

The background of the cover is a photograph of a cave entrance. The rock walls are layered and textured, with colors ranging from light tan to dark brown. The entrance is a dark, irregular opening, and the interior of the cave is visible in the background, showing more rock formations and a dark, shadowy space.

# DRY STORAGE HANDBOOK

Performance of Spent Nuclear Fuel  
during Dry Storage

# Dry Storage Handbook

## Fuel Performance in Dry Storage

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© March 2015

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Ecolabelled printed matter, 441 799

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# 1 Introduction

A technical assessment of the expected performance of spent nuclear fuel (SNF)<sup>1</sup> during extended dry-storage time periods and the condition of such fuel at the end of dry storage is given in this document. The principal focus of the reviews which follow is on SNF and the effects of dry storage rather than on dry-storage containers and the related storage facilities. The objective is to provide background information on the likely behaviour of materials comprising water reactor fuel assemblies and on the performance of integral assemblies under conditions typical of dry storage for extended intervals of time. In brief, the technical assessment supports a conclusion that, although technical issues have been postulated with regard to long-term storage, there are no high-risk concerns with the extension of dry storage to long times; with proper planning and implementation, the risks are expected to be low.

Dry storage of spent nuclear fuel is a relatively mature technology, which has emerged as the consensus, near-term method in most nuclear countries [Bunn et al, 2001]. As of 2014, spent nuclear fuel elements from commercial power plants and from research reactors have been stored in a dry state for nearly 30 years and 40 years, respectively. This experience involves fuel from a wide range of reactor types; e.g., CANDU, HWR, PWR, BWR, VVER-440, VVER-1000, RBMK, MAGNOX and the HTGR. Storage systems include vaults, concrete canisters, steel-lined concrete containers and metallic casks of various configurations. Although early efforts involved storage-only containers, SNF from commercial power plants is now typically placed in dual-use containers that are intended for both transportation and storage. These dual-use containers are in the form of bolted casks with integral shielding or welded canisters with protective over packs; i.e., silo (vertical) or bunker (horizontal) structures. Principal features of storage systems for LWR fuel are reviewed briefly in Section 4.6.

The relative importance of SNF performance during dry storage depends on the expected path of SNF from wet storage through reprocessing or disposal. The goal is for SNF to remain intact at least through post-storage retrieval for reprocessing or placement and sealing in a container at a final disposal repository. There may be cases where safety analyses take credit for SNF integrity beyond dry storage, for example, through some portion of the disposal time period. Such plans could result in the need to analyse performance through thousands to hundreds of thousands of years of disposal. Since the interest here is only for dry storage and some associated handling and transportation, SNF integrity during disposal is not addressed. Since dry storage already has been shown acceptable for tens of years, the emphasis is on any changes that may occur during extensions of the dry-storage time periods to a hundred years, or perhaps several hundred years. Information is included, however, on the expected performance of SNF during both the early and extended stages of dry storage.

Technical discussions in this section describe the type of information that may be needed to support dry storage and examples of the available information that may be used. The focus in selecting sample information to discuss is to support understanding of the issues involved. As such, the sample information is not exhaustive and will not cover all situations. Each evaluation needs to consider its unique circumstances to determine the specific types of information needed.

In selecting the amount and type of information to present, it is acknowledged that some phenomena are more extensively evaluated and that the available data are more readily available in open sources than for other phenomena. Also, consideration is given to some phenomena being more important, that is, having more risk, than other phenomena. The degrees of coverage here reflect these differences.

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<sup>1</sup> The term “spent nuclear fuel” (SNF) is considered equivalent to “used nuclear fuel” (UNF) in this document.

The information presented here is not intended to be the basis for any specific safety or licensing evaluation. Rather, it is intended to improve understanding of issues associated with dry storage.

The importance of SNF integrity during dry storage and associated handling and transportation is influenced strongly by the expected SNF path. There are two fundamental flow paths, each with its advantages and disadvantages.

