	American Society of Mechanical Engineers
CIRFT	Cyclic Integrated Reversible-Bending Fatigue Tester
CISCC	chloride-induced stress corrosion cracking
DOE	US Department of Energy
EI	effective bending rigidity
ISFSI	independent spent fuel storage installation
LC	long crack
MMTT	multimodal transportation test
MPC	multipurpose canister
NCT	normal conditions of transportation
NRC	US Nuclear Regulatory Commission
ORNL	Oak Ridge National Laboratory
PNNL	Pacific Northwest National Laboratory
R&D	research and development
SFWST	Spent Fuel and Waste Science and Technology
S-N	stress (S) – number of cycles (N)
SNF	spent nuclear fuel
SNL	Sandia National Laboratories
TSC	transportable storage canister

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DEVELOPING AN ANALYTICAL FRAMEWORK FOR CUMULATIVE EFFECTS

1 INTRODUCTION

The US Department of Energy (DOE) Spent Fuel and Waste Science and Technology (SFWST) program has made great progress in closing knowledge gaps related to spent nuclear fuel (SNF) transportation and extended dry storage. Mechanical loads recorded in transportation tests such as the ENSA/DOE multimodal transportation test (MMTT) are so small that a single application of the structural dynamic loads would not challenge the strength of the SNF cladding (Klymyshyn et al. 2018). But some concern remains about the cumulative effects of small loads and deterioration of the canister or cask systems caused by interaction with the environment over a potentially long time scale. A framework for analyzing these cumulative effects of storage and transportation is needed to resolve the final knowledge gaps the SFWST program is working to close. An analysis is needed to demonstrate that the cumulative effects of multiple phenomena do not combine to cause a structural integrity problem when a single phenomenon, considered separately from the others, looks safe or negligible. Pacific Northwest National Laboratory (PNNL) has had a strong modeling and analysis role in the SFWST program in this area, and the cumulative effects analysis is a natural fit for PNNL's expertise and experience. This report describes the progress made by PNNL in fiscal year 2020 to establish an analytical framework for evaluating cumulative effects on SNF and its storage and transportation systems during a service life that includes multiple phases of storage and transportation. The main progress made thus far is to propose a preliminary analysis framework and identify key areas for which numerical models need to be developed.

PNNL has performed many structural and structural dynamic analyses for the SFWST program in the area of SNF dry storage and transportation. Some of the notable modeling work was called "structural sensitivity" and later "structural uncertainty." Klymyshyn et al. 2013 investigated modeling cask tip over scenarios, canister handling drops, and dry storage seismic load cases using surrogate masses for all fuel assemblies. A generic vertical dry SNF storage canister system was evaluated to quantify the potential loads on the canister. Klymyshyn et al. 2014 added a detailed fuel assembly to the generic canister system to calculate the detailed structural dynamic response of the fuel assembly components. Klymyshyn et al. 2015 evaluated beam finite element modeling options for fuel rods in full fuel assembly models and began considering stress corrosion cracking in canister weld locations. Klymyshyn et al. 2016 evaluated bench-scale fuel cladding dynamic loads, considered canister failure conditions including elastic-plastic fracture mechanics, and summarized fuel cladding strain estimates from PNNL finite element modeling studies of transportation scenarios conducted in the 2012 to 2016 time period. The cumulative effects analysis is the next logical step to continue this work related to dry storage.

In addition, the cumulative effects analysis needs to include the transportation loads. The PNNL transportation modeling from 2012 to 2018 was summarized in Klymyshyn et al. 2018, which was primarily about the modeling and analysis of the MMTT. The following report, Klymyshyn et al. 2019, evaluated railroad SNF transportation loads anticipated from cross-country transportation using a purpose-built Atlas railcar design (AREVA 2018) and determined that the MMTT data was bounding for realistic SNF rail transportation conditions. Klymyshyn et al. 2020 modeled the 30 cm cask drop scenario and validated the model with test data reported in Kalinina et al. 2019 and Kalinina et al. 2020.

This cumulative effects analysis effort is bringing together the single scenario modeling work PNNL has done previously to essentially perform compound analyses that evaluate the outcome of many scenarios applied in series to SNF storage and transportation systems. This is a new analytical effort. The fiscal year 2020 activity on this task was to do some initial task planning and limited supporting analyses. The main topics of this report are described in the following sections.

1.1 Cumulative Effects Phenomena

The term "cumulative effects" is used in this report to refer to changes in the SNF and its surrounding containment system that occur over time or as the result of transient mechanical loads. Fatigue failure in structural materials is an important phenomenon. The propagation of cracks during dynamic mechanical structural loading is another important phenomenon. Section 2 describes cumulative effects phenomena, specifically the ones that are of most interest to SNF and its containment systems.

1.2 Time Scale and Variable Life Cycle

The time component of cumulative effects is important because it increases the potential for mechanical loads to occur. For example, strong earthquakes are more likely to shake a dry storage cask the longer it is kept in dry storage. Another example is that the longer a cask is kept in dry storage, the more likely it is to be handled, repackaged, or moved to a new location. Recent DOE research and development (R&D) has measured the loads expected from cask handling and normal conditions of transport. Future work is proposed to evaluate the effect of seismic loads on SNF casks, which is currently an important unknown. Section 3 discusses the time scale of interest and other factors related to time.

The variable life cycle, in this report, means the actual set of events and circumstances that each SNF assembly, cask, or canister experiences from initial dry storage to final disposition. Because the life cycle is not expected to be the same for all SNF and its storage and transportation systems, the cumulative effects analysis needs to be able to accommodate or account for the variation. We could always make conservative assumptions to estimate the most limiting cumulative effects for any SNF, cask, or canister in the US inventory, but doing so would not be the correct evaluation for most cases. For example, some casks might experience a magnitude 7.0 earthquake during storage, but assuming all casks will experience one magnitude 7.0 earthquake is not realistic because casks will begin their life cycles spread in locations throughout the country. The analytical framework for cumulative effects needs to evaluate different potential life cycles. Section 3 discusses both time scale and life cycle features.

1.3 Whole System Loads

Testing and analysis in this area has been focused on the maximum possible loads. This is normal and expected for safety-basis calculations that are concerned with demonstrating that safe loading limits are not exceeded. Stress analysis in the nuclear industry often takes the form of establishing consensus-standard stress limits and demonstrating the safety of a system by calculating stresses that are below those limits. This analytical problem requires us to consider loads and accumulated fatigue damage at locations at other than the most limiting location because cumulative effects are the result of many different loading conditions that cause a different response from the system each time they are applied. Section 4 discusses whole system loading, drawing from recent transportation testing and analysis.

1.4 Test Data Incorporation

We are learning about fuel characteristics, strength, and failure conditions in the sibling pin test program. These factors have to be incorporated into evaluations of SNF integrity. Chloride-induced stress corrosion cracking (CISCC), to which stainless steel canisters that hold SNF during dry storage and transportation are potentially subjected, is being studied extensively, and what the program learns about CISCC needs to be incorporated into evaluations of canister integrity. The framework must incorporate this information and Section 5 discusses how test data are incorporated into the analysis framework.

1.5 Cumulative Effects Analysis Results

The answer we are looking for will be derived from an evaluation of SNF and containment system integrity over the entire (variable) life cycle of SNF, from the time it comes out of the pool until it reaches its final destination. Peak stress analysis, full system fatigue evaluation, and crack propagation analysis are major parts of the final answer. As noted earlier, we need a framework for evaluating these topics for any SNF lifetime. The final analysis will tell us whether SNF and containment system integrity can be maintained under any conceivable SNF lifetime, or if there is reason to intervene and make sure certain conditions never happen. For example, the analysis might suggest that SNF should be repackaged at some point during dry storage to avoid material fatigue failure or a cracking failure. Section 6 discusses the proposed cumulative effects analysis framework in detail.

1.6 Identification of Future High-Priority R&D

The main goal of this report is to propose a cumulative effects analysis framework and identify the analysis and testing that are needed to complete the cumulative effects analysis. This work is expected to take a few years in total while the DOE SFWST program completes some experimental work. One important part of the research effort is the sibling pin test program (Saltzstein et al. 2020). Other important efforts are the 30 cm drop analyses being performed by PNNL (Klymyshyn et al. 2020) and the fuel in dry storage seismic testing that is still being planned (Kalinina and Ammerman). Many research efforts need to be completed before the cumulative analysis can be completed, but progress can be made to advance the models and analytical methods that are part of the cumulative effects framework. Section 7 identifies important R&D efforts that can be advanced in the near term. Two examples include transient thermal stress analysis that calculates canister thermal stresses during daily or seasonal temperature changes, and development of an analytical tool for calculating incremental crack propagation from transient mechanical loading. Both of these are necessary to determine the potential for canister cracks to propagate during dry storage mechanical loading events.

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2 CUMULATIVE EFFECTS PHENOMENA

In SNF storage and transportation applications, the normal conditions of operation are not expected to cause any significant structural failure of the SNF rods, SNF assembly structure, or the canister or cask that forms the physical containment boundary of the SNF. The mechanical loads that are expected to occur during normal operation are very small. Some analysis or testing remains to be completed (atypical transportation scenarios, earthquake scenarios in dry storage, etc.), but the general expectation is that mechanical loads associated with normal conditions of transportation and storage are not strong enough to cause a failure of SNF or related structures in one application. Hypothetical accident conditions are currently outside the realm of DOE's interest, but there is a relevant concern that over an extended period of time, and potentially more than one transportation campaign, the small loads, repeated often enough, could challenge the integrity of the SNF or related structures. The cumulative effects analysis is proposed to evaluate the potential for structural failures to occur during the SNF life cycle as a result of the accumulation of relatively small loads over time.

The following sections discuss the structural failure, fatigue failure, and cracking failure phenomena. Each section closes with a bulleted list of key recommended research topics.

2.1 Structural Failure

A structural failure of the containment boundary is a design failure condition. Such a failure should never happen during normal conditions of transport because the systems are designed to function, and safety evaluations, reviewed by regulatory bodies, demonstrate that the design meets safety requirements. However, structural failures of fuel assembly components, the fuel basket structure, or any other structure within a SNF canister or cask are generally not considered a system failure, or a safety concern, but they can compromise the ability to repackage the SNF. In addition, broken structures inside the cask or canister could affect the cask or canister system during extended long-term storage and multiple transportation trips. For the cumulative effects topic, it is critical to know whether any structural failures occur within the system, so the consequences can be fully evaluated and addressed.

DOE testing recently studied the response of a dual-purpose (storage and transportation) bare fuel cask to a 30 cm drop in the horizontal impact orientation (Kalinina et al. 2019). While the main purpose of the testing was to evaluate the response of SNF assemblies to an additional drop of a single fuel assembly (Kalinina et al. 2020), valuable impact response data were collected from the cask system. PNNL used the data to validate numerical models of the cask impact behavior and the fuel assembly response (Klymyshyn et al. 2020), and determined that a 30 cm cask drop with a 60-degree impact angle was more limiting than the horizontal drop. All of the testing and modeling results indicated that no structural failures of any cask or fuel assembly components are expected during non-irradiated beginning-of-life conditions. Some work remains to confirm that no fuel assembly component failures are expected during irradiated end-of-life conditions.

Older analyses in the literature (Rashid et al. 2007; Jiang and Wang 2016) predict that fuel assembly structural components could be vulnerable to damage from a 30 cm package drop or normal conditions of transportation (NCT) loads, but current DOE testing and analysis do not support that conclusion. PNNL recommended a task to compare current analytical work that is validated by test data to prior analytical work in the literature to reconcile the differences. The current understanding is that the previous work made unrealistic or conservative loading assumptions, but a more detailed comparison is recommended to fully reconcile the differences in conclusions.

Another factor that has not yet been evaluated is the possibility that fuel assemblies could be worn or damaged, or fuel rods could be bowed when they are placed in the cask or canister. Current PNNL models assume pristine fuel assemblies that have as-built geometry. Grid springs are relaxed to match the Sandia National Laboratories (SNL) fuel assembly configuration used in testing, but realistic SNF features like bowed fuel rods have not yet been explored. During NCT shock and vibration (as recorded during the MMTT) the excitation loads are so low in magnitude that damaged fuel assembly components can generally be ignored because it would take severe preexisting damage for such low loads to cause a component to fail. The 30 cm drop load case is strong enough that preexisting damage or deformation should be considered.

Recommended Research Topics Related to Structural Failure:

- Reconcile structural analysis differences in the literature with modern test data.
- Determine the influence of damaged, worn, or bowed assemblies.

2.2 Fatigue Failure

Fatigue failure is a material failure phenomenon that is known to occur in components that are subjected to cyclical or repeated loads, thereby weakening the structural material and resulting in progressive and localized structural damage and the growth of cracks. Fatigue failure can occur when loads are relatively small compared to the yield or ultimate strength. Material types have different fatigue behaviors. Some materials, like steel, have an endurance limit, which is defined as the load below which failure is highly unlikely to occur at an infinite number of load cycles. Materials like aluminum do not have an endurance limit such that even small amplitude fatigue loads will eventually cause failure if a sufficient number of load cycles are applied.

The O'Donnell-Langer stress-cycles (S-N) curve is a classic representation of irradiated zirconium alloy fatigue behavior. The Oak Ridge National Laboratory (ORNL) Cyclic Integrated Reversible-Bending Fatigue Tester (CIRFT) test is used in the sibling pin test program to determine S-N behavior for SNF rod segments. In earlier data the CIRFT data agreed well with O'Donnell-Langer data. Sibling pin data suggest that SNF could have a generally lower fatigue strength than the O'Donnell-Langer irradiated zirconium alloy S-N relationship at higher load amplitudes, but the reality of NCT shock and vibration loading means that the amplitude range of interest is much lower than can be practically tested.

To provide some perspective, a test rig that can apply cyclic bending loads to a test sample with a frequency of 2 Hz would take six days to reach 1E+6 cycles, almost two months to reach 1E+7 cycles, and more than one and a half years to reach 1E+8 cycles. The shock and vibration recorded on fuel cladding with surrogate fuel mass during the MMTT recorded a maximum peak strain of about 100 microstrains during a coupling event, and the fatigue life at that amplitude is projected to be 1E+10 cycles. Typical strain cycle amplitudes in the cladding from rail transportation were closer to 10 microstrains, which relates to a SNF cladding projected fatigue life of about 1E+16 cycles. Note that the fatigue life has to be extrapolated from test data in the range of interest for SNF transportation—the number of cycles of interest are many orders of magnitude higher than would be practical to test the material to the point of failure. Also note that the 2,000 mile westbound rail transportation leg of the MMTT only recorded about 4,000 fuel cladding strain cycles that exceeded 10 microstrains.

It can be concluded that fatigue is not an issue for fuel cladding during typical anticipated conditions of rail transportation, but some additional transportation configurations need to be considered to encompass atypical transportation situations such as light truck cask transportation, which is expected to cause higher loads on SNF. A canister integrity fatigue analysis remains to be completed for transportation, and a full system fatigue analysis of seismic loads during dry storage is needed.

Another technical area to consider for canister fatigue loading is cycling thermal stress, which was evaluated using preliminary thermal and structural models, as described in Appendix A. The analyses indicate that thermal stresses in the canister are present because of a non-uniform temperature distribution in the SNF canister wall. The type of thermal model used in Appendix A is a steady-state model, which assumes the ambient temperature (the environment) remains constant over time. In a real dry storage scenario, the ambient temperature would vary by the hour throughout each day. We do not yet know if hourly temperature variation has a significant effect on the thermal stresses or if an hour is too short to matter, but daily, monthly, or seasonal temperature variation could conceivably affect thermal stresses.

<u>Recommended Research Topics Related to Fatigue Failure</u>

- atypical transportation
- canister fatigue during transportation
- seismic fatigue loading
- canister cycling thermal stresses.

2.3 Cracking Failure

Cracking in containment boundaries of pressure vessels is a standard structural design concern. The internal pressure in a vessel provides a tensile stress state that can cause existing shallow cracks to advance through the wall and lead to a failure of the containment boundary. SNF rods have internal pressure and the zirconium alloy material experiences changes during its time in a nuclear reactor core, which make cracking an important technical issue that is still being explored under the sibling pin test program. Stainless steel canisters that hold SNF during dry storage and transportation are potentially subjected to CISCC, and this is a significant technical issue that DOE is exploring in current research.

Although the scientific research into this topic is still ongoing, PNNL can develop the analytical tools needed to evaluate crack advancement under transient loading conditions. PNNL has made progress in elastic-plastic fracture mechanics analysis of canisters (Klymyshyn et al. 2016), but that work focused on a significant structural loading scenario and used static fracture mechanics analysis methods. The previous work identified a need to develop a transient crack propagation analysis tool for predicting crack growth due to transient dynamic loading events. In the cumulative effects scenario, transportation, handling, and seismic events could all cause an incremental advancement of the crack. Extensive crack detection might need to be done on canisters periodically throughout the SNF lifetime, or prior to any transportation campaign. Conversely, the loads anticipated during NCT and storage might prove to be so benign that through-wall cracking is not a credible concern. PNNL proposes to develop an analytical tool, as described in Appendix B, to evaluate the potential risk of crack propagation.

Physically, crack initiation can potentially be caused by CISCC driven by weld residual stresses, voids left in the welds during fabrication, dings and scrapes caused by normal handling, or other events and processes. It is not necessary to know what physical process causes a crack initiation site to determine whether a crack will advance all the way through the wall of the vessel. PNNL will assume initial flaw sizes and initial crack lengths and then determine what initial crack state can threaten a through-wall crack based on the anticipated cumulative effects loads. The cumulative effects loads are anticipated to be so small that it would take a very long initial crack size to have any practical risk of a cracking failure caused by transient mechanical loads, but we need the analysis to support this hypothesis.

While the mechanical loads are expected to be relatively small for NCT, the dry storage environment needs evaluation. The two areas of importance to crack propagation evaluation from external loading are seismic loads and thermal stresses. Residual stress from fabrication is also important to consider in the complete stress state of SNF canister walls, as well as stress from internal pressure, but these topics are reasonably well known. Seismic loads and thermal stress in canisters are topics where more study is needed.

Seismic structural loads are unusual compared to other mechanical loading sources because earthquakes are random natural events that occur outside of any human control. While cask loading, handling, and transportation will all cause some amount of transient structural loading on SNF, the loads experienced by the SNF are limited by operational controls. Seismic loads are probabilistic, so there is a range of potential loading conditions to consider. A SNF canister might experience zero significant earthquakes during its life cycle, or it might experience many. How this will be resolved in the cumulative effects analysis remains to be developed, but we can anticipate the need to consider many possible earthquake scenarios using deterministic nonlinear analysis methods. In 2021, PNNL plans to perform some seismic modeling and analysis to help determine the range of seismic loads that are relevant to dry storage.

Thermal stresses, which are discussed in Appendix A, are part of the total stress state of a canister. As mentioned above for fatigue stress, it is not yet known how significant hourly, daily, monthly, or seasonal changes in environmental temperature affect the thermal stresses. Evaluating crack propagation is another topic about which we need to know the stresses. The same thermal expansion analyses will provide the information needed for fatigue evaluation and crack propagation.

