LAWRENCE LIVERMORE NATIONAL LABORATORY

LLNL-TR-659020

LLNL Input to SNL Report on the Composition of Available Data for Used Nuclear Fuel Storage and Transportation Analysis

M. Sutton, J. Wen

August 19, 2014

This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

LLNL Input to SNL Report on the Composition of Available Data for Used Nuclear Fuel Storage and Transportation Analysis

Used Fuel Disposition Campaign Milestone M4FT-14LL0810044

Mark Sutton and Jiaxuan (Josh) Wen

Lawrence Livermore National Laboratory, 7000 East Avenue, Livermore
California 94550

August 14th, 2014

LLNL-TR-659020

Acknowledgements

The authors greatly appreciate the input of Charles Bryan at Sandia National Laboratory (SCC model), Harold Adkins at Pacific Northwest National Laboratory (thermal profiles), and both Cedric Sallaberry and Remi Dingreville at Sandia National Laboratories (PCMM and mathematical characterization).

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

Table of Contents

List of Figures

List of Tables

Acronyms

BC	boundary condition
BRC	Blue Ribbon Commission
BWR	boiling water reactor
CFD	computational fluid dynamics
CISCC	chloride-induced stress corrosion cracking
DOE	Department of Energy
DRH	deliquescence relative humidity
DSC	dry shielded canister
FCT	Fuel Cycle Technologies
HLW	high-level waste
ISFSI	independent spent fuel storage installation
LLNL	Lawrence Livermore National Laboratory
M&S	modeling and simulation
NE	Nuclear Energy
NOAA	National Oceanic and Atmospheric Administration
NRC	Nuclear Regulatory Commission
PCMM	Predictive Capability Maturity Model
PNNL	Pacific Northwest National Laboratory
PWR	pressured water reactor
QA	quality assurance
RH	relative humidity
SA	sensitivity analysis
SCC	stress corrosion cracking
SET	separate effects test
SNF	spent nuclear fuel
SQE	software quality engineering
SRQ	system response quality
SS	stainless steel
ST	storage and transportation
UFD	Used Fuel Disposition
UQ	uncertainty quantification

1. Introduction

This report satisfies the Lawrence Livermore National Laboratory (LLNL) Level 4 milestone: M4FT-14LL0810044 for the Storage and Transportation Analysis area of the Used Fuel Disposition (UFD) Campaign, funded by the U.S. Department of Energy's Office of Nuclear Energy (DOE-NE). The work was performed under UFD work-package FT-14-LL081004. The information in this report will provide input to a parent Sandia National Laboratories (SNL) milestone and will be supplemented with input from other organizations including SNL, PNNL and INL.

The UFD Campaign within the Department of Energy's Office of Nuclear Energy Fuel Cycle Technologies (FCT) program has been tasked with investigating the storage and ultimate disposition of the nation's used nuclear fuel (UNF) and high-level nuclear waste (HLW). Following the Blue Ribbon Commission (BRC) report on America's Nuclear Future (BRC, 2013), additional emphasis is placed on science-based approaches to develop the technical bases in support of continued safe and secure storage of UNF for extended periods, subsequent retrieval, and transportation. UNF is currently housed in two different types temporary storage: (a) indoor pool storage at reactor sites and (b) outdoor cask storage. Storage within outdoor casks occurs both at currently operating nuclear facilities and in independent spent fuel storage installations (ISFSIs). The BRC recommends the implementation of a centralized interim storage facility to locate UNF prior to disposal. In order to assess the safety of UNF during transportation between sites and during storage at sites, the degradation of fuel, assemblies, canisters and casks must be considered.

This report documents two phenomena that could affect the safety and licensing of dry spent fuel storage casks and their contents, and discusses modeling frameworks and evaluations that will are being developed and implemented. This work will continue in the remainder of FY14 and into FY15. The report also presents a method for evaluation and communication of model and data maturity, and an introduction to uncertainty quantification (UQ).