- Option 1: If SNF is expected to be repackaged after storage, SNF integrity and resilience during handling is very important. An example of this expectation is the planning in Great Britain, where it is assumed that SNF will be repackaged from dry-storage canisters into other containers after a time period on the order of a hundred years. Also, the US Yucca Mountain Repository License Application (YMRLA) was based on the assumption that most SNF would be repackaged into Transportation, Aging, and Disposal (TAD) canister, but that US expectation is no longer certain. Sweden and Finland are selecting a different option; i.e., both plan to package SNF directly into copper canisters for disposal. The repository licenses are still under review, however, so significant delays could result in the need for dry storage, at least in Finland. In most other countries, decisions regarding repackaging have not been finalized.
- Option 2: If SNF is expected to remain in one multipurpose canister (MPC) from initiation of dry storage through disposal of that MPC into a disposal cask, SNF integrity is important but not as important as if repackaging is expected. This SNF path was planned in some early designs of some dry-storage containers and remains an option with significant advantages. This option continues to be considered, for example, by EPRI in Electric Power Research Institute, “Feasibility of Direct Disposal of Dual-Purpose Canisters: Options for Assuring Criticality Control,” [EPRI, 2008b].

The extent to which each option will be adopted still is to be determined. The discussion in this handbook is intended to provide information to support consideration of both options.

Technical issues related to long-term, dry storage of SNF and to subsequent transport and handling have been considered in a number of reviews. For example, the US Nuclear Waste Technical Review Board (NWTRB), in its “Evaluation of the Technical Basis for Extended Dry Storage and Transportation of Used Nuclear Fuel” [NWTRB, 2010], considered and reported on the issues associated with degradation of SNF, metal storage containers, and the concrete over packs and pads. The NWTRB report acknowledges that there are some technical issues that need better understanding to support extrapolations to long dry-storage times in stating “The review identified references to general metal and concrete deterioration mechanisms and modelling, but none included the information necessary to predict the degradation of dry-storage canisters, casks, or concrete structures during extended storage.” In the context of the complete NWTRB report, this statement is interpreted as indicating that dry storage to hundreds of years is supportable technically but that it would be beneficial for some technical concerns to have more data or better understanding. Related studies by the US Department of Energy [DOE, 2012b], Nuclear Regulatory Commission [NRC, 2012], International Atomic Energy Agency and an Extended Storage Collaboration Program (ESCP) [EPRI, 2011] identified and prioritized technical gaps. These gaps and their relative importance vary among countries and organizations, but are similar in many respects. The review given in [DOE, 2012b] and summarized in Table 1-1 considered gaps and priorities of the programs and countries in that participated in the reviews noted above. Issues are listed in Table 1-1 according to the approximate priorities as perceived by the DOE.

Table 1-1: Summary of technical gaps associated with extended dry storage listed according to the approximate priorities as perceived by the U.S. DOE, after [DOE, 2012b].

Issue	System, Structure, Component or Cross-Cutting Issue	Technical Issue	Comments
1	Cask, canister and overpack, SNF	Heat dissipation and thermal profiles	Cross-cutting issue
2	Cladding	Hydride embrittlement	Includes migration, reorientation and hydride growth
3	Cask or canister and overpack	Monitoring of performance	Cross-cutting issue
4	Welded canister	Atmospheric corrosion	Primarily in marine atmospheres
5	Cask, canister, SNF	Drying and residual moisture	Cross-cutting issue
6	Cladding	Delayed hydrogen cracking	
7	Cladding	Annealing	
8	Bolted cask lid and seals	Seal and bolt fatigue	
9	Cladding	Oxidation and wall thinning	
10	Cladding	Creep	
11	Welded canister	Aqueous corrosion	
12	Cask, canister and overpack	In-service examinations	
13	Cask, canister and overpack	Freeze-thaw cycling	
14	SNF assembly hardware	Corrosion	Related to residual moisture
15	Cask, canister and overpack, SNF	Fuel retrievability	
16	Bolted cask lid and seals	Atmospheric corrosion	Primarily in marine atmospheres
17	Neutron poison and shielding	Thermal aging and degradation	
18	Bolted cask lid and seals	Aqueous corrosion	
19	Neutron poison and shielding	Creep	
20	Neutron poison and shielding	Corrosion	Related to residual moisture
21	Cask or canister and SNF	Burnup credit and sub-criticality	
22	SNF	Fuel classification	Breached, non-breached; damaged, non-damaged
23	SNF	Damage definition	
24	Cask or canister and overpack	Corrosion	
25	UOx or MOx fuel pellets	Cracking, bonding	
26	Canister	SCC of welds	
27	Neutron poison and shielding	Embrittlement	
28	SNF	Verification of fuel condition	Verification prior to loading; exam. after storage
29	Bolted cask lid and seals	Creep of seals	
30	Fuel basket	Corrosion, SCC	
31	SNF	High burnup UOx and MOx fuel	
32	Moisture absorber	Thermal and irradiation effects	
ANT International, 2014			



Many of the top priority issues in Table 1-1 involve the storage container and its associated components, particularly as related to long-term confinement. The effects of atmospheric corrosion and the long-term performance of seals in casks with bolted lids are especially important. Other high priority issues relate to potential degradation of SNF and the effects on fuel integrity and retrievability. The issues identified in Table 1-1 constitute the bases for a series of research and demonstration programs that are currently being developed; e.g., see [IAEA, 2013] and [EPRI, 2014].