Crack propagation has not yet been evaluated for any transportation modes. The MMTT used a bare fuel cask (not a canister system), so a canister crack evaluation has not been done. The MMTT data and models exist already, so completing this evaluation is just a matter of completing the analysis after the crack propagation tool is fully developed. The NCT loading conditions are expected to be included in the set of loading conditions used to develop the crack propagation model.

Recommended Research Topics Related to Crack Evaluation:

- crack propagation model/tool
- seismic analyses
- canister cycling thermal stresses
- all transportation.

3 TIME SCALE AND VARIABLE LIFE CYCLE WORKING ASSUMPTIONS

This section discusses two important factors—the time scale and the variable life cycle of SNF dry storage and transportation. Time scale refers to how many years (or decades, or centuries) SNF will be in dry storage before it is finally dispositioned. Within the potentially long and uncertain time scale, specific time periods are chosen for evaluation. Life cycle refers to what happens to the SNF during its existence from the time it leaves wet storage until it arrives at its location of final disposition, which could be a geological repository or a fuel reprocessing facility. The cumulative effects analysis chooses specific time periods for evaluation, and the events that can happen during the life cycle have to be consistent with the choice of time period. We are concerned about mechanical loads, thermal effects, corrosion, and any other processes that might affect the integrity of the SNF containment boundaries. Life cycle is often discussed as a "variable" life cycle because all SNF is not currently expected to have the same life cycle. Cumulative effects analyses have to consider the range of potential SNF life cycles.

Time scale and life cycle are interrelated topics because more time in dry storage means a longer life cycle, and an increased opportunity for mechanical loads. While the time scale and life cycle variables might make it seem like an infinite number of combinations need to be considered, the variables can be broken down into a manageable number of cases for analysis. This is an important feature of the cumulative effects framework: breaking down a large and overwhelming topic into a tractable problem that can lead to a rational conclusions on the significance of these SNF loads. The time scale and variable life cycle are discussed independently in the following two sections.

3.1 Time Scale

The relevant time scale for cumulative effects is highly uncertain because it depends on political forces and US government policy decisions, but it can be assumed to be in the range of decades to centuries. A large amount of SNF in the current inventory needs to be dispositioned, and operating reactors are still producing power (and SNF) today. The Yucca Mountain Repository is not currently a viable destination, so realistically there is no place in the US that can receive SNF for final disposition. Interim consolidated storage sites are being proposed by commercial companies and related plans are moving through the regulatory review process. DOE is developing railcars that comply with Association of American Railroads (AAR) standards for the transport of SNF to help facilitate a transportation campaign, but even when a fleet of suitable railcars exists, it is projected that it will take decades to move the current inventory of SNF from its current locations to any centralized storage, disposal, or reprocessing site.

The time that any SNF cask or canister sits in dry storage before it is ultimately dispositioned is unknown. It is safe to assume that each canister of SNF in the US inventory could follow a different disposition path and will have its own unique life span. The difference of a year or two in dry storage is not expected to be significant, but if CISCC is a major challenge to structural integrity there could be a need to repackage SNF or perform repair or mitigation operations. At this stage, PNNL is taking the approach of establishing the framework for the analysis, and will propose a few time periods for evaluation, understanding that some refinement may be necessary to complete the cumulative effects analysis.

One of the big impacts of the time period is the seismic hazard. Seismic hazards have a probability component that varies by time period of interest. Longer time periods make a single large earthquake more likely to occur. Fifty-year hazard maps are common. A 300-year time horizon is six times as long as a 50-year hazard map, so the seismic hazard needs to be adjusted accordingly. The field of seismology is relatively mature and resources are available to construct hazard maps for the longer time scales. One of the important tasks that needs to be done is to relate seismology information to the mechanical loading environment for which we need to evaluate the stresses and loads on the SNF and containment system components. The 50-year seismic hazard map inspired the selection of initial time periods being multiples of 50 years.

Another large impact of the time period is the environmental exposure to canister and cask systems. This is where the cumulative effects analysis connects to CISCC research. If the environment inside an overpack is capable of causing CISCC to occur, cracks could start forming at some time. The tensile stress state in the canister may be sufficient to drive cracks to grow all the way through a canister wall during a sufficient time period, without any additional mechanical loading from handling, earthquakes, or a thermal stress cycle. This cumulative effects analysis can help inform the CISCC testing, and any knowledge gained from CISCC testing can be applied here.

Canister inspection requirements going forward are an important unknown. The American Society of Mechanical Engineers (ASME) is working on code case N-860 (as discussed by Cho et al. 2019) to define inspection requirements. The code case was requested by the US Nuclear Regulatory Commission (NRC) is still being finalized, but the current working assumptions are that one to two canisters would be inspected at each SNF dry storage site every 10 years. The inspection program would use visual methods to look for corrosion on the canister, or any other indications of a crack. PNNL will monitor the progress of the code case and make assumptions in the cumulative effects analyses to include a long-term inspection program. The 10-year inspection cycle is noted for potential future refinement of time scales, but the longer 50-year time period is selected for initial consideration to keep the number of cases relatively low.

The total time of SNF dry storage is proposed to be 50, 100, 150, 200, 250, and 300 years to start the cumulative effects study. Selecting these six specific time periods for evaluation simplifies the problem and covers a very long practical time period. However, given that the current SNF stockpile has accumulated over decades, the time to disposition the current SNF stockpile is estimated in decades. There is no plan currently in place to disposition the SNF stockpile so a 300-year time horizon might not be excessive. PNNL proposes to first evaluate cumulative effects in 50-year increments up to 300 years, and then decide if more granularity is needed (say, 10-year increments) or if an even longer time horizon is needed to clarify the long term trends (say, 500 years).

3.2 Life Cycle

In addition to uncertainty in the time scale, there is uncertainty about how each SNF cask will move from its point of origin to its final disposition site. The SNF could go directly from its point of origin to the disposition site, with no interim storage. It could go to a consolidated interim storage facility to wait until a disposition option is selected. Or in the most general sense, SNF could be housed in more than one location before it reaches its final destination. Regional collection facilities may also be used to receive SNF before moving it to a centralized interim storage facility. It is also conceivable that SNF could be moved from its origin site to a temporary holding facility before it reaches the normal disposition stream. It is difficult to anticipate all of the possible circumstances that might cause such additional movement and handling, but it is prudent to consider that SNF casks and canisters will not all experience the same path to disposition. This concept is discussed as the variable life cycle of SNF. The life cycle will determine how many vibrations, transportation legs, or potential earthquakes a SNF package might experience.

The life cycle for SNF as it is considered in the cumulative effects analysis is shown in Figure 1. All cases start with in-pool storage at a nuclear power plant. From there, one operation of cask or canister packaging is expected. The process includes moving fuel assemblies within a pool with a crane and placing them inside a submerged cask or canister. Then the cask/canister undergoes vacuum drying to eliminate all or most of the water. Then the dry fuel cask/canister is sealed and moved to a dry storage location. The cask/canister will sit at the dry storage location for a period of time that depends on what happens next. The three paths to final disposition are discussed in the following paragraphs. The variable N is introduced to represent the number of interim storage locations in a SNF life cycle.

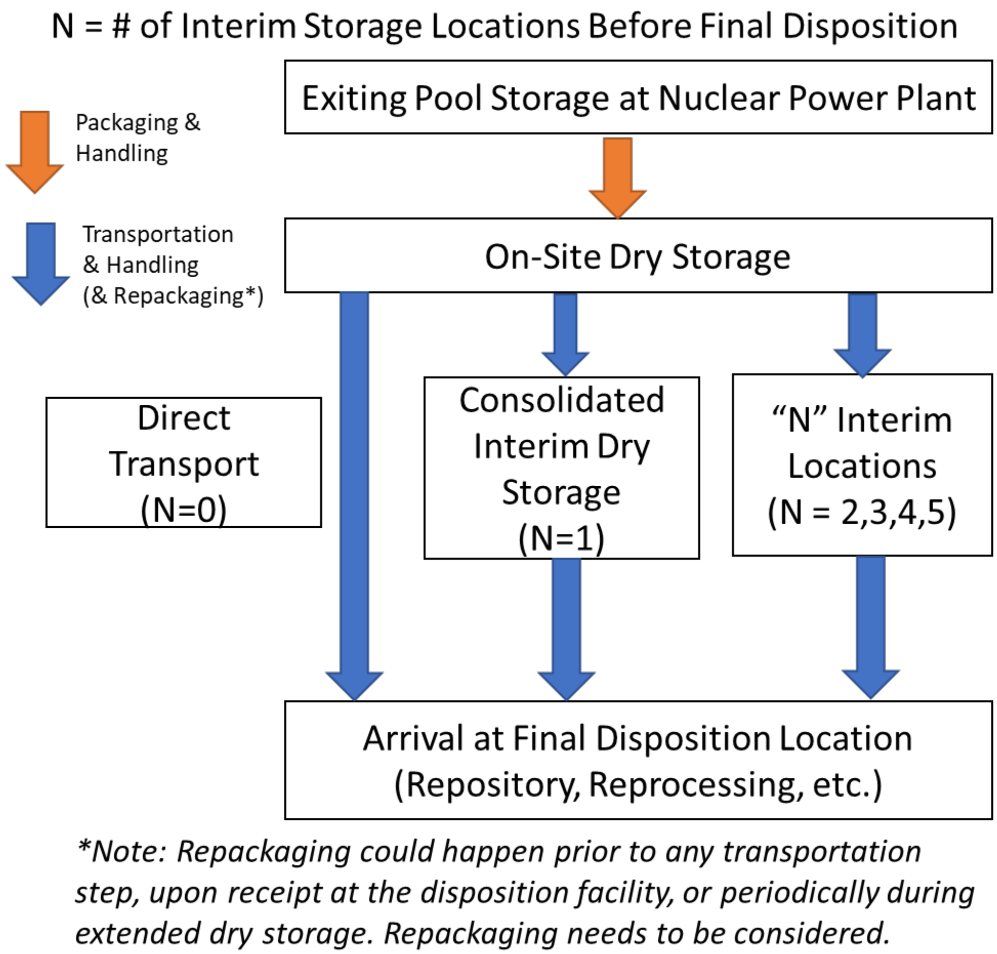

Figure 1. Cumulative Effects SNF Life Cycle

On the left side of Figure 1, the direct transport disposition path has the fewest steps from the reactor site to the disposition site. When the SNF reaches the disposition site the next step could be direct disposal of the cask/canister or repackaging, during which the fuel is placed in standardized canisters. This is important because the fuel assemblies might need to reach the disposition site intact (or nearly intact) to allow for repackaging. This direct disposition path represents the philosophy of the Yucca Mountain plan where most fuel was to be sent to the repository in standardized transportation, aging, and disposal canisters. Repackaging was intended only for the fuel not in these standardized canisters, which is currently all fuel in dry storage. Repackaging would facilitate the disposal of SNF stored in these non-standardized canisters. DOE is investigating the feasibility of direct disposal, which would remove the repackaging step. While this option only moves the SNF once, it involves the longest possible period of sitting in one location, which makes it vulnerable to local seismic events. The longer it sits, the higher the risk of a strong seismic event occurring.

The middle path in Figure 1, consolidated interim dry storage, assumes there is one stop on the path to dispositioning, which represents a current philosophy. Currently, two interim storage facilities are being planned, but they remain to be built and licensed. The primary assumption is that the SNF will be stored in the system it arrived in from the reactor site without repackaging. It will stay at the interim storage facility until a final disposition site is identified and operational. The final disposition site might require a repackaging step, which would require SNF assemblies to maintain their structural integrity. It is assumed that the interim storage facilities will be sited at locations that feature favorable seismic hazard characteristics, making the interim storage facilities potentially better locations than the reactor sites from the standpoint of cumulative effects.

The path on the right side in Figure 1, N interim locations, is a generic life cycle that includes multiple moves to different storage locations. The cumulative effects analysis is making a preliminary assumption that five is the maximum number of interim locations. The cumulative analysis is expected to show that there is no practical difference between life cycles involving four and five (or more) interim storage locations, because the MMTT results and related analyses indicated that transportation and handling provide negligible mechanical loads to SNF. If transportation and handling loads on canisters are also found to be negligible, then the scope of the cumulative effects problem can be decreased. Conversely, N can be increased as necessary to make sure all relevant life cycles are covered.

Note that the practical limits of N are not currently known. At this time, N=0 and N=1 seem to be the most likely scenarios, corresponding to direct transport and a single interim storage location, respectively. N=5 represents a high bounding value that was chosen to help answer the question of how many movements of the SNF might become a problem.

Two kinds of transition steps (arrows) are identified in Figure 1: packaging and handling, and transportation and handling. Each transition step corresponds to a set of mechanical loads and environmental conditions. A brief description of the loads and environment is provided below for each transition step.

3.2.1 Packaging and Handling

In this step, a crane moves fuel assemblies through the water of the cooling pool and places them inside a submerged cask or canister. The mechanical loads on the fuel assembly are likely negligible. The same mechanical process was used to move the fuel assembly out of the reactor and place it in the pool. Within the cooling pool environment we do not expect any significant corrosion or structural degradation to occur, so the crane motion should not be challenging, except in an accident caused by operator error or crane malfunction. A natural disaster (like Fukushima) might also cause significant structural damage to fuel assemblies, but in the event of that kind of disaster we can assume that SNF would be inspected and only undamaged assemblies would be treated like normal SNF. The crane motion and individual fuel assembly motion is identified as a mechanical load in the cumulative effects analysis framework for the sake of completeness; there is no expectation that this step of fuel assembly handling would cause significant cumulative effects during normal operations.

After loading, the cask/canister is drained and moved to a location where vacuum drying occurs. The handling step is identified but considered negligible. The vacuum drying step is significant because of the significant temperature, internal rod pressure, and the potential for complex material changes to occur. The vacuum drying step is identified as a very important thermal, mechanical, and material science event that needs further study.

After vacuum drying, casks and canisters are handled and moved to their place of long-term dry storage residence. Crawlers or heavy trailers are used to move the SNF from the reactor building to a nearby independent spent fuel storage installation (ISFSI), presumably on the power plant grounds. Dual-purpose bare fuel casks are designed to store and transport SNF. They are loaded in the reactor building and carried by crawler to the ISFSI where they are placed for storage. SNF welded canisters can be housed in vertical or horizontal dry storage overpacks. For some vertical canister units, the loaded canister is placed in an overpack before it is moved from the reactor building. A crawler carries the already-loaded overpack to the ISFSI. For horizontal canister storage units, a transfer cask is used to move the canister from the location where it is sealed to an overpack unit that is already in place on the ISFSI. The design of the system and the site procedures affect the mechanical loads. These post-drying and emplacement mechanical loads are noted in the cumulative effects analysis framework.

3.2.2 Transportation and Handling

Transportation activity includes handling to move the SNF cask or canister from a storage location to load it onto a transportation system, cross-country transportation from one site to another, and then handling to unload the cask/canister at its destination and a final handling step to move it into place at an ISFSI or a disposal or reprocessing site. Repackaging is noted as a potential consideration in this step, but the topic is discussed in more detail later in this section.

For transportation to occur, a loading handling activity has to happen first. The system is moved from its starting location to a transportation system. A dual-purpose cask is lifted and moved by a crawler to a loading location. Then a crane is used to lift the cask onto a railcar (or other conveyance system). The most likely scenario is train transportation using an AAR-S2043-compliant railcar like the 12-axle Atlas (AREVA 2018) or an 8-axle railcar (Ross and Feldman 2020) that DOE is developing. Crane lifting and loading of a dual-purpose cask was recorded during the MMTT (Kalinina et al. 2018). The peak strains on the SNF were relatively low, comparable to loads observed during railcar coupling, but they were higher than normal shock and vibration during transportation. Potential loads caused by canister manipulation during this kind of activity have not yet been explored.

Once loaded, the SNF experiences transportation mechanical shocks and vibrations associated with a transportation operation. Railcars might have to travel over low-grade track conditions. Railcars might be coupled during interchanges. The cumulative effects analysis will have to make assumptions about what can happen during transportation activities. The MMTT offers data to represent what happens to a dual-purpose cask. Analysis is needed to project what loads canistered SNF can experience. Klymyshyn et al. (2019) explored canister effects and found them to be negligible from a SNF fatigue standpoint, but more analysis is needed to determine if canister loads are also negligible.

After the transportation is completed, the SNF cask/canister needs to be offloaded at its destination. This includes a crane operation to take the cask/canister off the conveyance system and crawler movement to carry the cask to its storage location. A canister transfer operation might be needed to move the canister from the transportation cask to a transfer cask and ultimately its storage overpack. These kinds of details will be design-specific.

Repackaging of SNF can take a few different forms. Canisters are expected to be inspected before the transportation loading operation begins. If a crack or a sign of corrosion is found, the SNF could potentially be repackaged prior to transportation. The fuel could be removed from one canister and placed in an identical canister design, a different canister design, or a bare fuel cask. Alternatively, the damaged canister could be placed in a larger canister without manipulating the SNF assemblies at all. Under another possible alternative, a canister repair technology could be deployed to fix the original canister. All of these possibilities are plausible, but until actual procedures are defined for how to deal with damaged canisters, this remains a variable in the life cycle. The cumulative effects analysis will consider all options.

Another potential opportunity for repackaging fuel could come during extended dry storage. If regular periodic inspection reveals CISCC, signs of corrosion, or other types of cracking, the NRC might require the SNF to be repackaged, using options similar to the ones described in the previous paragraph. The point is that SNF containment systems in dry storage are expected to undergo regular inspections and the consequence of finding problems could be repackaging. The cumulative effects analysis considers repackaging at many times and under many circumstances during the SNF life cycle.

3.3 Key Time and Life Cycle Working Assumptions

The full scope of the cumulative effects problem is nearly infinite because there are so many variables and uncertainties. The following assumptions are made to set up the problem for future evaluation. The intent is to revisit these assumptions regularly as progress is made.

Key Time Working Assumptions:

- The total duration of the extended dry storage period is 50, 100, 150, 200, 250, or 300 years.
- The total time in dry storage will be divided equally between 1+N dry storage locations.
- The longest possible time spent in one location is the direct transport option (N = 0).

Key Life Cycle Working Assumptions:

- The life cycle involves combinations of handling, storage, and transportation activities.
- The life cycle can include repackaging steps.
- The shortest life cycle is direct transportation from an ISFSI to the final disposition site (N = 0).
- The longest life cycle passes through N interim storage locations before disposition. The cumulative effects analysis will initially consider a maximum of five locations (N ≤ 5).

These assumptions lead to the initial set of analysis cases summarized in Table 1. The table represents a starting plan. Tentatively, each life cycle scenario (cell of Table 1) will be evaluated using structural dynamic analyses, thermal analyses, and any other types of analysis needed to determine whether SNF cladding integrity or storage system integrity are challenged under the time scale and life cycle conditions defined for each life cycle scenario. For example, the 50-year direct transport scenario means that the SNF system is stationary and exposed to the environment for 50 years, and experiences one transportation campaign and a number of handling and inspection events. A complete evaluation of every scenario defined in Table 1 is not expected to be necessary.