1.1 High Priority Phenomena of Used Nuclear Fuel Storage

The UFD Campaign has chosen to demonstrate the UQ framework on two previously identified gaps associated with the storage and transportation of used nuclear fuel, namely degradation-specific *atmospheric corrosion* leading to stress-corrosion cracking (SCC) of a welded cask/canister, and the crosscutting *thermal profile* phenomenon. The thermal profile affects the degradation rates of all of the structure, system and components, which include corrosion, creep, cracking and embrittlement, etc. Therefore, identifying and reducing the uncertainty in the thermal profile can positively impact the uncertainty of many other degradation mechanisms and licensing factors in the storage and transportation of casks, canisters and fuel assemblies. These two cases represent two extremes of phenomena (a) *simple* with the benefit in improving uncertainties in one degradation mechanism, and (b) *complex* with potentially large benefits in improving uncertainties across a wider range of degradation mechanisms affected by crosscutting phenomena. The phenomena and degradation mechanisms affecting storage cask safety and licensing are not limited to only thermal profile and SCC, which serve as high priority examples of knowledge, model and data gaps than can be addressed through UQ.

1.1.1 Thermal Profiles

Almost all degradation mechanisms for storage casks are sensitive to temperature and in some cases, temperature history (Cuta et al., 2013). The basis for the transfer of thermal energy from used fuel pellets to the outer surface of the storage cask is involves conduction, convection and radiation of heat from the fuel through concentric layers materials that span from cladding, assemblies and internal structures (e.g., basket) to the canister and cask components (e.g. vent, support array, wall, shielding etc.), the ground pad and the atmosphere. In addition, spaces (gaps) between fuel rods, fuel assemblies, baskets, canisters and casks exist, in some cases filled with an inert gas, while in others can be represented by a flow of air. Figure 1-1 (Suffield et al, 2012, courtesy of AREVA) and Figure 1-2 (Cuta and Adkins, 2014, courtesy of Holtec International) provide a visual example of different material layers and gaps that should be considered.

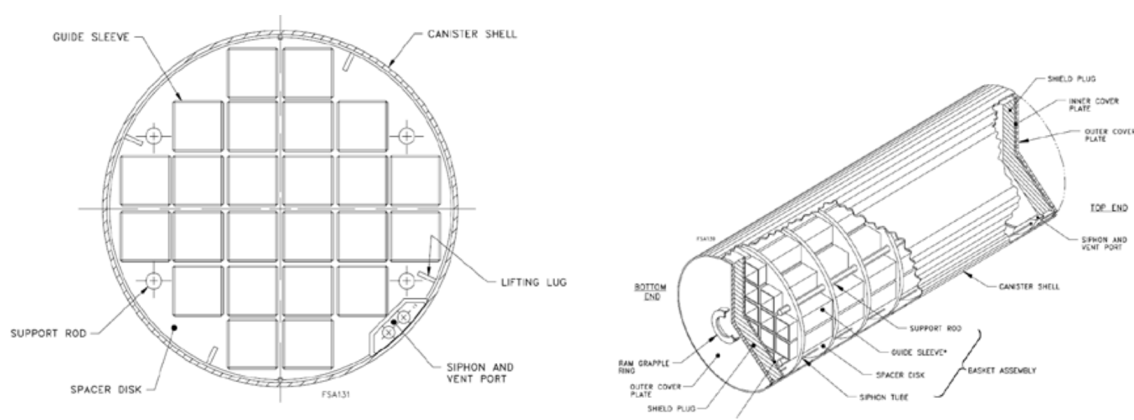

Figure 1-1. Illustrative diagrams of 24P DSC geometry (images courtesy of AREVA)