Issues related to dry storage containers, structures and systems are reviewed in a separate document. Issues related to the behaviour of SNF during long-term storage and subsequent transportation are reviewed in the sections which follow.

## 2 General conditions and cross-cutting issues

The key differences between dry storage and in-reactor, operating conditions relative to the performance of fuel are:

- Long storage time; i.e., 40 years, with the likelihood of storage for 100 or more years in the US and some other countries.
- Inert gas (helium) storage atmosphere instead of pressurized or boiling water for LWR fuel:
  - Decreased heat transfer.
  - But essentially no corrosion or hydrogen pickup<sup>2</sup>.
- The possibility of uncharacterized amounts of water vapour in the storage atmosphere due to water that remains in a storage container after the drying process; e.g., chemisorbed<sup>3</sup>, physisorbed water<sup>4</sup> or water trapped in breached rods, water rods or guide tubes.
- Decay heat that can raise local, peak cladding temperatures to high values during cask drying operations (e.g., up to 400°C in the US and many other countries) and that decreases over time, with potential cladding temperatures <200°C by the end of dry storage.
- Cladding heat flux at a given (axial) location that is small enough to produce negligible radial temperature gradients across the thickness of fuel cladding; i.e.,  $\Delta T_{radial}^{clad} < 0.01^\circ\text{C}$ .
- Heat transfer which varies with radial and axial location within a storage container so as to produce temperature gradients that are much greater along the length of a SNF rod than across the thickness of its cladding; e.g., the temperature at the ends of a fuel rod in a high temperature region of a storage cask can be approximately half the respective maximum temperature.
- Periodic fluctuations in temperature that depend on the location and the details of the dry storage systems.
- Storage at low-to-moderate pressures (near atmospheric), combined with high fuel rod temperature and internal gas pressure, results in high clad differential pressures and high clad stresses that decrease with time.
- No external radiation (no additional radiation damage).
- Possible recovery<sup>5</sup> of some radiation damage in zirconium alloys at the locations of maximum (allowed) temperatures.
- Fuel retrievability after dry storage and transportation by “normal means” for reprocessing or repackaging and final disposal.

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<sup>2</sup> The possibility of reactions of fuel materials with residual moisture and its radio lytic products is one of the reasons drying and residual moisture is considered an important cross-cutting issue.

<sup>3</sup> Adsorption which involves a chemical reaction between the surface and the adsorbate. New chemical bonds are generated at the adsorbent surface.

<sup>4</sup> Physisorption, also called physical adsorption, is a process in which the electronic structure of the atom or molecule is barely perturbed upon adsorption. The fundamental interacting force of physisorption is caused by van der Waals force.

<sup>5</sup> Resulting in a decrease in dislocation density and potentially recrystallization if temperature is high enough.

Six basic requirements are involved in the dry storage of SNF; viz.,

- 1) Maintenance of a sub-critical state,
- 2) SNF confinement,
- 3) Shielding,
- 4) Thermal performance (heat transfer and SNF temperature),
- 5) Maintenance of structural integrity (SNF and storage system) and
- 6) Fuel retrievability after normal storage or transport and fuel recoverability after potential accidents by “normal” means.

The first three items relate primarily to the storage or transport systems and to decisions regarding the SNF to be placed in such systems. The last three also depend on these factors, but contribute more to the behaviour of fuel materials, rods and assemblies during and after storage.

The technical gaps and cross-cutting<sup>6</sup> issues related primarily to long-term, dry-storage of SNF are listed in Table 2-1. This list came from the international Extended Storage Collaboration Program and reviews by the US DOE. Table 2-1 is a subset of the issues given in Table 1-1 and includes estimates of the relative priorities of each item. Note that conditions vary among countries, so the relative priorities also vary. The right-most column contains assessments by the US DOE which might or might not be relevant to conditions in other countries. Note also that priorities are expected to change as investigations of the technical gaps progress; e.g., the ranking of delayed hydride cracking is likely to be downgraded or eliminated with further study.

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<sup>6</sup> Cross-cutting is an editing technique most often used in films to establish action occurring at the same time in two different locations.