Table 1. Number of years spent at each SNF dry storage location (including the origination site).

Total Storage Time (Years)	Direct Transport (N = 0)	Consolidated Interim (N = 1)	Multiple Interim (N = 2)	Multiple Interim (N = 3)	Multiple Interim (N = 4)	Multiple Interim (N = 5)
50	50	25	17	13	10	8
100	100	50	33	25	20	17
150	150	75	50	38	30	25
200	200	100	67	50	40	33
250	250	125	83	63	50	42
300	300	150	100	75	60	50

Table 1 essentially proposes a number of hypothetical life circumstances for evaluation over the next year as this work continues. The process of completing the evaluations defined in Table 1 is expected to help identify the most important phenomena for cumulative effects analysis and lead to regular revisions of the table. For example, the 50-year row might be unnecessary because it is too short of a time period to cause any significant problems. As another example, the N = 5 column might be unnecessary because for practical purposes it is no different than N = 4. The expectation is that Table 1 will be revised before all of its scenarios are completed, but as the scope of the problem changes the decisions will be justified and documented. The goal for future work is to perform some analyses and refine the scope of the cumulative effects problem.

Recommended Research Related to Life Cycle Evaluation:

- Perform a few life cycle evaluations to guide revision of Table 1.

4 WHOLE SYSTEM LOADS

SNF and its containment systems are often evaluated using standard engineering analysis methods. Analysis drives the design of systems. Often the design-basis analyses and calculations remain proprietary to the cask vendors. Safety-basis analyses are a special kind of analysis used to demonstrate that regulatory requirements are met. Safety-basis analyses are often conservative, because their purpose is to demonstrate that clearly defined acceptance criteria are met and making conservative assumptions can often simplify calculations, thereby reducing the time and effort required. When the goal is to make a best estimate of what will happen, the results will often look different than the design-basis calculations. Recent research projects like the high burnup demonstration cask (Fort et al. 2019) showed that thermal models significantly overpredicted key temperatures, even with a very good understanding of the cask geometry and its SNF contents. The cumulative effects analysis will ideally be based on best estimate analysis results that provide an accurate estimation of the system’s response to loads.

Another important point is that analyses of SNF casks/canisters often report the results for the most limiting fuel rod. In thermal analysis, the peak cladding temperature is a key metric. Reporting the peak cladding temperatures provides assurance that all other fuel cladding temperatures are below the peak. For a safety-basis calculation, this is all that is needed to demonstrate that all fuel remains below a temperature limit (for example, 400°C to avoid burst/cladding failure). There could be more than 8,000 fuel rods in a canister, but when the results of analysis only identify the highest cladding temperature we do not know the temperature of all of the other fuel rods. Structural analyses are often the same in that they report the highest stress or strain that occurs at any point on the SNF cladding or the canister. As we start to consider compounding effects, like cracking, it may not be reasonable to assume that the highest transient loads always occur at the locations where flaws exist. For cumulative effects analyses, we need a better understanding of the locations and overall distributions of loads.

In the MMTT, the distribution of loads was not a critical piece of information because the loads were so low. Klymyshyn et al. (2018) reduced the analysis of shock and vibration of fuel rods to an analysis of a single fuel rod. When the peak cladding stress recorded in the MMTT was only about 100 microstrains (about two orders of magnitude below yield) the single fuel rod model was enough to demonstrate that the loads on the fuel rods remained low enough to neglect. Klymyshyn et al. (2019) applied the single fuel rod analysis methodology to the Atlas railcar design and all 17 casks in the US fleet. In all cases, the conclusion was that the Atlas railcar would provide a gentler ride. With Atlas prototype testing nearing completion, validation data are expected to become available for model validation, which is recommended, but there is no reason to suspect the conclusions of Klymyshyn et al. (2019) to change. The cumulative effects analyses will proceed with the assumption that the NCT shock and vibration loads are evenly and uniformly distributed within the cask and canister.

The load distribution is a more important factor under the 30 cm cask drop loading condition because the loads are much higher. Klymyshyn et al. (2020) calculated the peak cladding strain to be almost 5,000 microstrains for a 60-degree impact angle, which was the most adverse drop orientation modeled. Kalinina et al. (2020) recorded the test data from a single fuel assembly 30 cm horizontal drop experiment to be near 2,000 microstrains. These values are an order of magnitude higher than the NCT shock and vibration recorded during the MMTT (Kalinina et al. 2018) and in the range of 20% to 50% of the material yield strength (the precise value of which depends on temperature and burnup). The test data and the analyses point to the conclusion that 30 cm drop loads are large enough that they need to be considered in detail for cumulative effects analyses.

An example of the distribution of fuel cladding strain (as calculated using the current PNNL deformable grid fuel assembly model) is shown in Figure 2 The figure is a histogram, where the vertical axis identifies the number of fuel rods and the horizontal axis is the approximate peak cladding strain in each fuel rod. For example, in the 30 cm horizontal drop scenario more than 180 fuel rods have a peak strain of 2,750-3,000 microstrains. Given that there are 264 fuel rods in each assembly, 180 fuel rods is a strong majority. A few fuel rods are higher (20 rods between 3,000-3,250 microstrains), but all the rest are lower. The 30 cm drop case with the 60-degree impact angle had one fuel rod up to 4,500-4,750 microstrains, but about half of the fuel rods were in the same range as the 30 cm horizontal drop case (3,250 microstrains and below). Interestingly, when the cask drop height is increased to 9 m (horizontal impact angle) the peak fuel rod strain goes up to 5,750 microstrains, but most of the fuel rods remain in the range of the 30 cm drop. The 9 m drop case is outside the normal range of cumulative effects because it represents a hypothetical accident condition drop, but the analysis shows that the 9 m drop case is not significantly higher than the 30 cm drop range. Risk analyses that assume 100% failure of fuel rods in a hypothetical accident condition appear to drastically overestimate the extent of rod failure. PNNL's 9 m drop model does not predict any rod failures, but it has not been validated by test data. Similarly, the 30 cm 60-degree impact angle case was not validated by test data, and although the 30 cm horizontal drop case was validated with test data, the model results reported in Figure 2 are higher than the recorded values because the model made conservative assumptions about the pre-impact gap condition. Technically, most of the model results reported in Figure 2 are beyond the range of test data because the maximum recorded strain was under 2,000 microstrains. PNNL recommends performing a full scale fuel assembly 9 m horizontal drop test to validate the model in the range of interest. Based on the distribution depicted in Figure 2, PNNL estimates a high likelihood of recording cladding strains in the 4,000+ microstrains range in a 9 m horizontal drop test. In addition, PNNL has predicted the localized stresses due to SNF rod-to-rod and rod-to-basket contact during 30 cm and 9 m drop cases. The results of these analyses determined that the maximum contact stresses were under yield, but further contact modeling to evaluate the total stress state and its role in cumulative effects is of interest.

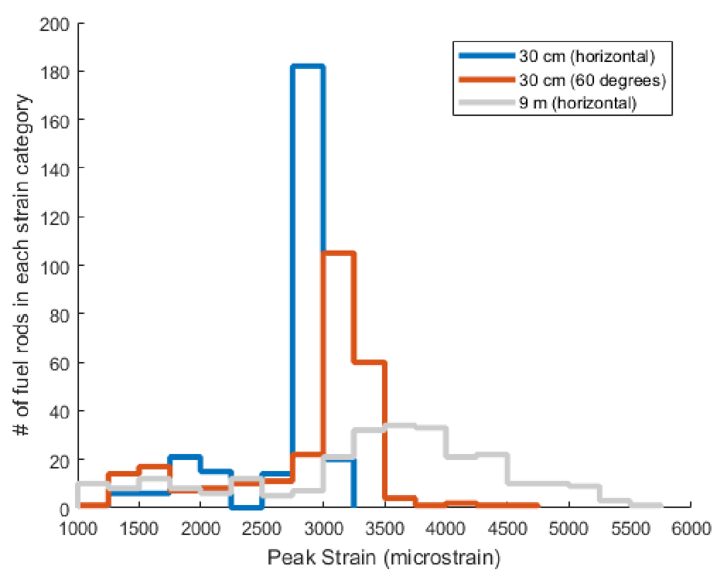

Figure 2. Peak fuel rod strain distribution in a 17x17 PWR fuel assembly in three cask drop conditions. The predictions are from finite element dynamic impact analysis of a loaded cask.

When considering canister stresses, there is a similar concern about identifying where high stresses occur. For safety-basis analyses it is reasonable to report the peak stress in the canister wall to demonstrate that all stress is below the safety criteria. For cumulative effects, we are very interested in the stress state in the weld regions and the heat-affected zones, where the steel forgings and plates are welded together to form the canister structure. Mechanical loads happening in the middle of plate are less important than loads happening where the plates join. Figure 3 shows an example of the thermal stress distribution in the outer wall of a section of a hypothetical SNF canister. The geometry and details of the analysis are discussed in more detail in Appendix A. The narrow lines in Figure 2 show where hypothetical welds are located. Near the top and bottom are where the canister shell is welded to the lid and base plate. The color contours show von Mises stress in units of pascals (Pa). Note that the thermal stress is not uniform throughout the canister, so peak thermal stresses do not necessarily occur at the most vulnerable locations. We need to understand both the peak stress and the spatial distribution of thermal stresses. Appendix A discusses the canister thermal stress analysis and describes how PNNL has started developing the thermal expansion model to include the weld region. This is an area where more work is needed.

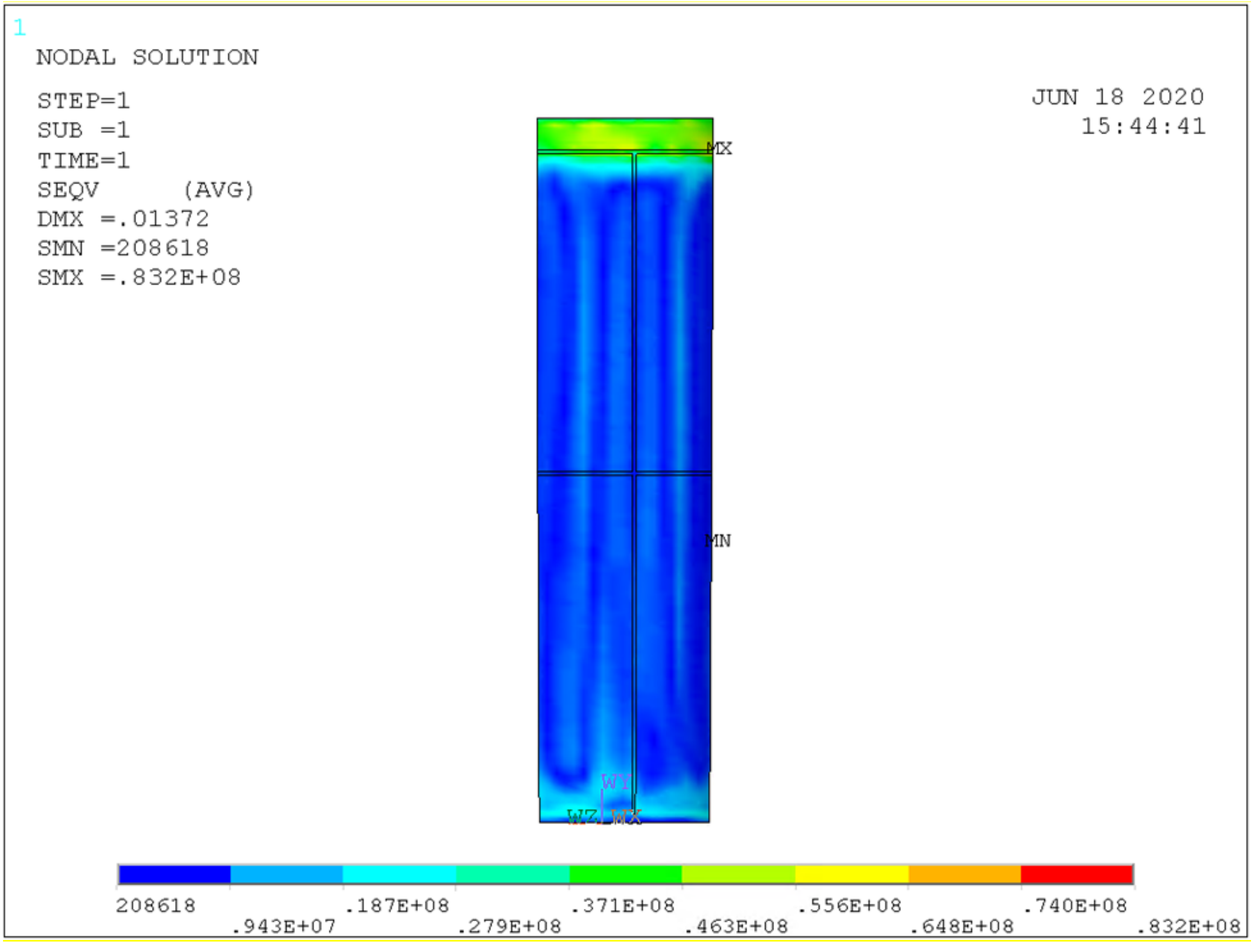

Figure 3. Von Mises stress (Pa) in canister at 305.4K (90°F) ambient temperature.

Another area that needs more analysis is the characterization of canister loads during NCT transportation. The strongest mechanical loads on the fuel rods were measured during coupling tests. PNNL needs to revisit the MMTT data to determine the mechanical loads on a hypothetical canister. The MMTT used a bare fuel cask, so analysis is needed to determine what stresses would be applied to the canister during NCT and, importantly, where those loads would occur on the canister. The same thing is needed for seismic loading conditions during dry storage. PNNL is helping plan a future seismic test campaign with SNL and recording canister stresses is an important goal of that test campaign.

<u>Recommended Research Topics Related to Whole System Loads</u>:

- 30 cm cask drop whole system loads.
- Normal transportation whole system loads.
- Dry storage seismic whole system loads.

- Dry storage thermal expansion loads.

5 TEST DATA INCORPORATION

The SFWST program is actively researching topics that are vital to evaluating the structural integrity of SNF rods, fuel assemblies, and canister storage and transportation systems. As new information becomes available, it can affect the cumulative effects analysis. For example, if the research determines that the risk of CISCC is negligible because of the limited exposure of the SNF canister to the environment, then CISCC can be removed from the cumulative effects analysis framework. Conversely, if CISCC remains a potential failure mechanism for SNF canister integrity, then the results of crack initiation studies and crack growth rate studies need to be incorporated into the analysis. The analysis will be conducted using assumed or best estimate parameters until the final data become available.

For SNF rods, the research is primarily related to identifying cladding failure criteria, such as the strength of irradiated cladding on its own or the combined strength of SNF cladding and fuel pellets, evaluated as a composite structure. This type of research is mainly relevant to failure criteria. The models and tests calculate loads that are compared to failure criteria. The models generally do not internally calculate survival or failure, so failure criteria are applied to the results of the structural modeling step. In the cumulative effects analyses, the loads and failure criteria will be reported so future adjustments can be made.

The PNNL damage model described by Klymyshyn et al. (2020) is one modeling application where damage criteria are needed. The 30 cm cask drop scenario has so many important variables that a numerical model of the loading trends is recommended to close the knowledge gap. The damage model will incorporate initial failure criteria in future work, and the failure criteria should be reassessed and updated in the future as more is learned.

A second exception is that the ORNL CIRFT tests are measuring the effective bending rigidity (EI = elastic modulus times area moment of inertia) of SNF rod segments. This information affects the structural dynamic finite element models of SNF. So far, the difference between the minimal EI of surrogate SNF used in testing and realistic, as-measured SNF EI has not been significant in terms of predicting survival or failure during transportation scenarios. The EI of real SNF is higher than the EI of surrogate fuel rods used in the MMTT and 30 cm fuel assembly drop tests, but that typically means that the as-tested surrogate SNF rods bend more than they realistically should. The higher EI of real SNF means that it takes stronger loads to deflect the fuel rods, so the surrogate SNF is more flexible than it should be, which is a conservative condition.

For fuel assembly structural components there are plans to evaluate strength through testing at PNNL, but that effort is mainly intended to assist in model validation. Nevertheless, the test program could reveal important information about component strength. At this point, the MMTT and 30 cm cask drop efforts both indicate that fuel assembly structures are not expected to experience gross failure. Grid spacers are expected to buckle/crush/deform plastically during the 30 cm drop, but the assembly skeleton is not expected to experience gross deformation or failure during any NCT loads. It remains to be determined whether the fuel assembly is vulnerable to damage during extended dry storage. All structural dynamic analyses will evaluate fuel assembly components using material strength estimates.

Canisters are the subject of relatively large research activities aimed at understanding the potential for CISCC in a dry storage environment. Tests are being planned to study the coastal environment CISCC crack initiation, and CISCC crack growth rates. Canister cracking is an important concern. CISCC could be such a large problem that repackaging frequently is necessary to avoid through-wall cracks. CISCC could be no problem at all because the environment inside an overpack is not suitable for CISCC. The cumulative effects framework will make initial assumptions about crack presence, crack initiation, and crack growth rates. Recent canister surface corrosion research is summarized in Schaller et al. 2020.

Bare fuel casks are not the subject of significant current R&D. Unlike welded canister systems, bare fuel casks have bolted lid systems that form the containment boundary. Bolted closures can be complex in their behavior, and some R&D work was done within the last 10 years on the ability of nonmetallic seals to withstand fire conditions. Fire conditions are beyond the scope of cumulative effects because they are a hypothetical accident condition, but a literature search is needed to determine if any technical issues are within scope.

In general, this area needs more work done to ensure that the latest research is incorporated into the cumulative effects analysis. One area is to monitor the progress of SFWST program research and identify how the research fits into the cumulative effects framework. A regular, yearly effort is recommended to study the reports and determine whether or not their content affects the cumulative effects analysis. The gap study (Saltzstein et al. 2020), which is regularly updated, is an important document for monitoring and providing input about the cumulative effects analysis progress.

Beyond the SFWST program, it is important to monitor the progress of the ASME canister inspection code case and the research being done and discussed through the Electric Power Research Institute Extended Storage Collaboration Program. It is also important to maintain contact with our international collaborators from Spain, Germany, and Korea. In addition, a general literature review is recommended, particularly to include published technical research from international sources.

Recommended Research Topics Related to Test Data Incorporation:

- Monitor SFWST program research developments.
- Monitor the ASME code case.
- Monitor international developments through Electric Power Research Institute Extended Storage Collaboration Program.
- Perform a literature search for cumulative effects topics.

6 CUMULATIVE EFFECTS ANALYSIS MODELING FRAMEWORK

The analysis of cumulative effects requires the use of numerical models that are similar to the models that have already been developed and validated for the SFWST program. The type of models discussed here is engineering mechanics models, which implement physical laws and commonly accepted engineering theories to calculate the response of systems to applied loading conditions. While some test data are available from SFWST experiments, the information needed for the cumulative effects analysis has to be fully consistent with the scenario being evaluated. Cumulative effects analysis is primarily a modeling application. The role of testing in this application is to validate the models and provide confidence that the engineering-level models adequately represent the behavior of the as-tested scenarios. This section discusses the cumulative effects modeling framework. The goal is to explain how the different models fit together within the framework to complete the analysis, which has a larger scope and time scale than typical engineering models.