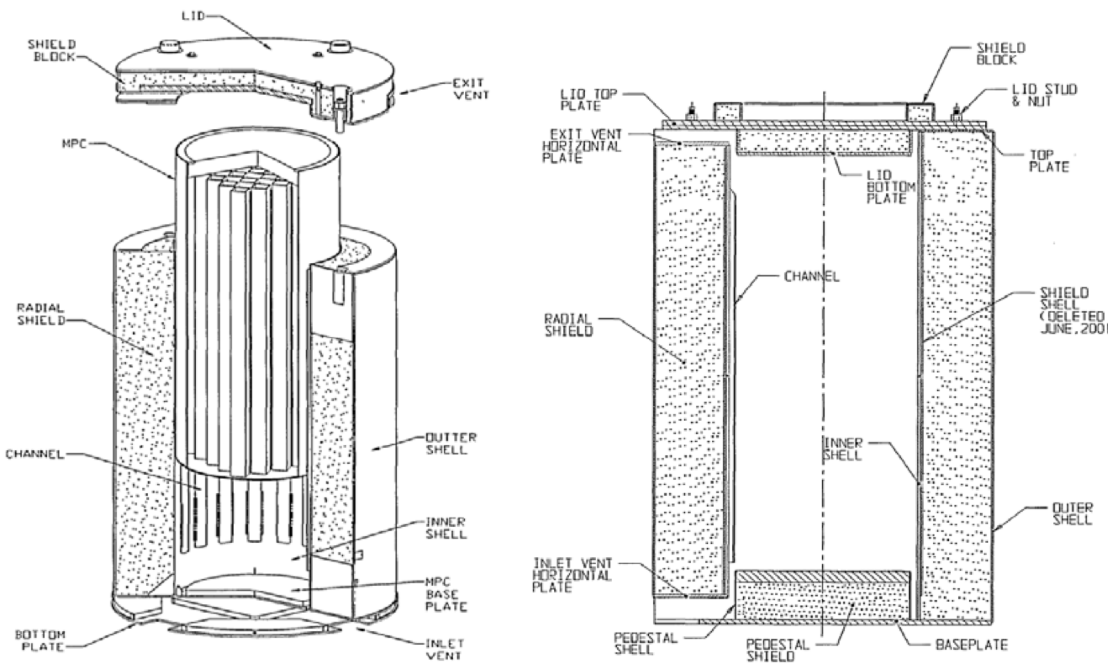

Figure 1-2. Typical HI-STORM 100S vertical storage module (image courtesy of Holtec International)

More information on the considerations of heat transfer on the thermal profile of storage casks and contents is given in Section 2.1.

In an evaluation of technical gap prioritization, all organizations and counties (with the exception of Spain and Japan) ranked both the consequence and the likelihood of thermal profile uncertainties affecting licensing ability as very high and that more thermal modeling is needed (U.S. DOE, 2012). Regulations in Japan limit peak cladding temperature to only 275°C, much lower than the 400°C peak cladding temperature limit in the U.S. (U.S. DOE, 2012). Further information can be found in the Mathematical Characterization document under revision for UFD's Storage and Transportation Analysis work package (WBS 1.02.08.10).

1.1.2 Atmospheric Corrosion of Welded Canisters

The atmospheric-induced SCC can be divided into 3 model levels, each of which are a condition that needs to be realized before SCC can occur:

1. Corrosive environment (including chemical environment on the surface of the canister, surface temperature and relative humidity; all of which are influenced by the geographic location of the storage cask)
2. Tensile stress (as observed in welded canisters)
3. Susceptible material (e.g. *201, 301, 302, 304, 309, and 316 steels, although –L steels have less susceptibility)*

Many storage cask designs utilize ventilation that allows decay heat to dissipate by thermal convection to the atmosphere. Cooler air is drawn into the cask ventilation, passing over the canister with warmer air exiting the cask. The flow of air over the canister also allows atmospheric dust to follow the same path, some of which is deposited on the surface of the canister. The geographic location of the storage facility impacts the composition of dust, with coastal sites containing higher amounts of chloride-bearing sea-salts (EPRI, 2005) and ammonium salts (Enos et al., 2013). Inland sites containing higher levels of silicate, carbonate and aluminate material impacted by local soil and geology. As the temperature and relative humidity fluctuate at a site, components of the deposited dust (particularly chlorides) can dissolve in absorbed moisture (deliquescence). The dissolved ions are then available to participate in corrosion of the canister. Research has shown that with deposited sea salt, a relative humidity at or above 15% can support deliquescence and subsequent corrosion of the canister steels.