Table 2-1: Technical gaps and cross-cutting issues related to long-term, dry storage of SNF, after [EPRI, 2012], [DOE, 2012a] and [DOE, 2012b].

Component	Technical issue, Degradation Mechanism	Extended Storage Collaboration Program							Integrated Assessment (DOE)
		Germany	Hungary	Japan	Korea	Spain	UK	USA	
Cross-cutting issue	Temperature profiles	Medium	High		High	Medium	High	High	High
Cladding	Hydrogen embrittlement		High		High	High	High	High	High
Cross-cutting issue	Monitoring	Medium	High	High			High	Med-High	High
Cladding	Delayed Hydrogen Cracking		Medium		High	Medium	High	High	High
Cross-cutting issue	Drying and residual moisture	Medium	High			Medium	High	High	High
Cross-cutting issue	Fuel transfer options		High		Medium	Medium		High	High
Cross-cutting issue	Sub-criticality, burnup credit		High					High	High
Cross-cutting issue	Post-storage examinations		High				High		High
Cladding	Annealing of irradiation Damage		Medium	High	Medium	Medium	High	Medium	Medium
Cladding	Oxidation	Medium	Medium		Medium	High	High	Medium	Medium
Cladding	Creep	Medium	Medium		Medium	Medium	High	Medium	Medium
Assembly hardware	Corrosion		Medium		High			Medium	Medium
Cross-cutting issue	Damage definition				High	High	High		
Cross-cutting issue	Verification of fuel condition			High		Medium	High		
Cross-cutting issue	Fuel classification				High	High			
Pellet	Cracking, bonding			High	Low	Medium			
Cladding	High-burnup fuel, MOX	Medium							

ANT International, 2014

Most of the technical issues identified in Table 2-1 are self-explanatory. Brief discussions of those with the highest apparent priorities are given in the following paragraphs.

**Thermal profiles:** Temperature and thermal profiles (spatial and temporal distributions) are identified as a cross-cutting issue because of their effects on other aspects of storage and transportation; i.e., fuel materials, rods and assemblies as well as the storage systems, structures and components (SSC). Concerns in these areas include the accuracy of local temperature calculations and their variations with time, which are fundamental to the performance of SNF during and after dry storage.

**Hydrogen embrittlement:** Hydrogen embrittlement refers to the effects of hydrogen migration and hydride reorientation and growth on the ductility and impact resistance of Zr-alloys given the thermal and stress histories associated with drying and long-term dry storage. Issues in this area involve the microstructure of fuel cladding (stress-relieved vs. recrystallized), hydrogen concentrations at the beginning of storage, temperatures, stresses and their gradients during drying and the first few years of dry storage, migration of soluble hydrogen, precipitation of hydrides with cooling during storage and the effects of such hydrides on Zr-alloy ductility at low temperatures (less than ~200°C) after extended storage. These issues are reviewed in detail in sections that follow.

**Monitoring:** Monitoring refers to assessing the state and performance of SNF, its storage cask or canister and SSCs to detect adverse changes under conditions where preventative actions are possible. Concerns in this area relate primarily to the storage systems, structures and components, but also involve the integrity and retrievability of the SNF. The importance of monitoring and preventative actions increase as storage times become longer.

**DHC:** The possibility of delayed hydride cracking (DHC) is considered a technical gap by some groups because of the presence of hydrogen in Zr-alloy fuel cladding and the temperature and stress histories to which SNF is subjected during drying and subsequent storage. That is, the concentration of soluble hydrogen increases due to the high temperatures of the drying process and then decrease as decay heat and temperature falloff during storage. Soluble hydrogen can migrate in response to thermal, concentration and stress gradients so that hydrides form in regions of high stress. Such hydrides can contribute to cracking under certain conditions. DHC is considered a technical gap because of uncertainty regarding these conditions. DHC is discussed as a separate topic later in this document.

**Drying and residual moisture:** Container drying and residual moisture constitute technical gaps because of uncertainty regarding the effectiveness of the basic drying process and because of the potential effects of water and the products of its radiolytic decomposition on the SNF as well as the storage systems, structures and components. The actual amount of water remaining in a container after drying is inferred from pressure measurements, but is unknown. Similarly, the behaviour of residual moisture and its effects on SNF and storage systems vary in an irregular, ill-defined manner with the amount of moisture, temperature and radiation fields.