The cumulative effects modeling framework is illustrated in Figure 4. The top of the figure shows a number of single-scenario models. All of these models exist in some form already. PNNL has been modeling and analyzing the relevant scenarios for the SFWST program, other DOE Office of Nuclear Energy programs, the NRC, and other sponsors for many years. Each of these single-scenario models defines how the SNF and its surrounding system behave in a particular loading and physics environment. For example, transportation generally refers to the rail transportation of a cask containing SNF. The physics of interest are dynamics (motion) and structural dynamics (transient structural deflections) that happen as a result of the mechanical shock and vibration during transportation. The topic is large enough that many PNNL technical reports and technical papers have been written to describe and discuss the models, including Klymyshyn et al. (2018). The point is that the array of single-scenario models is needed to provide input to the life cycle cumulative effects analysis. Each of the life cycle scenarios defined in Figure 4 is a separate life cycle evaluation. The life cycle evaluation draws information from the single-scenario models. It is anticipated that the magnitude of cumulative effects will be very small, so each scenario can be calculated separately, and the results can be summed or superposition can be used to combine all of the loads. If that turns out to not be the case, then combined scenario or multiphysics models might prove to be necessary. An example of a multiphysics model is a combined structural and thermal analysis that solves for stress, strain, and temperature at the same time.

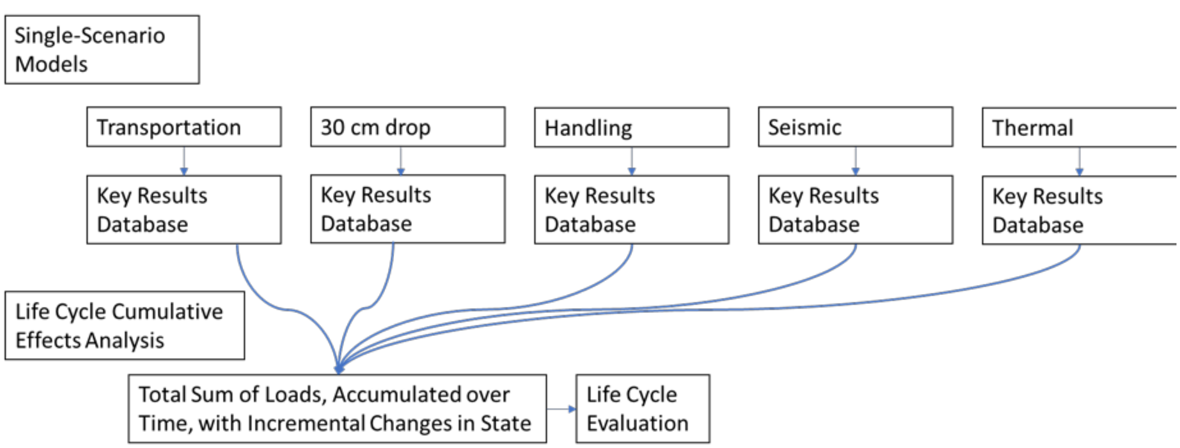

Figure 4. Cumulative Effects Modeling Framework

All of the single-scenario models point to a key results database. For structural dynamic models, the database could include stress, strain, bending moments, forces, accelerations, and other possible results. The thermal analysis database would include temperature, but it might also include air velocity at the vents, particle deposition metrics, or other technical information. The key results of interest to cumulative effects still remain to be determined.

One challenge of the single-scenario models is that they need to select a cask or canister design as well as SNF assembly design for evaluation. There are too many casks, cradles, and fuel assembly designs to evaluate every combination. PNNL is developing a damage model to generalize the 30 cm drop scenario (Klymyshyn et al. 2020) to understand the potential range of response of SNF to the 30 cm cask drop scenario. A similar level of generalization is needed for the other single-scenario models. The transportation scenario might be so benign that it can be ignored in the context of cumulative effects, but more evaluation needs to be completed before that can be concluded.

An important point about Figure 4 and the cumulative effects analysis problem in general, is that while it might look like an enormous problem, the intent is to use analysis to economically reduce the size of the problem to reach a useful conclusion. PNNL engineers already have a significant understanding of the phenomena represented in the single-scenario models, plus existing models that were used for similar analyses. This modeling task is less about building new models than it is about upgrading existing models to provide the results in the format needed for cumulative effects analysis and to generalize the models so they can reasonably cover the cask, canister, and SNF assembly designs in the US inventory. PNNL's expertise in this area makes this is a very manageable task.

One area in which new modeling is needed is the thermal stress analysis discussed in Appendix A. This modeling is not listed in Figure 4 because it is a hybrid thermal/structural problem. The thermal models of canister systems exist, but new structural models of canisters are needed to calculate thermal expansion stress. This modeling effort is a priority because it is needed to acquire information related to crack growth and fatigue.

One area in which a new modeling tool is needed is crack growth analysis. The crack analysis tool is described in Appendix B. This tool is intended to evaluate the results calculated in the single-scenario models shown in Figure 4 to determine the potential for cracks grown during structural dynamic events. It is essentially a post-processing tool that will be run in MATLAB. This is a high-priority activity because the new tool and capability are needed to address the significant concerns about CISCC in the cumulative effects analysis. Previous fracture mechanics work in this area (Klymyshyn et al. 2016) used a static elastic-plastic fracture mechanics methodology to determine that gross structural failure of a canister section was more likely than a through-wall crack developing during a cask tip-over event. The crack analysis tool is meant to use a dynamic crack propagation methodology that will track the growth of a hypothetical crack in a canister over a variety of loading conditions.

<u>Recommended Research Topics Related to the Modeling Framework:</u>

- Thermal stress analysis model development
- Crack propagation analysis tool
- Generalizing existing single-scenario models.

7 CONCLUSION AND HIGH PRIORITY NEXT STEPS

The cumulative effects analysis task began this year, and some technical work and planning were accomplished. This report explains the cumulative effects issue and explains how PNNL proposes to approach the problem. This is seen as a multi-year research task, but PNNL's goal is to simplify the problem as much as possible to reach effective closure on this technical issue.

An initial set of working assumptions (up to 300 years and 5 interim storage locations) was proposed to evaluate the uncertain time scale and variable life cycle of SNF. The working assumptions provide a target for evaluation and are larger than what we think would be reasonable estimates. The working assumptions are expected to be updated regularly as the work progresses. The problem is expected to grow smaller as we perform the analyses and learn the importance of the various factors. For example, all handling and transportation activities might be negligible and the 50-year time period might be too short to bother considering. Initial cumulative effects analysis is needed before these types of conclusions can be made, which makes starting the analyses a high priority.

The thermal stress modeling performed during fiscal year 2020 determined that thermal stresses in canister walls are significant enough that they need to be considered as part of the total canister stress state. The stress state is expected to affect the susceptibility of the structure to cracking and the rate of crack growth. PNNL needs to continue this area of analysis by considering transient temperature variations, including daily, yearly, and extended time periods up to the working assumption limit of 300 years. Thermal stress modeling remains a high priority for this task.

Evaluating canister failure due to cracking is currently a high priority. PNNL needs to develop a dynamic crack propagation model to determine whether transient structural loads can cause an existing crack to advance. Transportation loads are very small on SNF, but canister loads have not been fully evaluated yet. Existing PNNL models can calculate transient canister stresses and strains, but the crack tool is needed to relate stress or strain history to crack advancement. Developing a crack propagation model is a high-priority task because it will help identify the minimum threshold necessary for cracks to grow in length, and that affects which phenomena are negligible for cumulative effects.

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Appendix A

Thermal Stress in Canisters

Thermal stress in welded steel spent nuclear fuel (SNF) dry storage canisters is an area about which more understanding is needed to fill knowledge gaps related to the long-term dry storage of SNF. The total stress state in canister walls is affected by residual stress from the fabrication process, which is estimated to be tensile through the wall thickness, which makes the canisters susceptible to chloride-induced stress corrosion cracking (CISCC). The constant tensile stress provides an environment for cracks to propagate all the way through the canister wall. The internal pressure of the welded canister also provides tensile, axial, and hoop stress, and a typically small compressive radial stress. Thermal stress during extended dry storage conditions is not a widely analyzed or well understood phenomenon. Thermal analyses generally show the temperature state is not uniform in a canister system under design-basis thermal conditions. Non-uniformities of temperature (temperature gradients) cause thermal stresses in a structure as cooler material restrains the expansion of hotter material. The goal of this work is to determine whether thermal stresses are negligible in magnitude (can be ignored) or if further modeling and analysis is needed to close this knowledge gap.

The modeling work conducted under this project indicates that thermal stresses are too high to be neglected when considering a SNF canister's total stress state. Section A-1 describes the canister thermal modeling, Section A-2.2 describes the thermal stress modeling, and Section A-2.3 discusses what needs to be done to fill the knowledge gap for the Spent Fuel and Waste Science and Technology (SFWST) program.

A-1 Canister Thermal Modeling

Thermal modeling of SNF canister systems is often done to confirm the system will remain below design-basis temperature limits. The decay heat of SNF tends to heat its enclosure, so the goal of the thermal design of SNF canister dry storage systems is to facilitate transmission of heat to the environment, without compromising the system's radiation shielding, containment, criticality, or structural functions. Pacific Northwest National Laboratory (PNNL) has extensive experience in thermal modeling of SNF canister systems. Fort et al. (2016) is a publicly available example of this kind of thermal modeling. This study uses the thermal model from Fort et al. as the basis for estimating canister temperatures that are then used to estimate canister stresses. This section describes the thermal modeling used to extract temperature data for input into the thermal stress models described in Section A-2.

The thermal model described by Fort et al.(2016) is a "High Heat Load Thermal Analyses" developed using two computational codes, COBRA-SFS and STAR-CCM+. In this report, however, analyses focus on Fort et al.'s STAR-CCM+ models, which are a representation of the MAGNASTOR storage system at the Catawba Nuclear Station independent spent fuel storage installation (ISFSI). The MAGNASTOR canister system contains a basket that holds SNF assemblies, a transportable storage canister (TSC), and a ventilated concrete storage overpack (or cask). The MAGNASTOR model in STAR-CCM+ focuses on the storage system basket region, along with the encompassing components, while treating the fuel as an average heat load. The models used by Fort et al. assume "best estimate" considerations and therefore omit conservations associated with safety-basis calculations and design bases for spent fuel storage systems. Fort et al. kept the ambient conditions consistent, throughout all models, at 298 K.

The model of Fort et al. (2016) was re-meshed using version 14.02.010 of STAR-CCM+. The re-meshed model contains a total of 380 interface boundaries connecting 78 separate regions. The volume mesh contains 7,509,880 cells, 36,683,412 faces, and 29,673,739 vertices. Results presented here focus solely on the TSC shown in Figure A.1B.

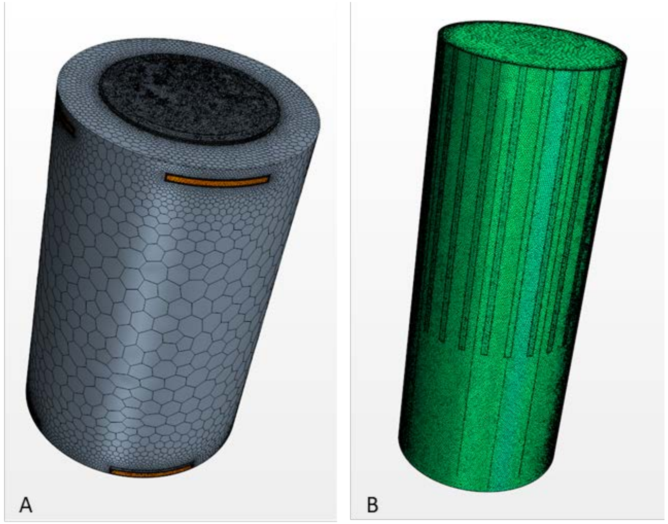

Figure A.1. Images showing the updated MAGNASTOR mesh of the (A) entire assembly, and the (B) transportable storage canister.

In addition to re-meshing the model, ambient temperatures were varied to reflect annual changes at the Hanford Site in Washington State.[1] All other initial and bounding constants were unchanged. A total of four thermal cases encompass the ambient temperature range: 0ºF (255 K), 45ºF (280 K), 76ºF (298 K), and 90ºF (305 K). In all cases, the same heat load was maintained to identify the effect that a temperature variation would have on the thermal storage canister. The four cases benefit the investigative effort because understanding the ambient temperature changes under steady-state (non-time varying) conditions will provide a baseline for long-term transient (time varying) decay heat models.

[1] https://weatherspark.com/y/145321/Average-Weather-at-Hanford-Washington-United-States-Year-Round

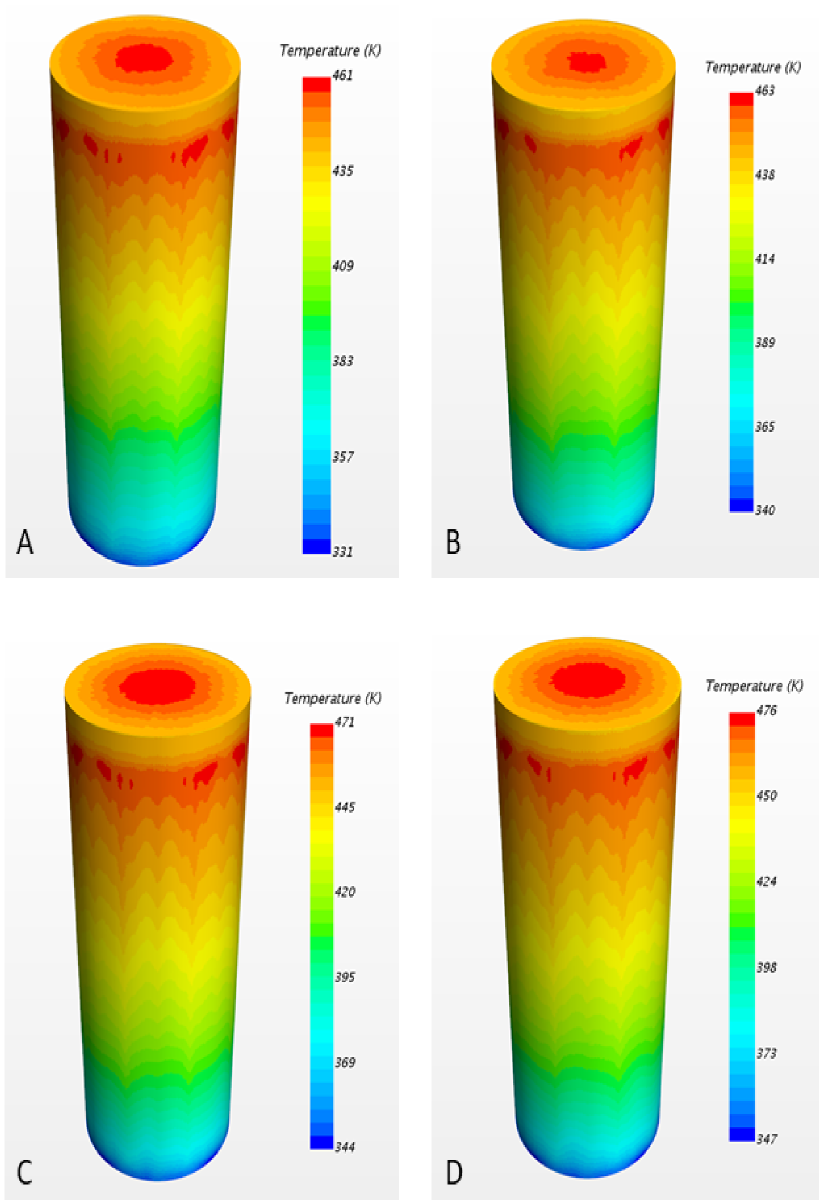

Figure A.2. Temperature distribution of the transportable storage canister for the temperature cases, (A) 255 K, (B) 280 K, (C) 298 K, and (D) 305 K.

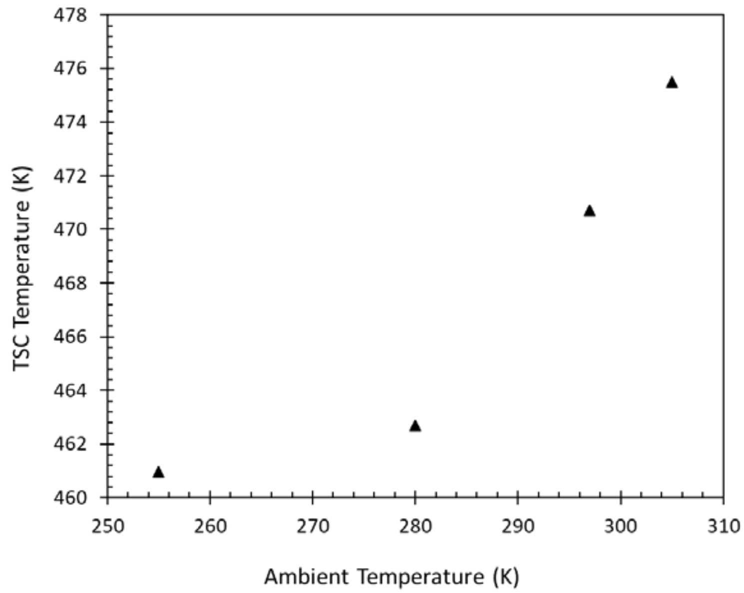

Figure A.3. Temperature plot showing maximum storage canister temperature in relation to ambient temperature.

Results from the thermal models show that temperature variation of the canister is minimal in comparison to the ambient temperature range. Such a minimal change may not have a significant impact on thermal stresses; however, such a conclusion may not be drawn without conducting transient studies on the model. From Figure A.3, it can be seen that the maximum canister temperature increases with the ambient temperature, although not linearly. Higher ambient temperatures appear to have a more significant effect on the canister because the plot shows a steeper gradient beyond an ambient temperature of 45^{o}F (280 K). Running additional models beyond the temperature extremities presented here will serve to better understand thermal conditions and thermal effects during rapid temperature gradient days, i.e., large temperature changes during a single day and long-term (20–100 years for example) thermal effects.

The focus of the current study is on long-term thermal stresses on the TSC, and the stress analyses are performed using ANSYS APDL. Each mesh cell containing temperature data is therefore exported from the STAR-CCM+ model for use in the ANSYS APDL model. Section A-2 provides details about the use of the extracted temperature data.

A-2 Canister Thermal Stress Modeling

The objective of this modeling effort is to create an initial model to quantify the thermal stresses that exist in a MAGNASTOR canister to guide further research into the topic. This modeling effort is intended to be for information purposes only. This model has not been verified or validated. These thermal stresses are of particular interest for determining the impact of corrosion and cracking in the canister. Stress, corrosion, and cracking can have a greater impact on discontinuous zones, such as on the weld regions and where the lid and bottom of the canister meet the body.