Tensile stress can be either residual (pre-existing) or exerted. Residual stresses are the most prominent and problematic of the two stress components in the case of storage canisters and occur after welding of the canister. During fabrication, two cylinders are cold-rolled from sheet steel. The edges of the cylinder are joined using a double-V longitudinal (axial) weld to form complete cylinders. The two cylinders are joined using a double-V butt-joint circumferential weld and a further circumferential weld is used to apply the bottom plate to the cylinder. The canister is then closed with a single-V circumferential weld. The welding leaves the steel vulnerable to intergranular corrosion and high residual stresses are known to be present in the heat-affected zone (HAZ) of the welds (Ferry et al., 2013; Kusnick et al., 2013).

Enos and Bryan (2012) identified key materials for construction of welded interim storage containers, including shell and lid. The materials include 304, 304L, 316, 316L, "steel" and "coated carbon or stainless steel". Jones (1996) states that austenitic stainless steels such as those listed here in chloride hot environments are perhaps the most widely known and intensely studied examples of SCC. Jones (1996) also notes that although relatively rare, SCC at ambient temperature in the presence of concentrated chlorides and strong oxidizers (McIntyre and Dillon, 1985; Dillon, 1990).

Another factor that can affect corrosion (including SCC) is the presence of gamma radiation from the encased fuel leading to the formation of radials and molecules after radiolysis of the water (and brine) on the surface of the waste canister. Some of the species are highly oxidizing and their reactions in pure water are numerous. In brine solutions, the reactions (and shear number of species) is complex, including radials and molecules of chloride species. Farmer et al. (1988) reviews work performed on gamma irradiation of austenitic stainless steels (such as 304) in water and salt solutions, generally finding that the irradiation increased intergranular SCC even at low chloride concentrations.

In summary, the three requirements for SCC are presenet at the weld region of UNF canisters when chloride-containing salts deposit via deposition of dust during passive cooling. Additional information on each of these three requirements (and the understanding of each as they relate to SCC initiation) is given in Section 2.2 of this report. Once SCC is initiated, the environmental conditions need to be evaluated for propagation leading to a through-wall crack. The Nuclear Regulatory Commission highlighted the concern of chloride-induced SCC (CISCC) in a note sent to ISFSI license holders and applicants (NRC, 2012). In an evaluation of technical gap prioritization, all organizations and counties (with the exception of Spain) ranked both the consequence and the likelihood of SCC affecting licensing ability as very high (U.S. DOE, 2012). Spain ranked SCC resulting from atmospheric corrosion low due to planned vaults housing UNF canisters. Further information can be found in the Mathematical Characterization document under revision for UFD's Storage and Transportation Analysis work package (WBS 1.02.08.10).

1.2 Uncertainty Quantification

Both the thermal profile of storage casks and the degradation of the welded canister (from deposition and subsequent deliquescence of dust resulting in SCC) involve multi-physics processes. Uncertainties arise in simulation models due to a lack of precise knowledge about the physical processes, the model parameters, initial and boundary conditions, etc. As a result, the credibility of a model cannot be established without a thorough and rigorous uncertainty quantification (UQ) that can (Tong, 2008):

- characterize the output uncertainties of a simulation model (or, uncertainty analysis)
- identify the major sources of uncertainties of a model (or, sensitivity analysis, SA)
- establish the integrity of a simulation model (validation)
- tune a simulation model to match better with experiments (calibration)
- assess the region of the validity of a simulation model (risk analysis)
- provide information on which additional experiments are, needed to improve the understanding of a model (parameter exploration)

The first stage of the uncertainty quantification is to identify all of the input parameters and relevant multi-physics equations. The level to which the investigation will go should be determined at this stage, either back to basic principles or higher-level assumptions and knowledge.

The second task (which is the beginning of the UQ process) is to identify the model. This will involve compilation of detailed specifications including the simulation model, uncertainty parameters that will be varied, uncertain parameters which will