**Fuel Transfer:** Issues related to fuel transfer options involve retrieval or recovery after damage to a storage system and repackaging for continued storage, transportation or disposal. In some cases, they also involve concerns about re-wetting and re-drying. The transfer issue is most severe in cases where SNF is stored at a site where a fuel pool or other hot cell facilities are unavailable (as through closure of a nuclear power plant). The issue exists, however, anywhere fuel must be removed from its dry storage container.

**Sub-criticality and burnup credit:** Maintaining a subcritical state during all conditions of storage and transportation is a fundamental safety requirement. Sub-criticality issues tend to be more pronounced with higher enrichments, more varied fuel designs, increased burnups and the need to store fuel that has been discharged before its normal end of life. Burnup credit and its effects on nuclear safety are topics of ongoing investigation. Burnup credit accounts for the decrease of reactivity of spent PWR fuel in criticality analyses of cask loadings due to decreased amount of fissile material and the formation of transmuted elements absorbing thermal neutrons in high burnup fuel. The use of burnup credit in nuclear-safety analyses is specific to PWR fuel; as of today, regulations do not allow such credit in the analysis of spent BWR fuel. The alternative to burnup credit is to assume base criticality calculations on the full initial enrichment of the fuel. This work is intended to improve the efficiency and operating flexibility of dry storage of commercial SNF. The investigations of burnup credit are driven more by the introduction fuel designed for high-power, long-residence operation than by increases in the duration of dry storage. Isotopic data, improved analytic methods and validation (critical experiments) are needed in this area.

Creep: Creep and creep rupture were identified as a potential failure mechanism in early studies of dry storage. Although subsequent assessments show such failure to be unlikely, the dependence of creep in Zr-alloys to temperature and stress combined with an absence of experimental data directly relevant to the temperatures, stresses and times of dry storage continue cause the issue of creep to remain on lists of technical gaps. Creep is reviewed separately in a later section of this document.

Post-storage examination: The issue related to post-storage examination centres primarily on high-burnup (>45GWd/MTU) fuel typical of the SNF now being discharged from LWRs, including the new Zr-alloys that have been developed to facilitate higher burnups. The issues also involve inspection of the storage system, structures and components. Both areas of investigation replicate the demonstration programs that were conducted in the 1980s and 1990s in support of current dry-storage and transport practices. The research, development and demonstration programs noted earlier of the DOE-ESCP [EPRI, 2014] and IAEA are intended to address this topic.

Fuel damage classification and verification: Technical gaps regarding the examination and verification of the physical state of SNF relate to the classification and treatment of SNF in accordance with the relevant regulatory policies. Issues arise primarily in the identification of leaking rods within an assembly and, in cases where breached rods are allowed in dry-storage containers, the subsequent classification of a cladding breach as restrictive; e.g., small (restrictive) versus large (non-restrictive) paths for the dispersal of fuel material and degraded versus non-degraded cladding. Assessment of the state of fuel rods and other structural elements essential to the handling and retrieval of fuel assemblies can also be difficult. Gaps in these areas include the classification of fuel rods or fuel assemblies that satisfy the letter of the storage requirement, but might fail or sustain damage during storage and thereby adversely affect SNF retrieval.



### 3 Thermal profiles and conditions

One of the cross-cutting issues with greatest importance to the safety of dry storage SSCs involves temperature, its variation within the storage system and its variation over time. These temperature-related conditions, which are collectively identified as thermal profiles, are considered significant factors in dry storage since degradation mechanisms and material performance typically depend strongly on temperature. Currently, cladding temperatures are limited to peak values that vary slightly among regulatory authorities based on the expected effects on factors such as cladding creep, hydrogen solubility, the formation of hydrides that are unfavourable to the ductility and impact resistance of Zr-alloy cladding and the preservation of fuel integrity and retrievability after extended storage; e.g.,  $T_{\max} \leq 400^{\circ}\text{C}$  in the US and parts of the EU and  $\leq 200^{\circ}\text{C}$  to  $\leq 300^{\circ}\text{C}$  in Japan, [Kamimura, 2010].

#### 3.1 Decay heat

Temperature is determined by a number of factors, which begin with decay heat; i.e.,

- Decay heat generated by the SNF,
- The fuel assemblies placed in a storage cask and their relative position in the storage container,
- The heat transfer capability of the cask and
- The surface temperature of the cask in its storage environment.

The heat generated by radioactive decay of SNF is typically calculated by means of isotopic generation and decay codes (e.g., SAS2H-ORIGEN-S), but can also be specified by the regulatory authority; e.g., U.S. NRC Regulatory Guide 3.54, [NRC, 1999].