A-2.1 *Model Description*

The thermal stress model is based on a standard height MAGNASTOR SNF storage system canister. The canister is close to 5 meters high and almost 1.75 meters in diameter. The canister model is not a precise match to the MAGNASTOR canister design, but it is close enough that the thermal and structural models are generally consistent. The intent is to calculate thermal stresses that are similar to those expected in a real SNF canister, without precisely calculating thermal stresses that are specific to the MAGNASTOR design. This geometry was modeled, and stresses were analyzed in ANSYS APDL. For enhanced computational efficiency a one-quarter symmetry section of the canister was modeled. A plot of the model geometry and ANSYS APDL mesh elements are shown in Figure A.4.

Representative canister welds were included in the model geometry. A plot of the volumes used to model the canister in ANSYS APDL is shown in Figure A.5. Different material properties were used for the weld regions. All welds consist of 2.54 cm wide seams. The welds are between the canister lid and body, horizontal through the middle of the canister body, and vertical from the canister lid to the canister base in the middle of the quarter section. Note that the placement of the canister welds is hypothetical and does not attempt to match the specific MAGNASTOR design.

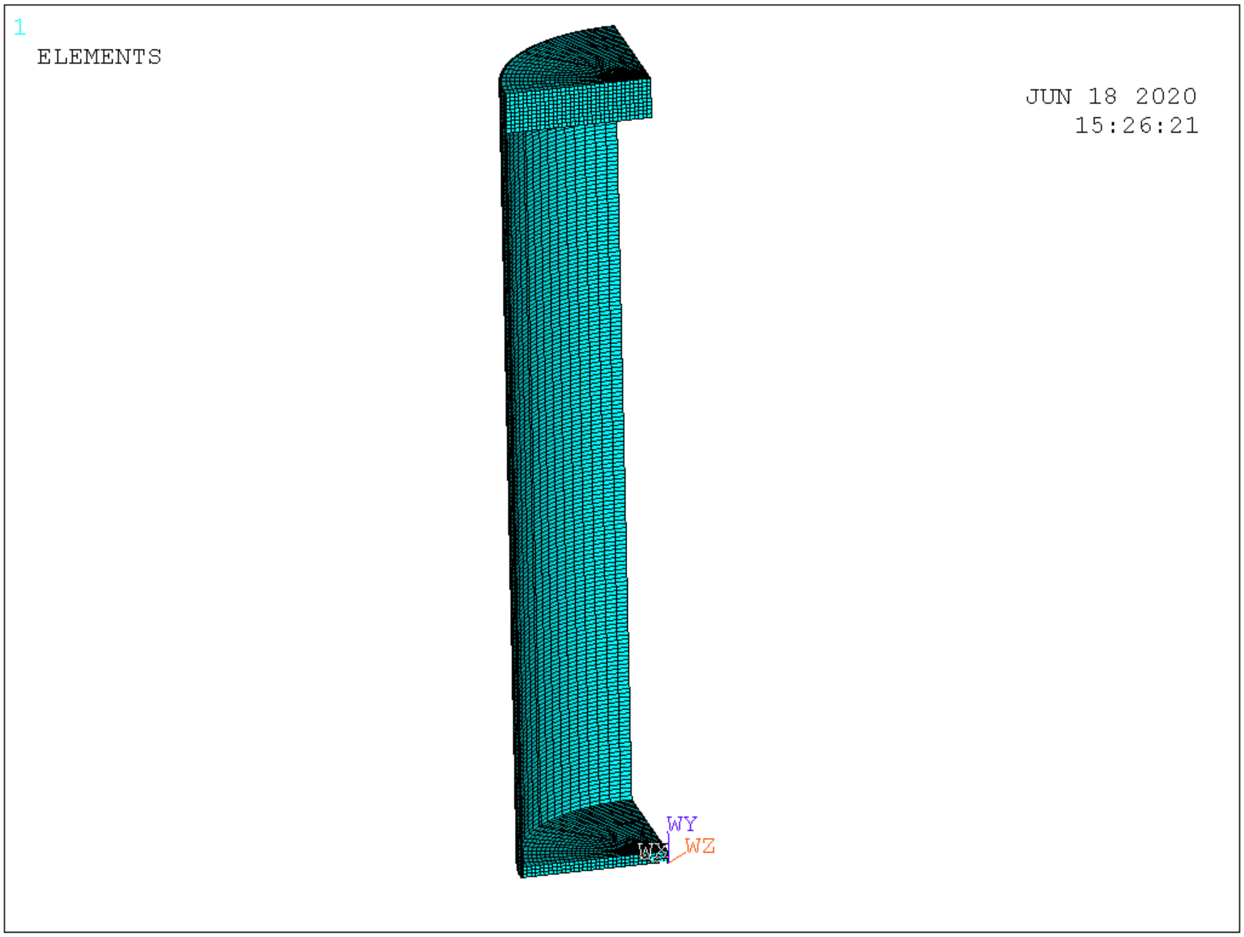

Figure A.4. ANSYS APDL model elements.

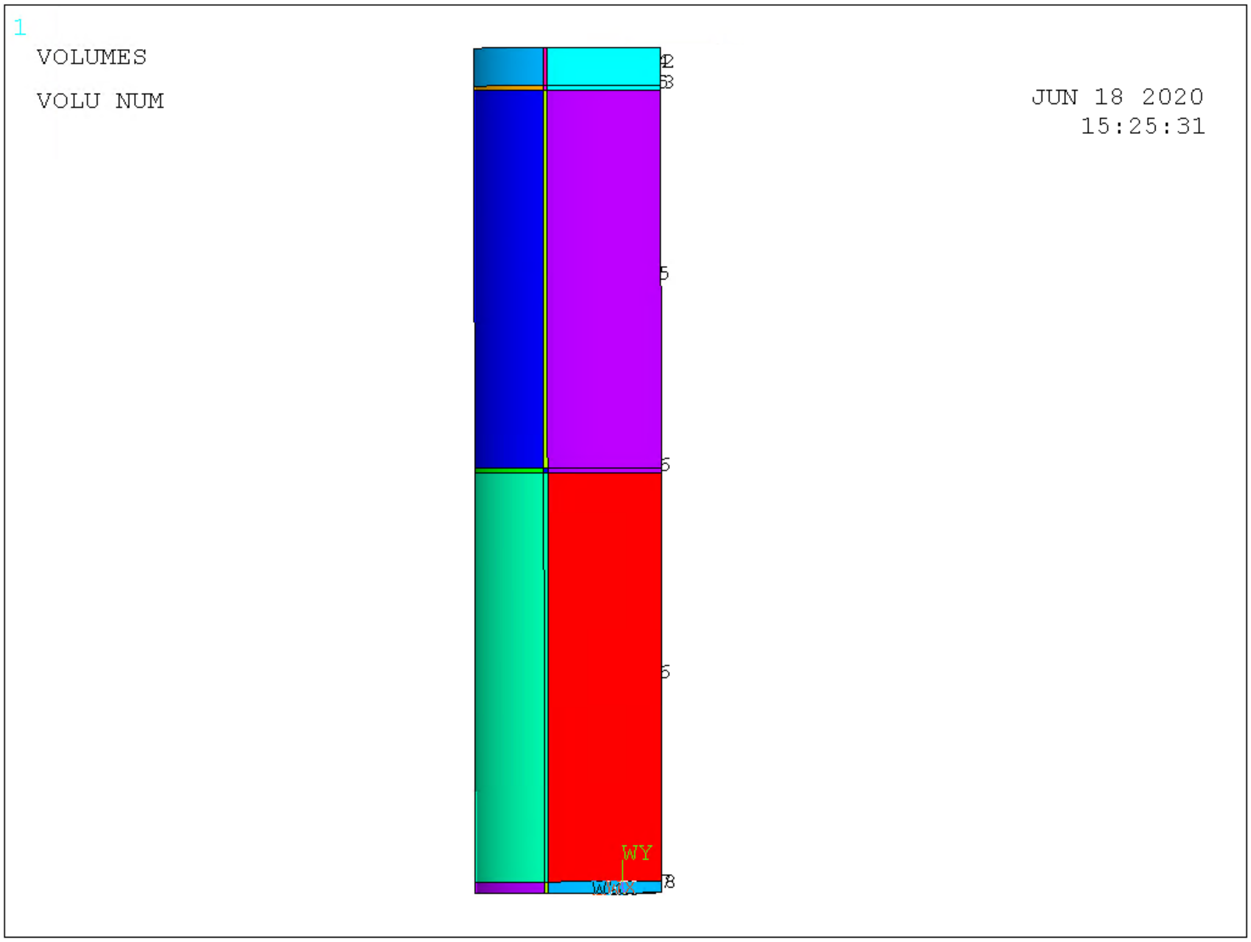

Figure A.5. Model weld geometry.

A-2.2 *DOF and Symmetry Boundary*

To enforce the symmetry boundary conditions the nodal degrees of freedom were fixed as shown in Figure A.6. Radial expansion on the edges was fixed. Also, the y direction degree of freedom was fixed on the bottom to model the canister sitting on a pedestal inside the overpack. The x, y, and z degree of freedom was fixed at the very center of the bottom to fix the canister in space and enable ANSYS to converge on a structural solution.

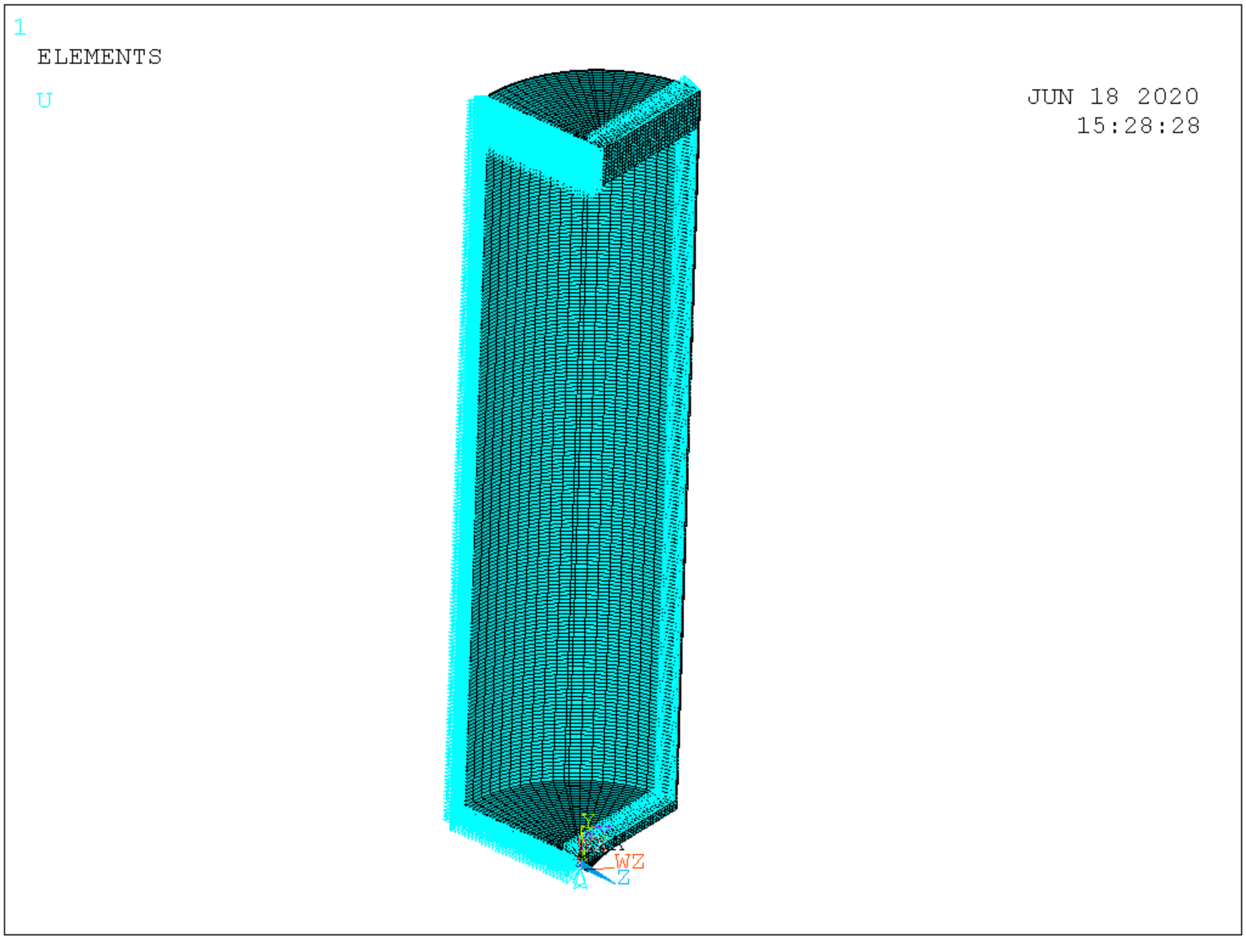

Figure A.6. ANSYS APDL boundary conditions on the symmetry planes.

A-2.3 *Material Properties*

For this model, material properties for 304 stainless steel were used for the canister. Weld joints were included in the geometry of the model and were modeled as 308 stainless steel. The material properties for the weld region are slightly different than for the canister body. These material differences contribute to stress discontinuities between the canister body and the weld region.

The material properties used for this model are summarized in Table A.1. Note that the material properties used in this study are constants. Future work will consider if temperature-dependent materials are needed or if constant values are sufficient for the analysis.

Table A.1. Material properties used for the canister.[a]

Material	Thermal Conductivity (W/m-k)	Coefficient of Thermal Expansion (m/m-K)	Modulus of Elasticity (Pa)	Poison's Ratio
304 SS	16.2	17.8e-6	193e9	0.29
308 SS	15.2	17.8e-6	195e9	0.29

(a) These material properties were selected from matweb.com, a general material information database whose entries list references that support the listed information (see reference list for each material type).

A-2.4 *Thermal Boundary Conditions*

The main objective for this study is to determine the thermal stresses in the canister. Thermal data from a separate STAR-CCM+ thermal fluid model of the MAGNASTOR full cask system was used to determine the surface temperatures inside and outside of the canister. These surface temperatures were applied to the ANSYS APDL model. The ANSYS model solves for the thermal gradients in the canister. Then the thermal gradients are used to determine the thermal expansion and subsequent stresses in the MAGNASTOR canister. In the STAR-CCM+ model, four different ambient temperatures cases were applied to the cask with a constant heat load of approximately 26.4kW. The resulting canister surface temperatures were used in the ANSYS APDL model.

Table A.2 summarizes the ambient temperatures surrounding the canister and resulting minimum and maximum canister temperatures. Because of the gas in the canister and ventilation air around the canister and inside the overpack, the maximum temperatures occur at the top center of the canister and the minimum temperatures occur at the bottom. For all cases, there is a gradual temperature gradient up the side of the canister. There are more extreme temperature gradients radially through the lid. Figure A.7 shows the temperature profile of the inside and Figure A.8 shows the temperature profile of the outside of the canister for the 297.6 K ambient case. The temperature gradient through the side of the canister is small, as shown in Figure A.9.

Table A.2. Canister temperature summaries.

Ambient Temp (K)	Minimum Canister Temperature (K)	Maximum Canister Temperature (K)
255.4	330.8	469.3
280.4	340.5	471.6
297.6	344.6	481.8
305.4	347.5	486.4

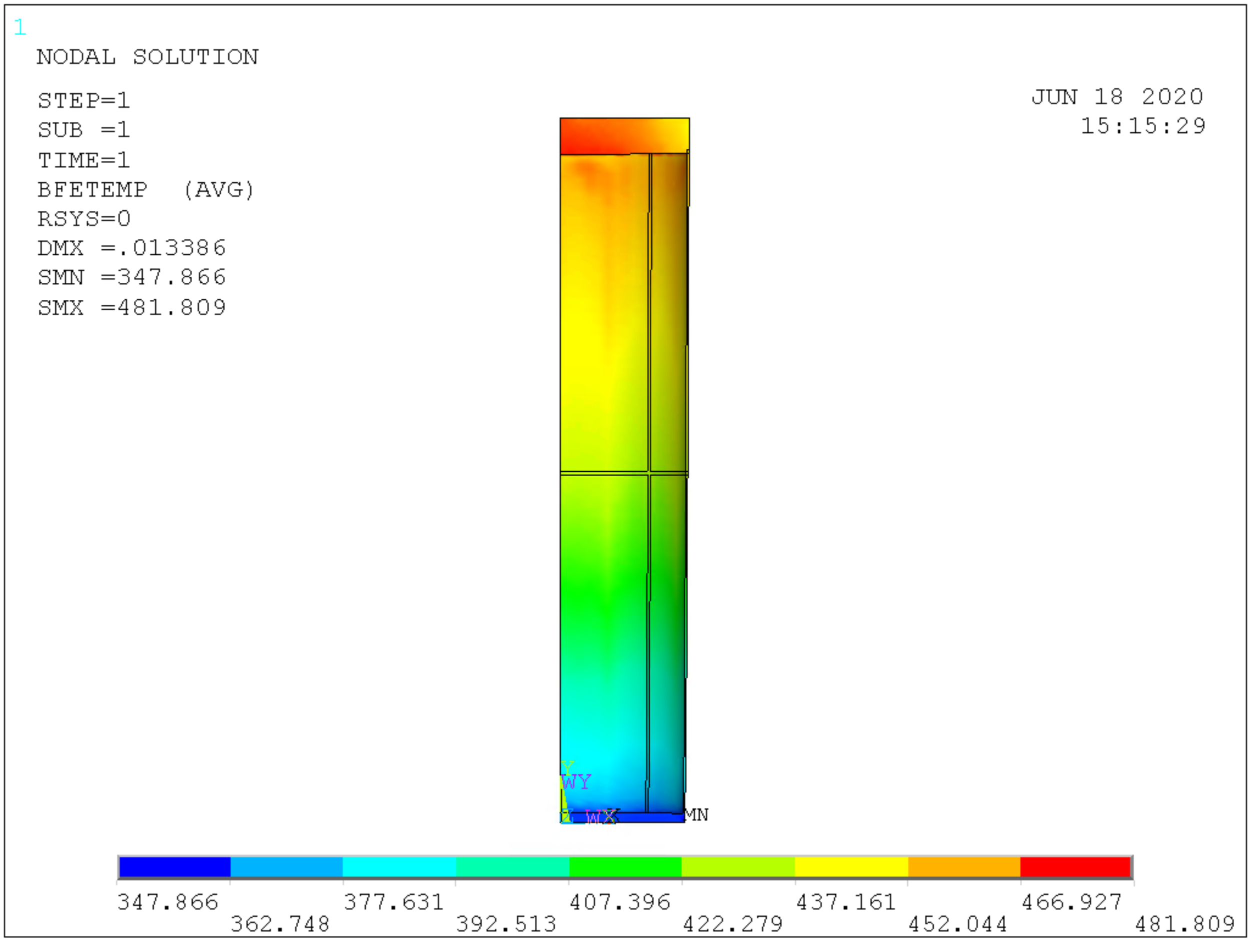

Figure A.7. Inside surface temperature contours (K) at 297.6 K.

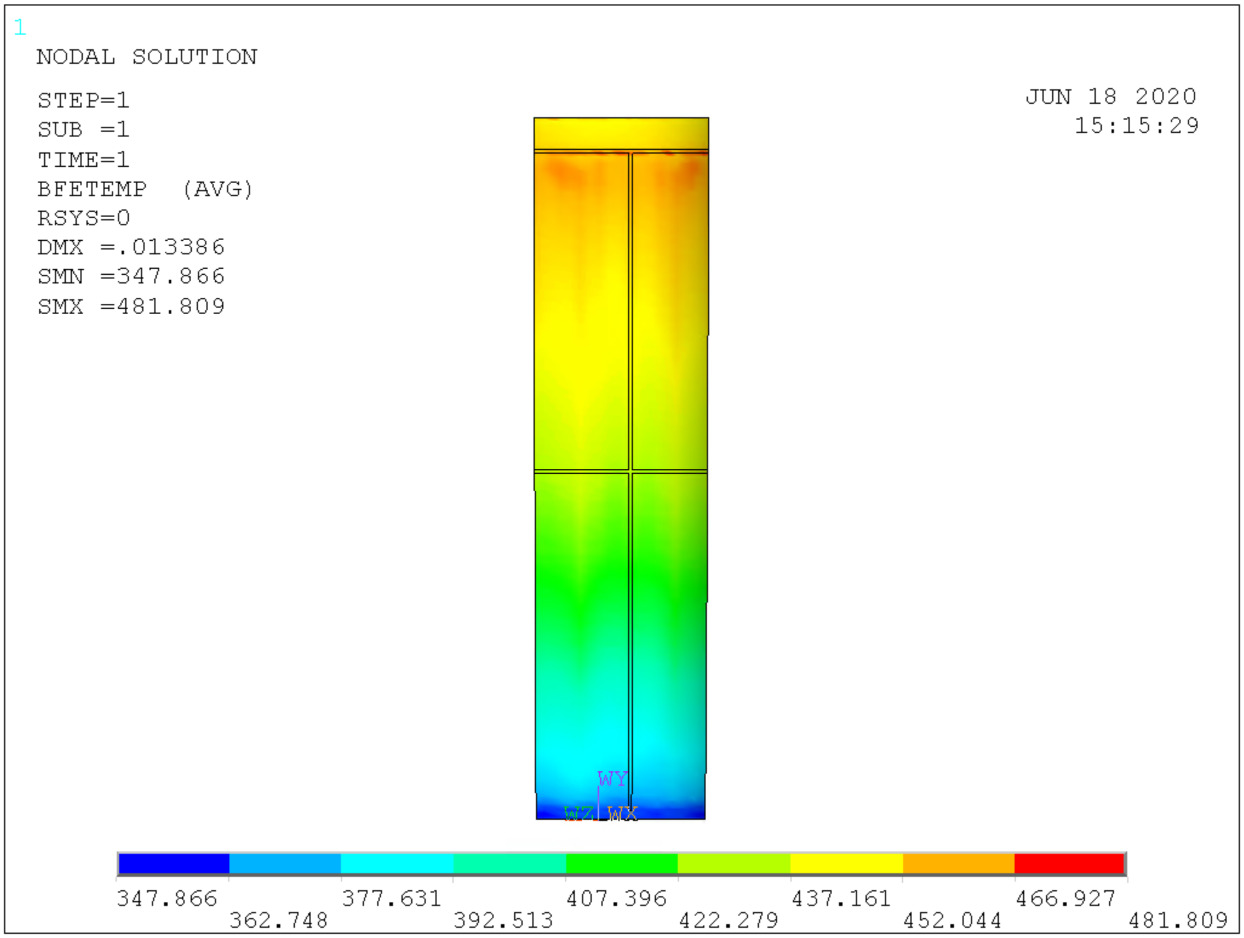

Figure A.8. **Outside surface temperature contours (K) at 297.6 K ambient temperature.**

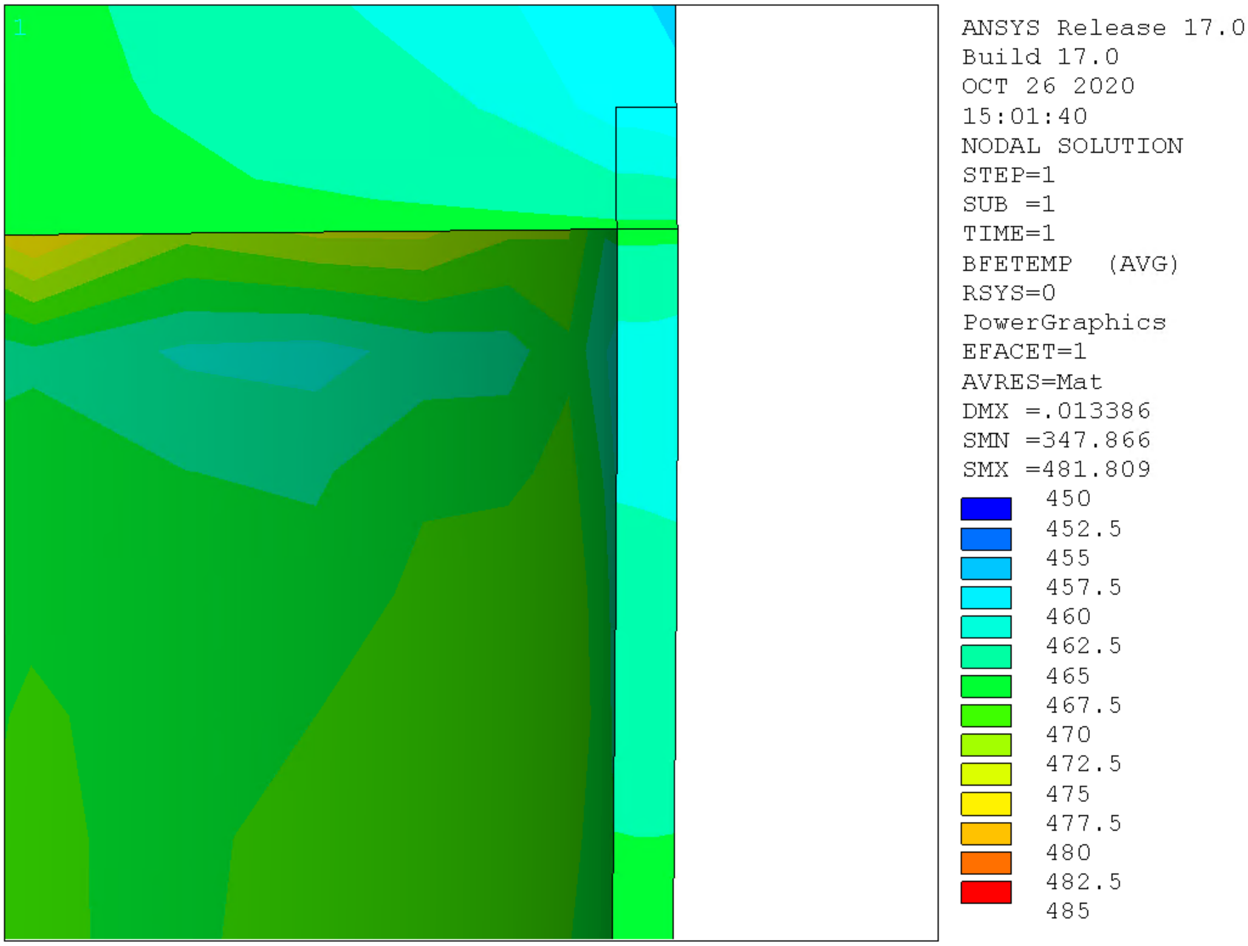

Figure A.9. Temperature gradient (K) through side of canister at 297.6 K ambient.

A-2.5 *Modeling Results*

From the ANSYS thermal model, the thermal expansion and mechanical stress can be resolved. The maximum von Mises stress that occurred in the canister at each ambient temperature are summarized in Table A.3. For all cases, maximum stress occurred in the weld region. This is due in part to a significantly higher amount of stress in the region where the canister lid and body meet, which is where the top horizontal weld is. The higher stress is due to a larger thermal gradient in this area. A detailed plot of the von Mises stress in the upper weld region is shown in Figure A.10. As seen in the figure, there is a significant difference in the stress between the canister lid, weld region, and canister body.

Figure A.10 through Figure A.13 show the von Mises stress in the outer surface of the canister. The stress profiles are almost identical between the different ambient temperature cases. Because of the similar stress profiles, the case where the ambient temperature was 297.6 K was selected to present more detailed plots of the stress in certain sections of the canister. The 297.6 K temperature is a somewhat standard temperature that falls within the typical temperature to which a MAGNASTOR system is subjected outside on a spent fuel storage installation. Figure A.14 through Figure A.18 show these detailed plots of the von Mises stress in the canister.

Table A.3. Maximum von Mises stress in canister and weld region.

Ambient Temperature (K)	Max Stress Canister Body (Pa)	Max Stress Weld Region (Pa)
255.4	59.0E6	63.2E6
280.4	62.0E6	66.4E6
297.6	69.0E6	75.9E6
305.4	69.8E6	76.9E6

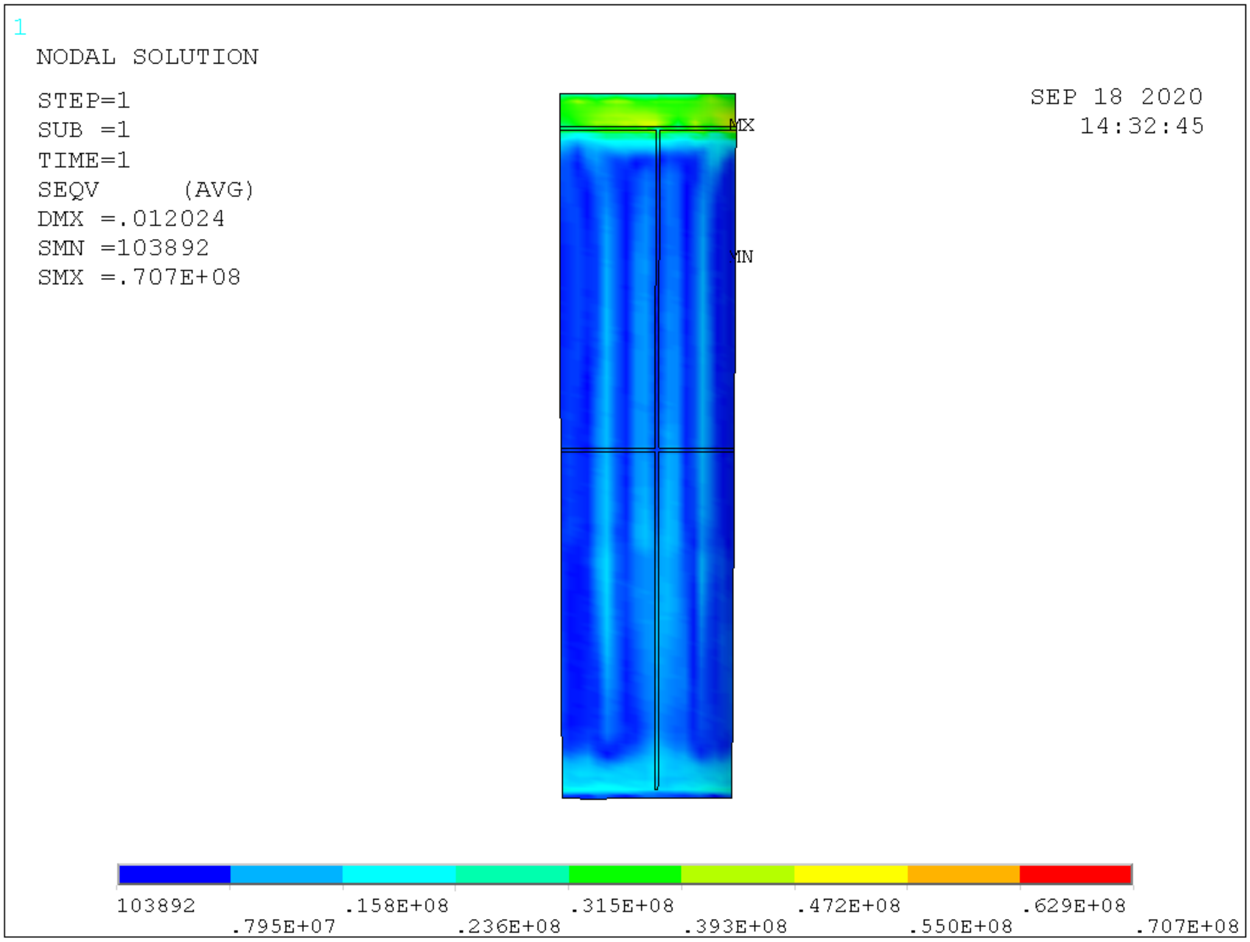

Figure A.10. Von Mises equivalent stress (Pa) outside canister at 255.4 K ambient temperature.

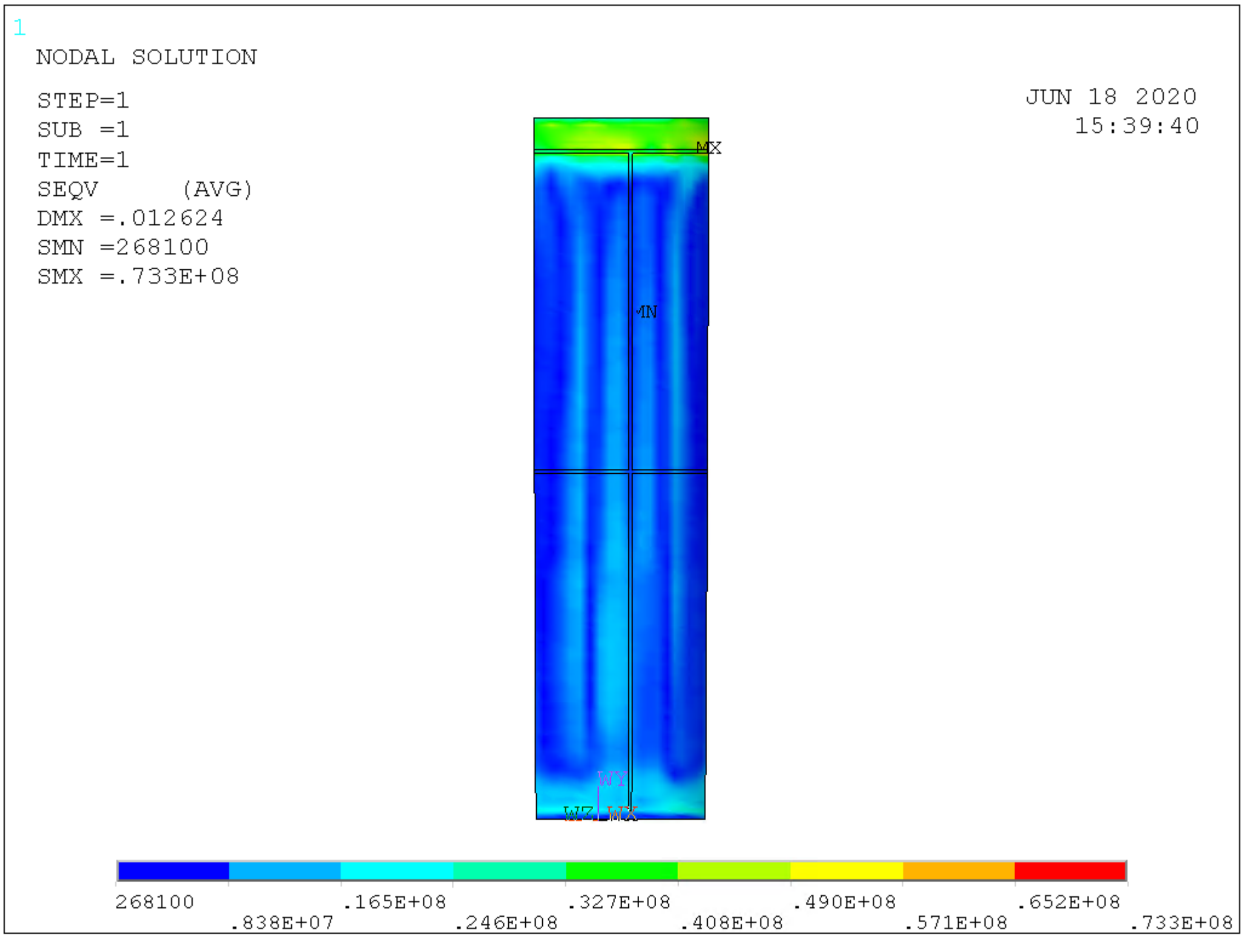

Figure A.11. **Von Mises equivalent stress (Pa) outside canister at 280.4 K ambient temperature.**

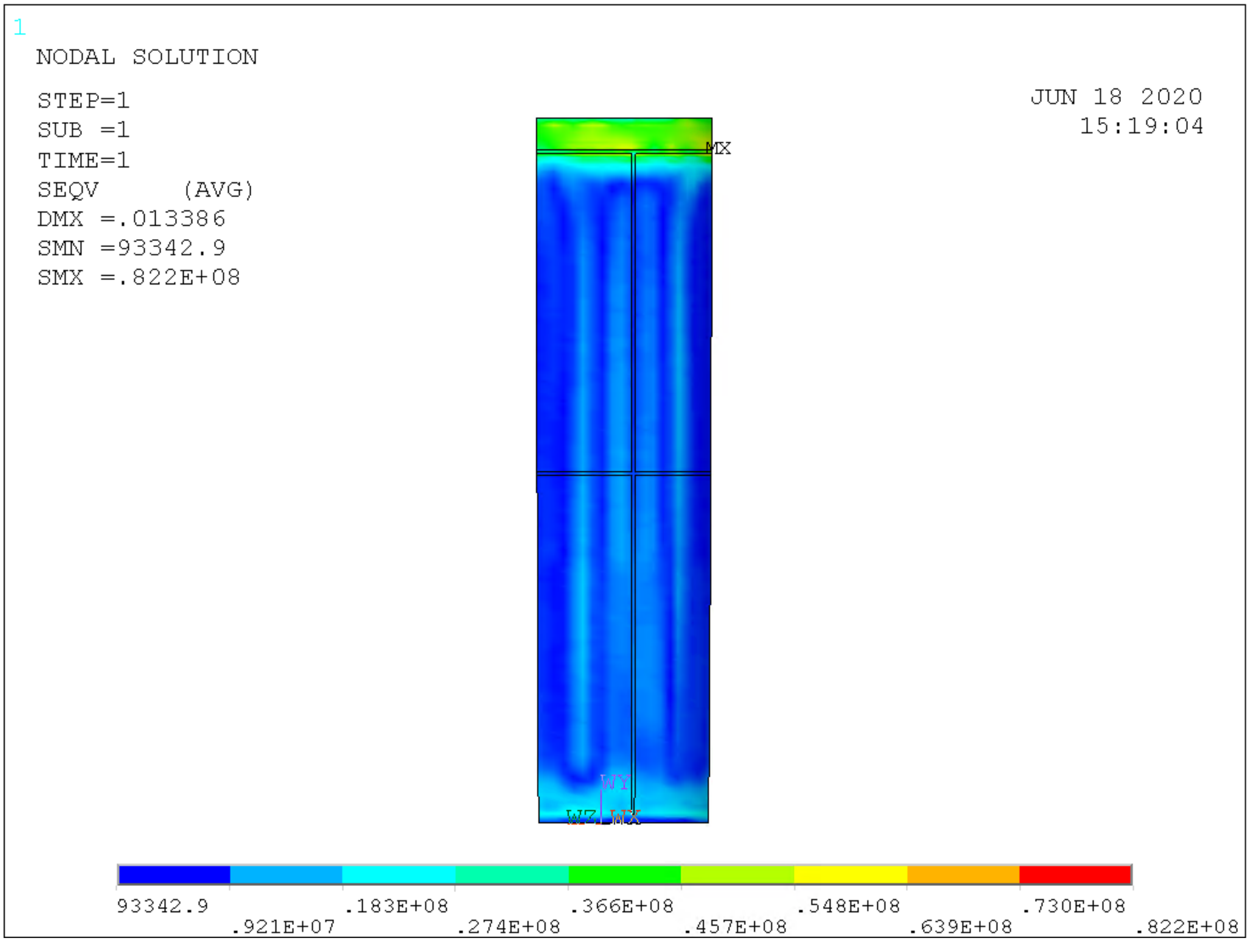

Figure A.12. Von Mises equivalent stress (Pa) in canister at 297.6 K ambient temperature.