The radionuclides that contribute to decay heat vary with time according to their initial concentration and their respective decay constants and decay chains. The sources of decay heat in a typical PWR assembly discharged at 60GWd/MTU are shown relative to time in Figure 3-1. At cooling times relevant to interim storage, a significant fraction of the heat is produced by the decay of transuranic radionuclides; i.e.,  $^{239}\text{Pu}$ ,  $^{240}\text{Pu}$ ,  $^{241}\text{Am}$  (from  $^{241}\text{Pu}$ ) and  $^{244}\text{Cm}$ . The concentration of transuranic increases with burnup due to the capture of (epithermal) neutrons by  $^{238}\text{U}$  and the subsequent fissioning and transmutation of the resulting plutonium; see the review by [Patterson & Garzarolli, 2010] for background information on fission-induced changes.

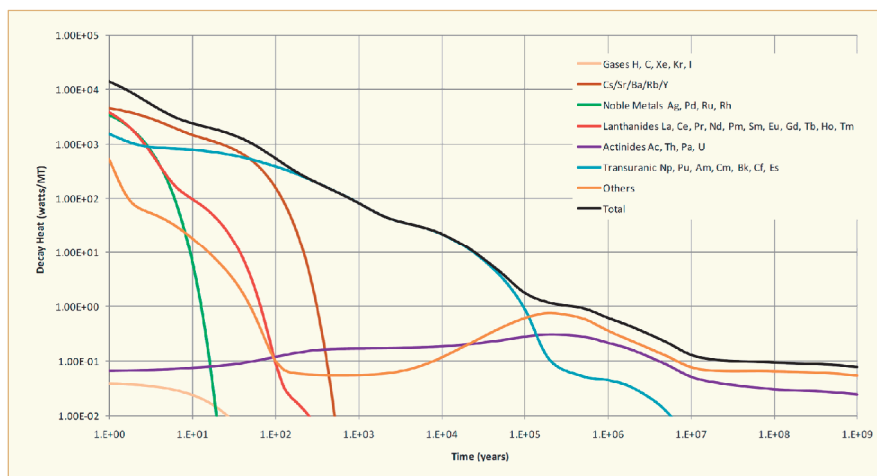


Figure 3-1: Sources of decay heat relative to time, PWR fuel assembly at 60GWd/MTU, after [Carter et al, 2011].

The concentration of transuranic nuclides is greater in spent LWR-MOX fuel than in spent  $\text{UO}_2$  fuel at the same nominal burnup because MOX begins life with plutonium as the primary fissile material and leads to the production of greater concentrations of transuranic elements. This increased concentration of transuranic increases decay heat and, thereby, greater cladding temperatures in dry storage. As shown in Figure 3-2, the heat loading for spent MOX fuel is 2–3 times greater than the corresponding heat load from spent  $\text{UO}_2$  fuel over the time interval relevant to dry storage.

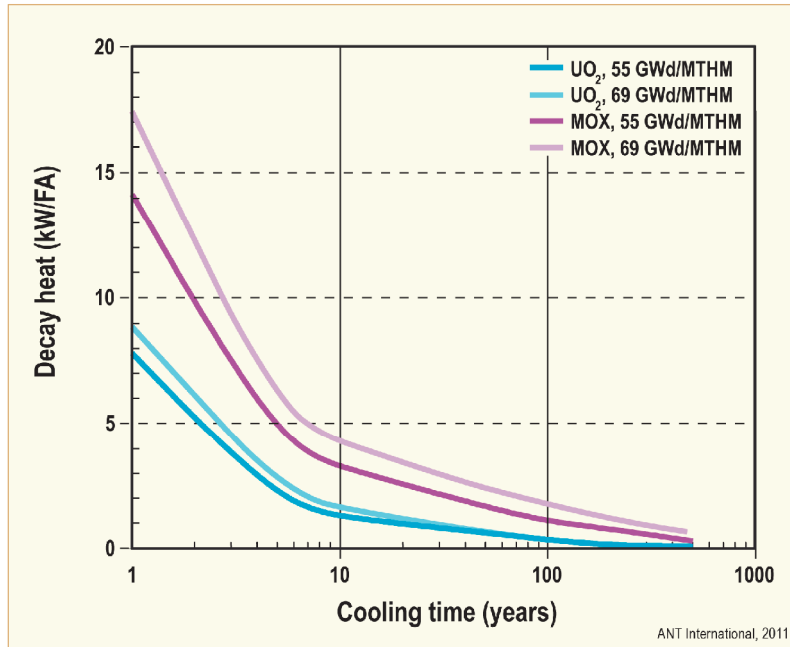


Figure 3-2: Decay heat of spent MOX and  $\text{UO}_2$  fuel relative to time, after [Goll et al, 2003].