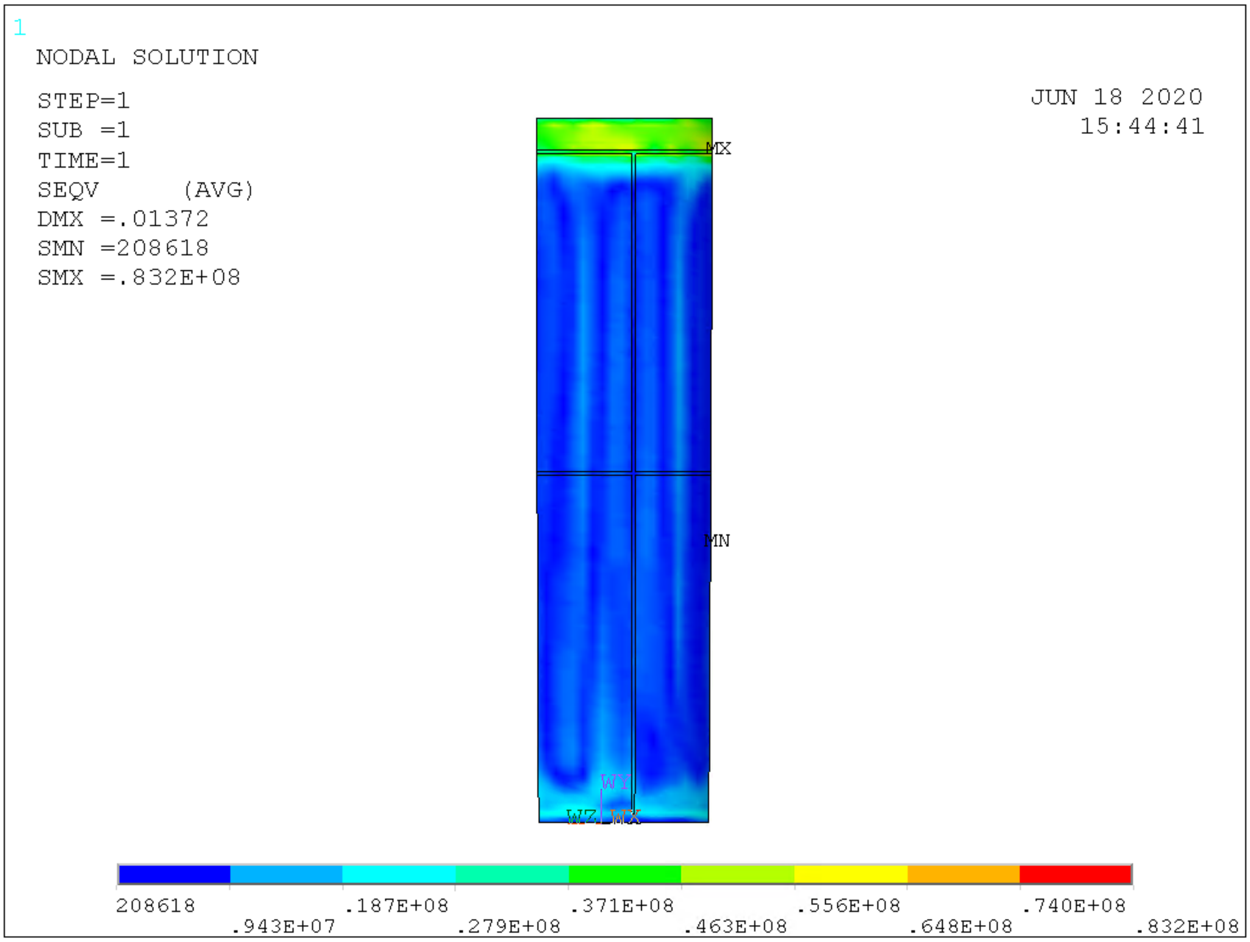

Figure A.13. Von Mises equivalent stress (Pa) in canister at 305.4 K ambient temperature.

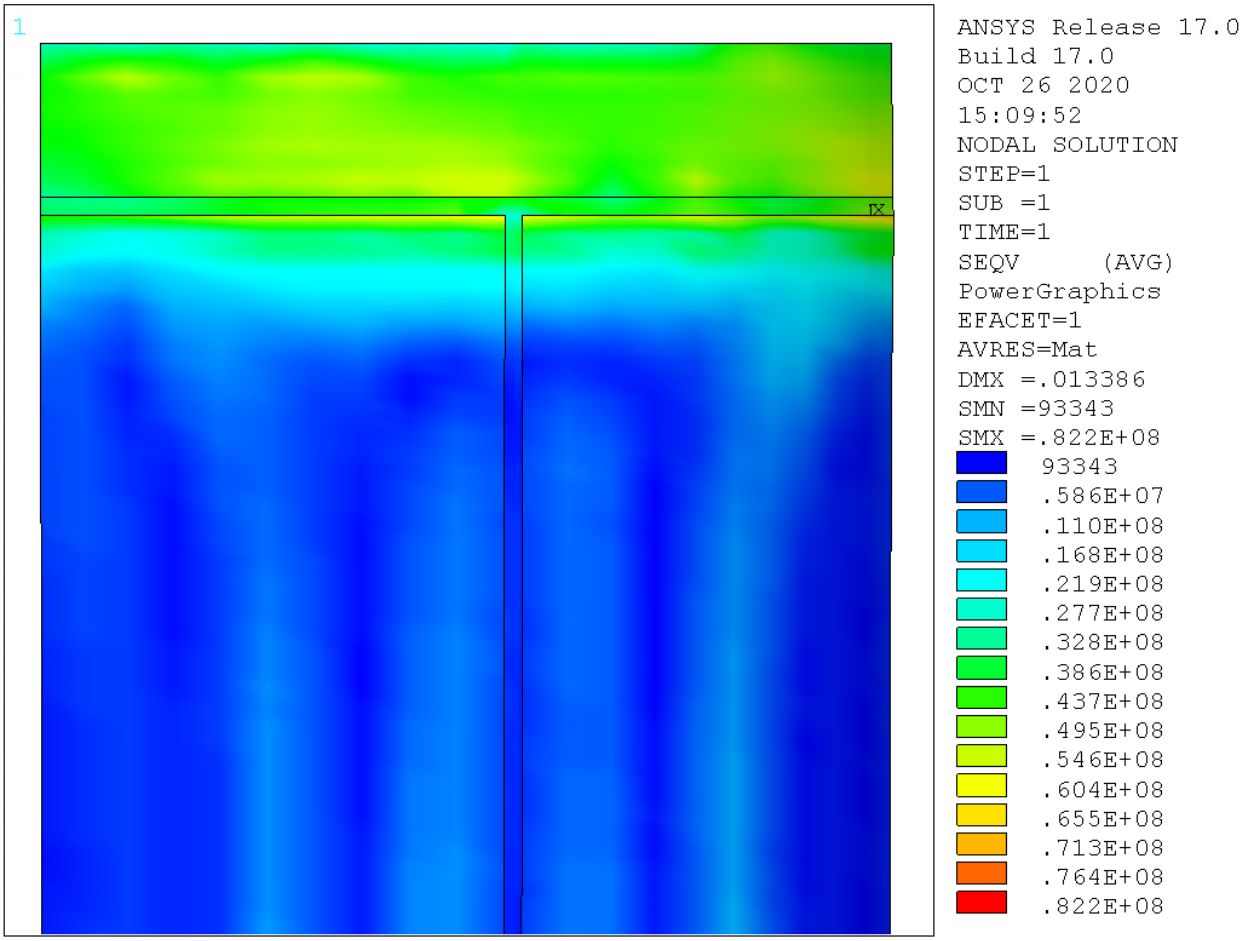

Figure A.14. Von Mises equivalent stress (Pa) in outside lid body weld region at 297.6 K ambient temperature.

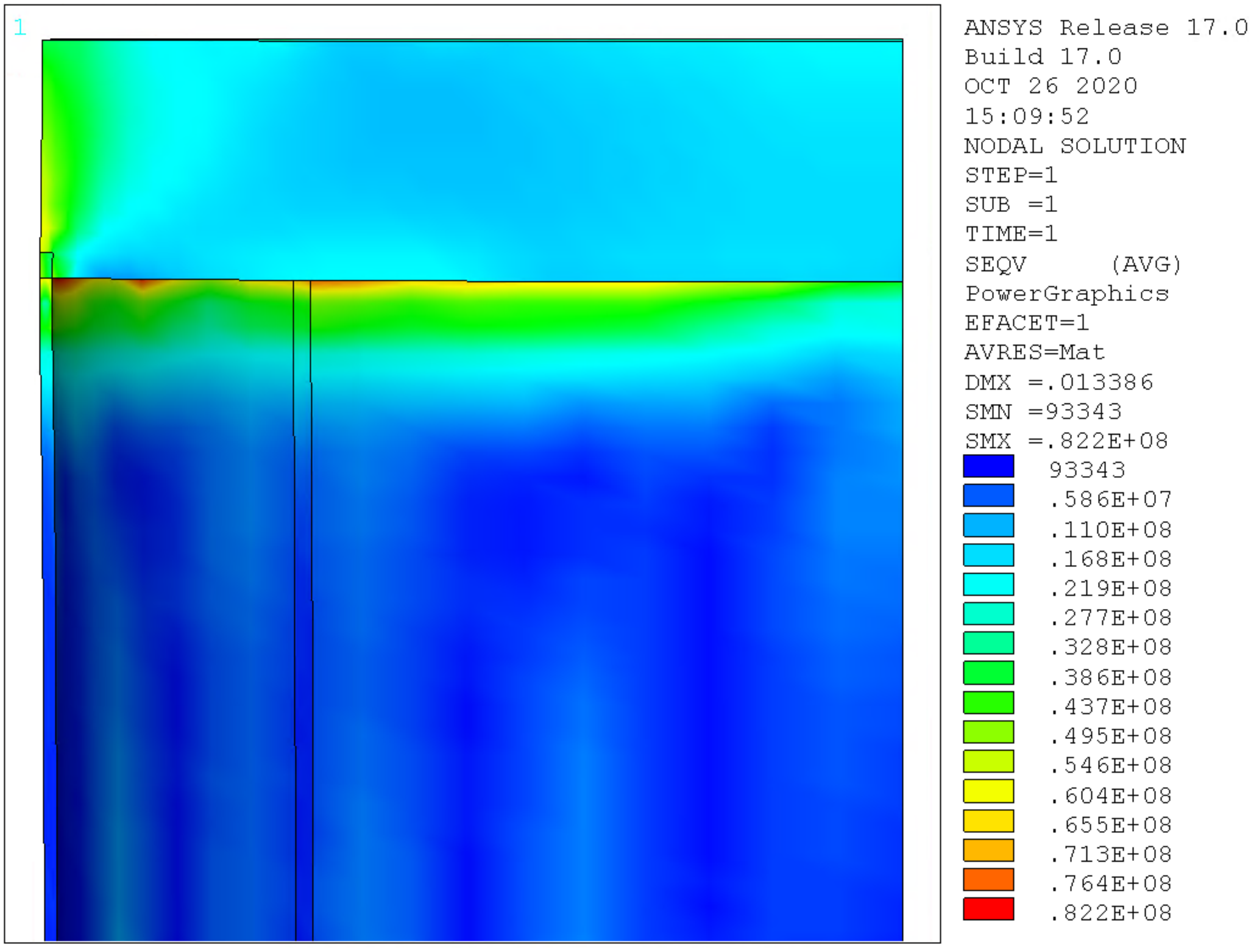

Figure A.15. Von Mises equivalent stress (Pa)inside top lid at 297.6 K ambient temperature.

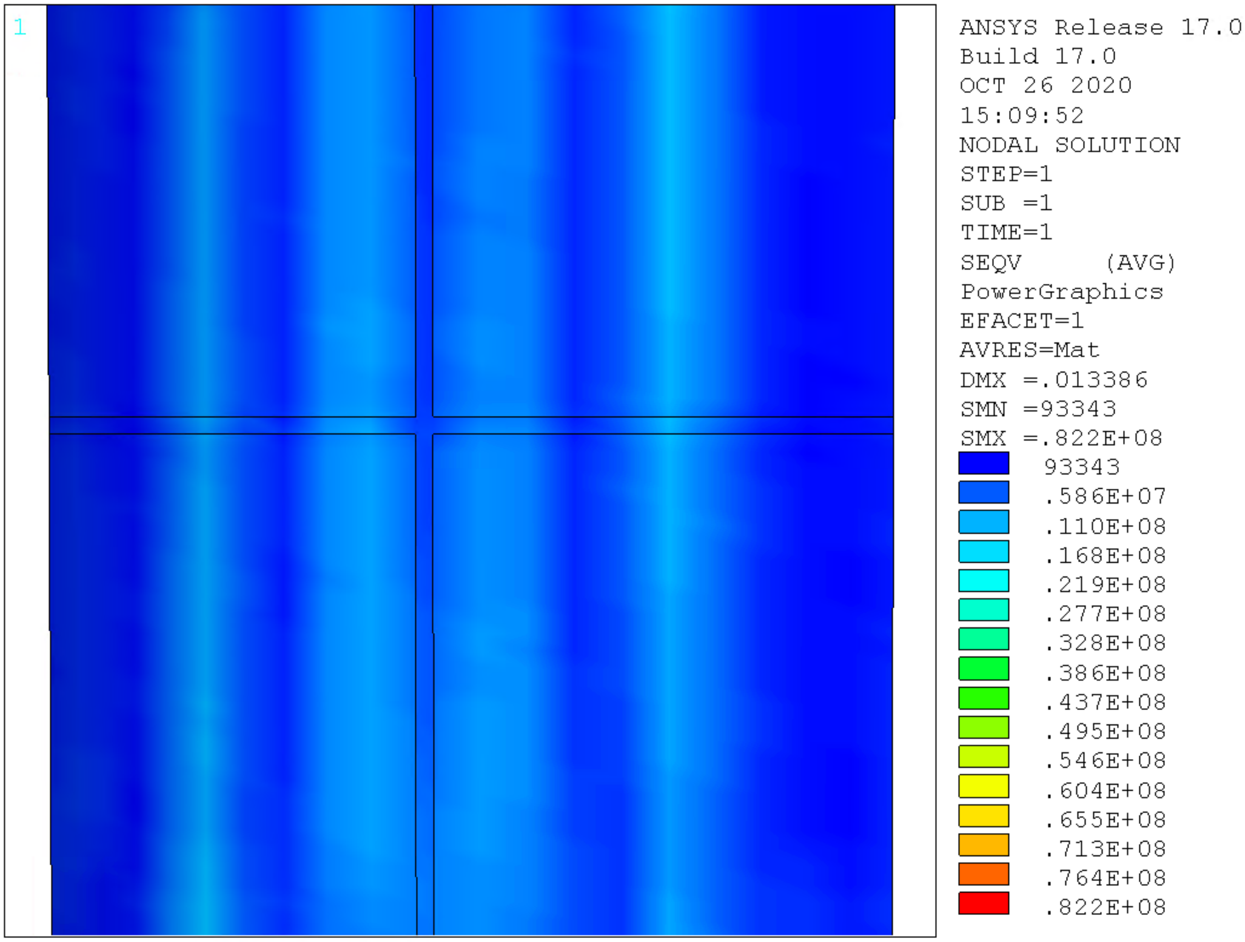

Figure A.16. Von Mises equivalent stress (Pa) outside middle weld region at 297.6 K ambient temperature.

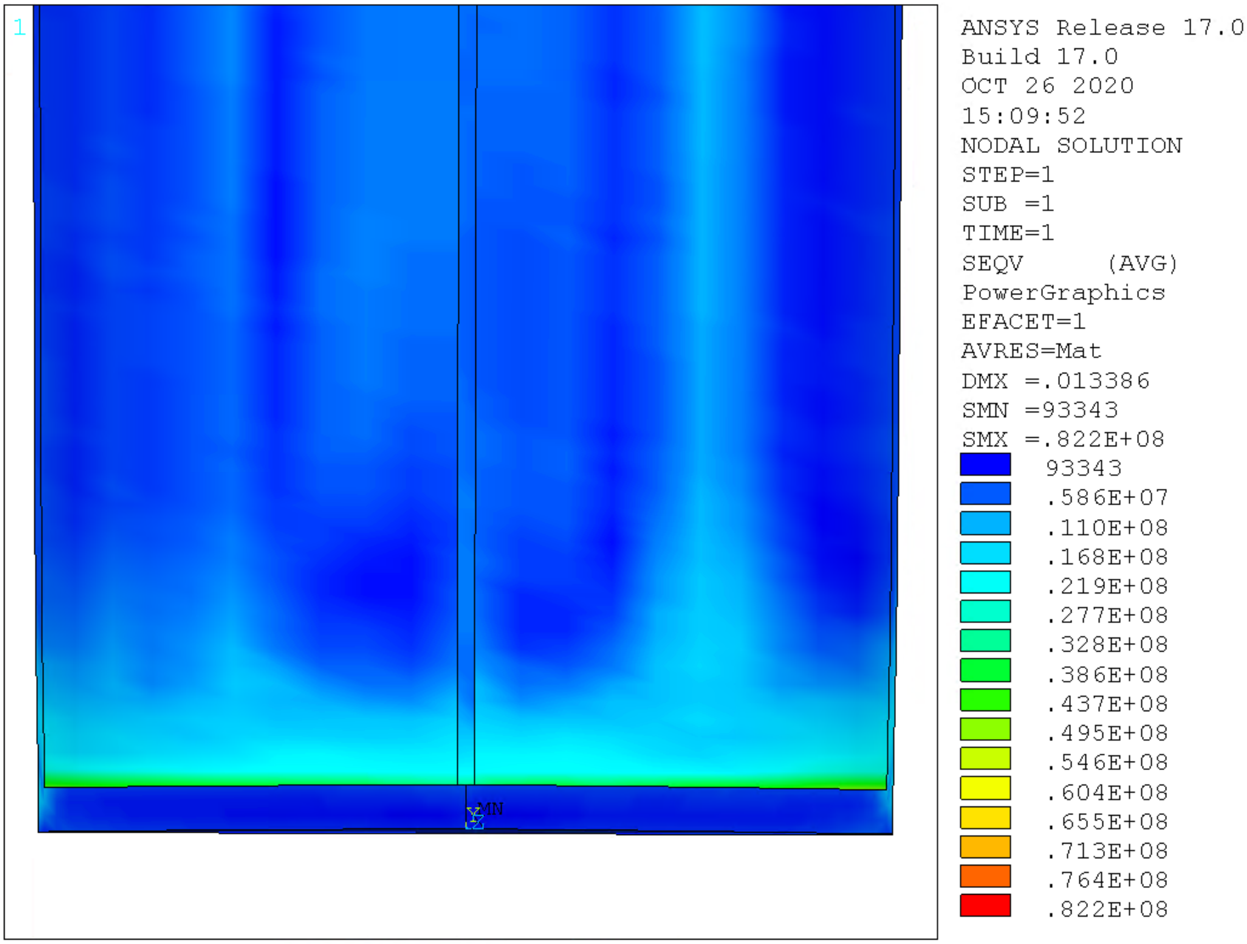

Figure A.17. Von Mises equivalent stress (Pa) bottom inside at 297.6 K ambient temperature.