## 3.2 Dry storage temperature

### 3.2.1 Overview

The temperature experienced by SNF during dry storage depends on a factors involving decay heat and the specific conditions of the cask loading and storage. That is, temperature is a non-unique function of decay heat which varies with the number and conditions of the fuel assemblies in a storage container (composition, burnup, cooling time – as noted above), their placement in a storage container relative to heat transfer surfaces, the atmosphere within the container, the orientation of the container (horizontal or vertical), ambient conditions and time.

For reference, the decay heats, estimated peak temperatures and cooling rates of SNF at 40GWd/MTU and 60GWd/MTU are shown relative to time in Figure 3-3 and Figure 3-4. In both of these figures, SNF is assumed to begin dry storage at 350°C after 10 years of wet storage. Estimates of decay heat are based on fits of ORIGEN-2.2 results which were reported by [Carter et al, 2012] for PWR fuel. Temperatures and cooling rates are assumed to vary with decay heat as in studies by [Einzig et al, 2003]. Cooling rates represent temperature changes after drying due to the falloff of decay heat. Ambient temperature is assumed to remain constant at 25°C. These estimates are provided as background information; assessments of actual storage conditions should be based on the methods reviewed in Section 3.2.3.

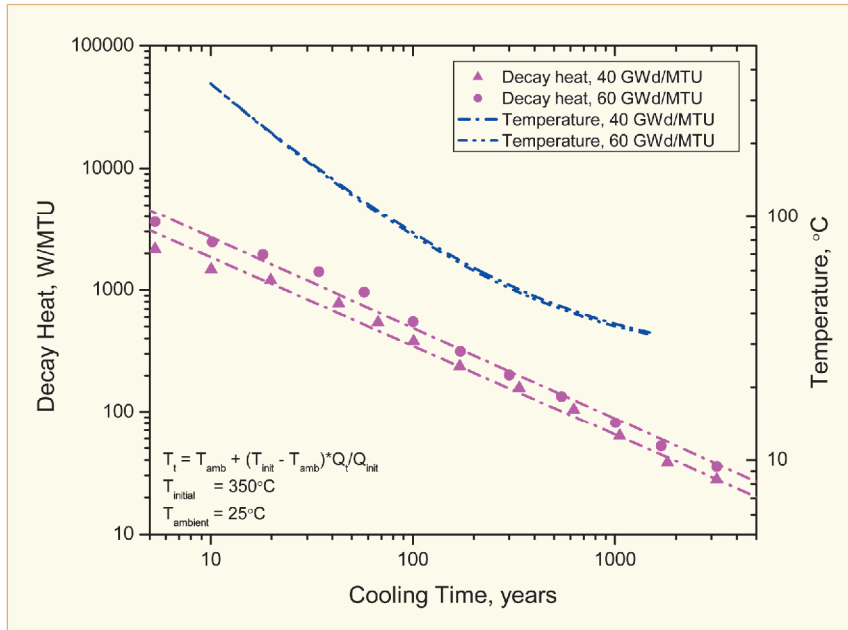


Figure 3-3: Decay heat and peak temperatures of PWR fuel at 40GWd/MTU and 60GWd/MTU relative to cooling time, after [Carter et al, 2012].