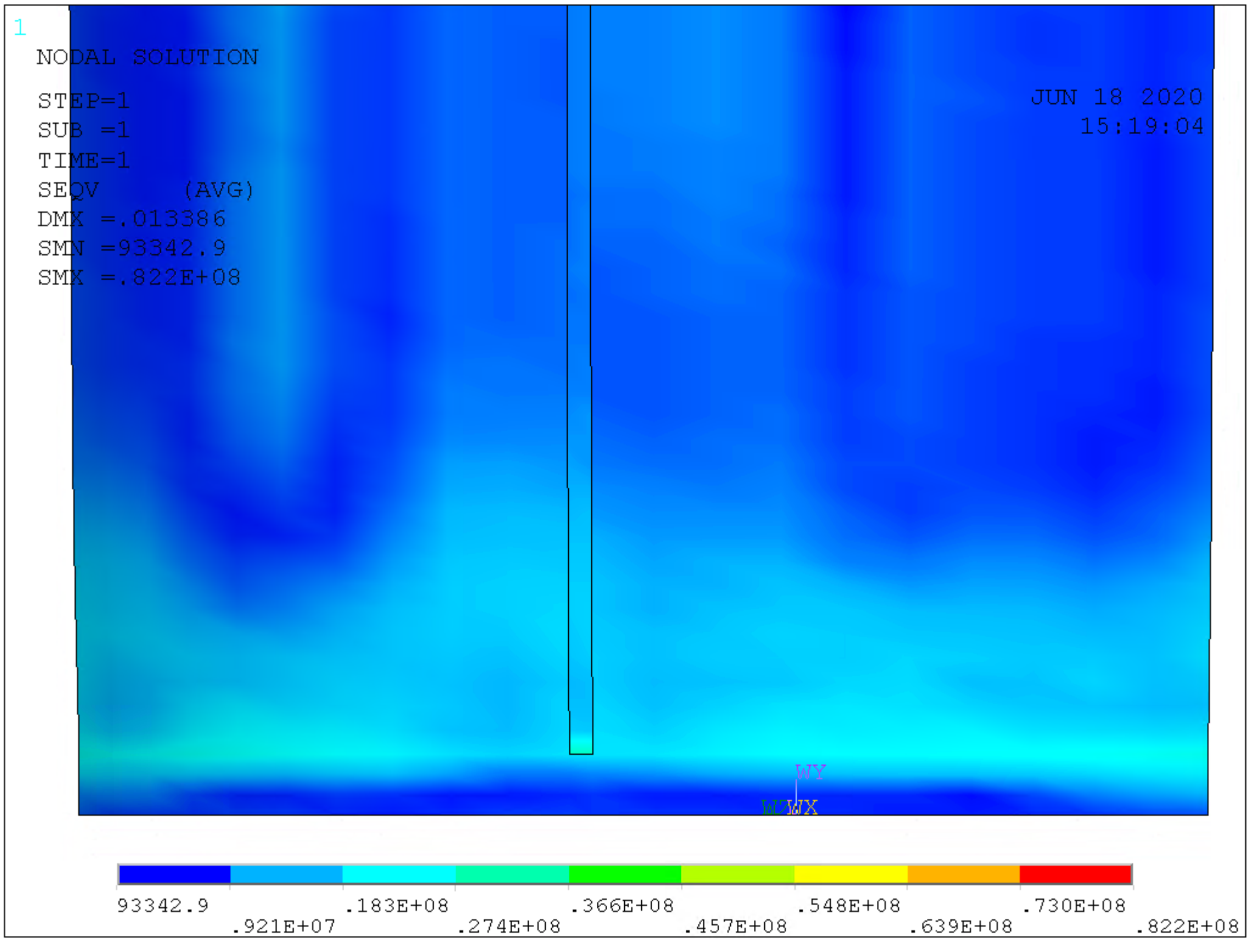

Figure A.18. Von Mises equivalent stress (Pa) bottom outside at 297.6 K ambient temperature.

A-2.6 *Next Steps in Canister Thermal Stress Evaluation*

The fiscal year 2020 modeling effort determined that peak thermal stresses in the canister can be in the 60 MPa to 80 MPa range. The room temperature yield strength of annealed 304 stainless steel is around 205 MPa and the yield strength of 308 stainless steel weld material is about 240 MPa, which makes the thermal stress during operation a significant fraction of the yield strength. When residual stress from the manufacturing process and the internal pressure are also considered, it is clear that there is an important need to understand the full three-dimensional (3D) stress state of the in-service canister material.

This first analysis demonstrates that this topic needs to be explored. The thermal and structural models both need to be refined and enhanced to provide the level of detail needed. The SFWST program has already invested in testing to determine the residual stress state in mockup canisters, and the internal pressure inside canisters is reasonably well understood. The unique modeling of this work (in-service thermal stress evaluation) needs to be completed in a way that is consistent with the residual stress work and the internal pressure estimation, so the full 3D stress state of canisters can be predicted over a full life of a dry storage system.

For the thermal model, we need to evaluate transient thermal behavior so we can predict cycling (daily or seasonally) thermal stresses to determine if they are significant for crack propagation or canister fatigue loading. Another consideration for the thermal modeling is the reduction of decay heat over time. The lower temperatures over long time periods is expected to reduce thermal stresses, and there is probably a point at which thermal stress becomes negligible. For the SFWST program, the goal is to clearly define where thermal stresses are negligible and provide relevant information about in-service thermal stress for the time periods during which the thermal stresses are significant.

The structural model needs some additional development to export results in a local coordinate system. The von Mises stress is a useful measure to estimate the magnitude of stress, but the directional stress components are also important for CISCC, crack propagation, and fracture mechanics studies. The model also does not realistically model the lid weld region, and this is an area of technical interest for which additional model development is needed.

Another area in which DOE has already invested in studying the residual stress of canisters is addressed in a modeling report (Wu et al. 2017, SAND2017-5514C) that predicts residual stress during canister fabrication. The modeling work that PNNL does in this area needs to be consistent with other program-sponsored work, so PNNL plans to more directly reference SAND2017-5514C in next year's work scope, and make sure our thermal stress model is easily compared to the results of that study.

A-2.7 *References*

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Appendix B

Crack Propagation and Prediction

Predicting crack growth and subsequent failure of a multipurpose canister (MPC) is imperative in quantifying the structural integrity of MPCs during storage, transport, or an unforeseen loading event. A robust high-fidelity model needs to be developed to incorporate microstructural and mechanical properties of 304 and 316 stainless steel to predict final crack length due to a series of loading events. Due to the long storage times and possible unknown loading history of these MPCs, a damage tolerance approach must be taken whereby it is assumed that preexisting cracks or flaws are present within the component. The proposed crack growth model below will be implemented to enable use of finite element analysis data to predict locations within the MPCs that will result in significant crack growth resulting in depreciation of the structural integrity of the MPC.

Three distinct and experimentally observed stages of fatigue damage are represented by Eq. (B.1):

$$N_{Total} = N_{Inc} + N_{SC} + N_{LC} \tag{B.1}$$

Where,

N_{Total} = the total number of cycles to failure,
N_{inc} = the number of cycles to incubate a crack,
N_{SC} = the number of cycles in the small crack growth regime, and
N_{LC} = the number of cycles for the long crack (LC) regime.

Because of the damage tolerance approach being applied and the preexisting crack assumed, the incubation portion of the model is not required; therefore, only the small crack growth and LC growth regimes will be accounted for. Figure B.1 shows a standard crack growth rate curve for a given material. A crack growth rate curve is classified into three stages, labeled 1, 2, 3. Stage 1 is the small crack growth regime, which will be modeled using the crack tip opening displacement equation (Eq. (B.2)) developed by McDowell (2003):

$$\left(\frac{da}{dN}\right)_{SC} = \chi(\Delta CTD - \Delta CTD_{th}) \tag{B.2}$$

where, ΔCTD_{th} is the crack tip displacement threshold, ΔCTD is the crack tip opening displacement range, and χ is a material constant that signifies crack tip irreversibility for a given material. The crack tip opening displacement threshold (ΔCTD_{th}) is equivalent to the Burger's vector for the given material. The crack tip opening displacement range, ΔCTD, separated to account for low cycle and high cycle fatigue and is given by Eq. (B.3):

$$\Delta CTD = C_{II}\left(\frac{GS}{GS_0}\right)^{\omega}\left(\frac{GO}{GO_0}\right)^{\varpi}\left[\frac{U\Delta\hat{\sigma}}{S_{ut}}\right]^{\zeta} a_i + C_I\left(\frac{GS}{GS_0}\right)^{\omega}\left(\frac{GO}{GO_0}\right)^{\varpi}\left(\frac{\Delta\gamma^P_{max}}{2}\right)^2 \tag{B.3}$$

Where,

C_I = the low cycle fatigue coefficient,
C_{II} and ζ = material constants for the high cycle fatigue regime,
S_{ut} = the monotonic ultimate tensile strength, and
a_i = the initial crack length.

GS, GS_0, GO, GO_0, ω, and ϖ are grain size and orientation material constants. The equivalent uniaxial stress amplitude, $\Delta\hat{\sigma} = 2\theta\bar{\sigma}_a + (1d\theta)\Delta\sigma_1$, is defined as the linear combination of effective stress amplitude, $\bar{\sigma}_a = \sqrt{\frac{3}{2}\frac{\Delta\sigma'_{ij}}{2}\frac{\Delta\sigma'_{ij}}{2}}$, and the maximum principal stress range $\Delta\sigma_1$. The coefficient U is used to model the mean stress effects pertaining to crack growth, where $U = \frac{1}{1-R}$ is for the case when $R \le 0$ and

U = 1 for R > 0. The small crack portion of the model is calibrated to fit given materials microstructural features and fatigue life curves for a variety of strain amplitudes. For the most accurate results, it is recommended that the calibration of the small crack portion of the model standard microstructural characterization (i.e., grain size, particle distribution, nearest neighbor distance) and fatigue experimentation be performed on 304 and 316 stainless steel extracted from the MPCs, as well as the heat-affected zone and weld nugget.

Once the crack has grown to several millimeters in length, the crack will be in the LC growth regime, which is represented by Stage 2 in Figure B.1. LC growth will be captured using traditional linear elastic fracture mechanics. Traditional Stage 2 growth is represented by the Paris et al. (1999) equation, Eq. (B.4):

$$\left(\frac{da}{dN}\right)_{LC} = C\Delta K^{n} \,. \tag{B.4}$$

However, the Paris equation assumes a constant stress ratio. Because of the variable amplitude loading applied to the MPCs the stress ratio is not constant. Therefore, to account for the change in stress ratio the Walker (1970) equation must be implemented (Eq. (B.5)):

$$\left(\frac{da}{dN}\right)_{LC} = \frac{C_0}{(1-R)^{n(1-\gamma)}} * \Delta K^{n} \tag{B.5}$$

The Walker equation is similar to the Paris equation, except that the value C_0 is the intercept constant at stress ratio (R) equal to zero. γ is the material constant representing how much the stress ratio affects crack growth. The stress intensity range (ΔK) is given by Eq. (B.6):

$$\Delta K = Y\Delta\sigma\sqrt{\pi a} \tag{B.6}$$

where, Y is a dimensionless geometry factor dependent on geometry of the crack, geometry of the component, and loading configuration and a is the crack size. The determination between small crack growth and LC growth for this model is determined by which equation results in the maximum growth rate. Once ΔK exceeds the critical stress factor (K_c), the crack growth rate enters Stage 3 (Figure B.1). During Stage 3, the crack growth rate becomes unstable and results in failure. The LC growth portion of the model is calibrated via the fatigue crack growth test at varying stress amplitudes and stress ratios. For the most accurate calibration of the model, it is recommended that fatigue crack growth experimentation be performed on 304 and 316 stainless steel base material, heat-affected zone, and weld nugget taken from the MPCs.

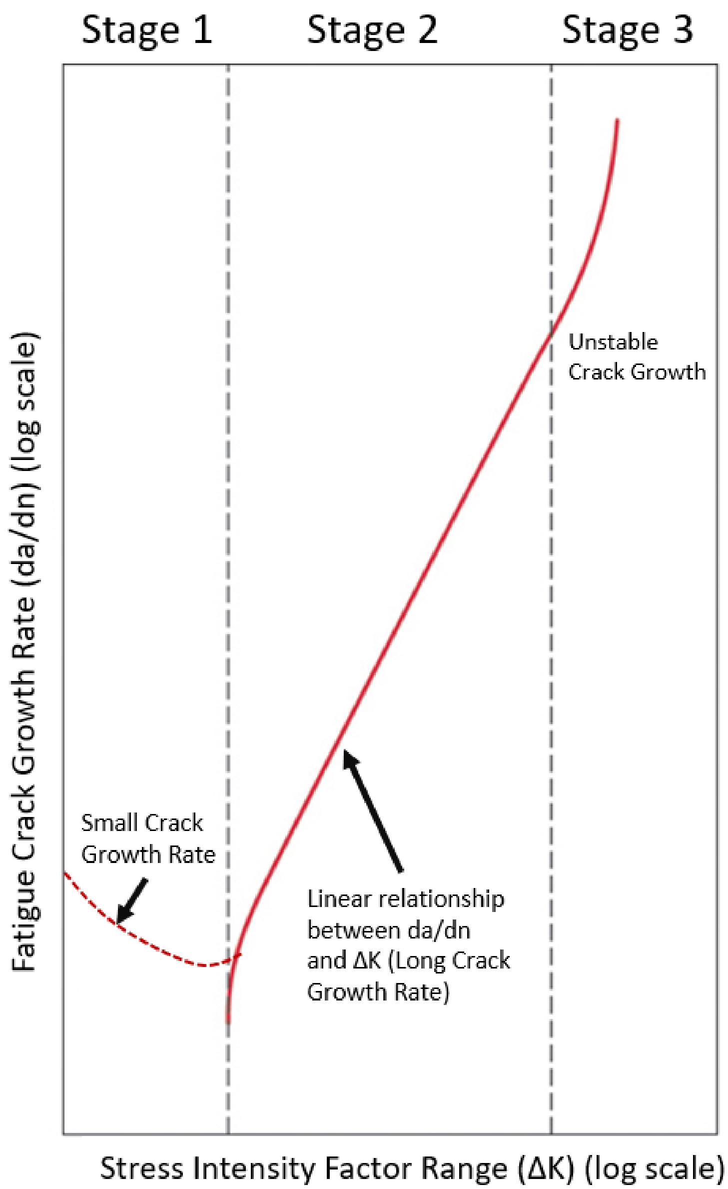

Figure B.1. Crack growth rate as a function of stress intensity factor range for a material. This is categorized into three stages of crack growth: small crack growth, LC growth, and unstable crack growth.

The original equations for both small crack and LC growth assume a constant stress amplitude, but for use in the MPC case a constant load amplitude cannot be assumed. The stress data acquired from finite element models will be similar to the stress values shown in Figure B.2. To account for the varying stress amplitudes, rainflow cycle counting will be implemented according to American Society for Testing and Materials standard E1049-85 (ASTM 2017). Rainflow cycle counting allows random loading to be categorized into a series of load amplitudes. Each load amplitude will then be applied to the fatigue model to determine the crack growth for each iterative stress amplitude.

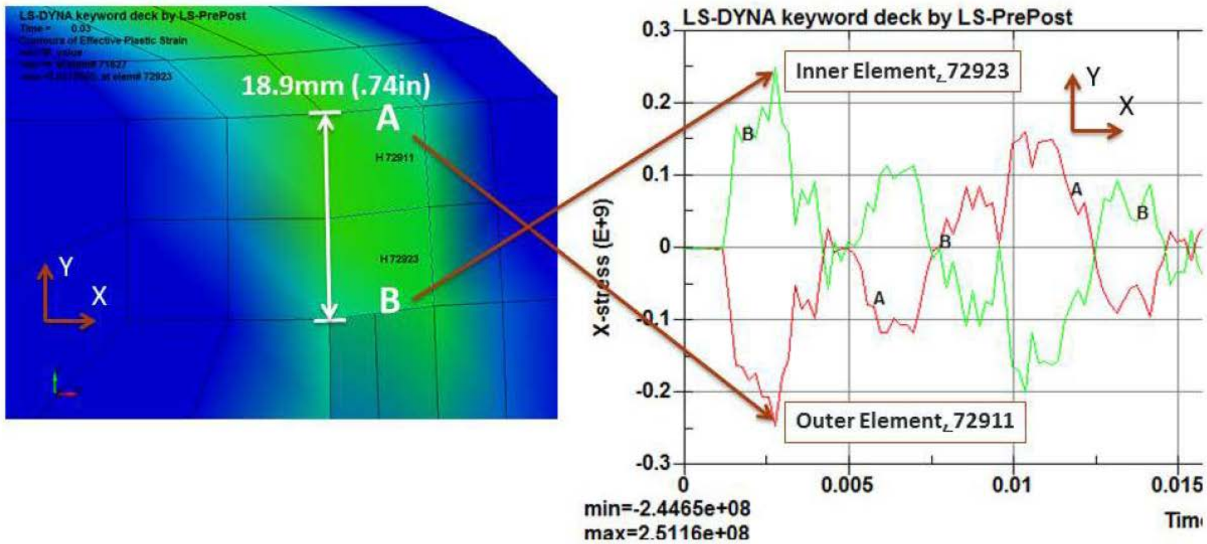

Figure B.2. Example of stress data extracted from finite element modeling of MPCs that will be used by the proposed crack growth model.

B-1 References

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