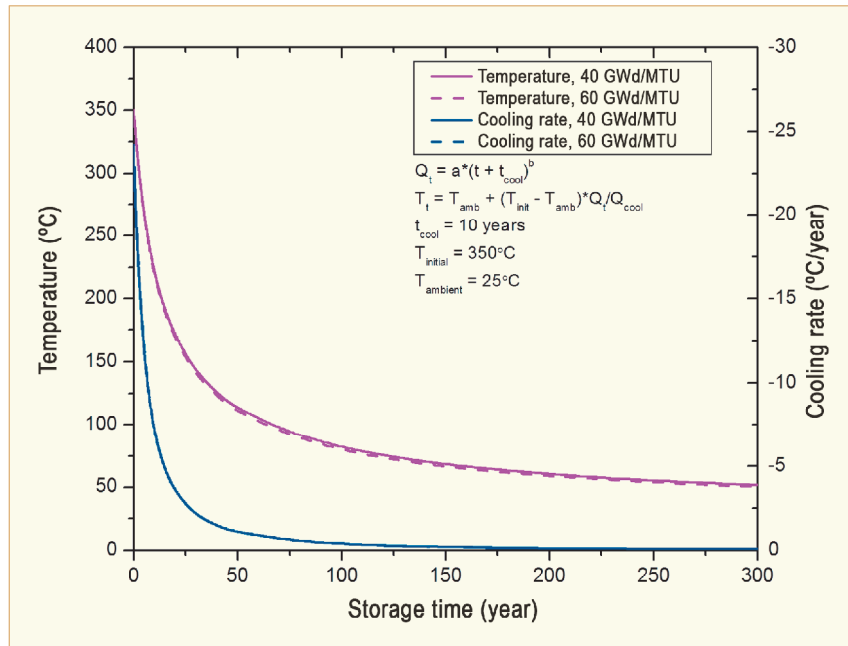


Figure 3-4: Peak temperatures and cooling rates of PWR fuel at 40GWd/MTU and 60GWd/MTU relative to storage time, after [Carter et al, 2012].

For a given SNF loading, temperatures typically vary axially and radially within a storage (or transport) container. Assuming fuel is transferred from pool to dry storage after 5 or more years of cooling, the temperature drop across the cladding wall is less  $<0.01^{\circ}\text{C}$  based on the MATPRO material properties [Hagrman, 1993]. As discussed below, axial variations can be larger than the radial variations.

### 3.2.2 Temperature measurements

A number of experimental programs have been conducted to determine the temperatures inside and around dry storage containers. Temperatures in such tests are typically measured with thermocouple probes inserted into loaded containers and with thermocouples located on the exterior surfaces. External temperature data are frequently augmented with measurements of convective flow. In most cask demonstration programs, the interior probes enter a container through penetrations in one of the container lids. The probes are generally located at varying radial and azimuthal positions through the inner region of the cask and contain measuring junctions at pre-selected elevations. The combined output of these probes provides 3-dimensional mappings of temperature relative to container conditions; e.g., container design, fuel loading, atmosphere (vacuum or various fill gases and pressures) and, in some cases, container orientation (vertical or horizontal). A summary of temperature measurements and related studies performed in the U.S. is given by [McKinnon & DeLoach, 1993].

The thermocouple probes used to measure temperatures in the instrumented cask tests are generally located within and among fuel assemblies; e.g., guide tubes in spent PWR assemblies and spaces among assemblies. The spent fuel itself is typically not instrumented to provide direct measurements of cladding temperature in such demonstration programs. The resulting values can, however, be used with related instrumented tests of electrically heated rods to estimate conditions in SNF assemblies. As noted in the next section, this work has led to thermal and computational fluid dynamic models that enable calculation of local temperatures.

For the reviews of the effects of temperature on cladding behaviour which are given in later sections, temperature measurements and correlations developed from a demonstration program involving a CASTOR-V/21 cask and 21 15×15 PWR fuel assemblies from the Surry Nuclear Power Plant are summarized in this section. For notational convenience, this program is identified as the “Surry test”. This demonstration program extended through a storage interval of ~15 years with pre-storage characterizations, temperature and activity measurements and post-storage examinations. The work is well documented (see for example [EPRI, 1986], [McKinnon & DeLoach, 1993], [Bare & Torgerson, 2001] and [Einzig et al, 2003]) and provides a good, but limited, basis for assessing SNF behaviour during dry storage.

Temperature measurements at the start of the Surry test were reported at six axial locations in fuel assemblies and gap positions at the container centre, mid-radius and edge locations. Measurements were made with three different atmospheres (vacuum, helium, and nitrogen) with the cask in both the vertical and horizontal positions. Examples of the temperature distributions with the CASTOR-V/21 in the vertical position are shown in Figure 3-5 under vacuum and in Figure 3-6 with helium fill gas. The full set of temperature measurements are given in [EPRI, 1986]

As shown in Figure 3-5 and Figure 3-6, temperatures vary with storage condition and location in the cask. A vacuum environment produced the highest cladding temperature<sup>7</sup> of 424°C. After backfilling with helium, the peak cladding temperature at the centre of the fuel region was 347°C with the cask positioned vertically and 360°C in a horizontal cask. With helium in the vertically oriented CASTOR-V/21 cask, the peak temperature near the edge of the fuel region was 34°C lower than at the centre; i.e., 313°C. In addition, temperatures at the ends of the fuel are about half those at the peak temperature locations. Note that these values are unique to the Surry test; temperatures are provided to show general trends.

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<sup>7</sup> Temperatures are measured in guide tubes and assumed to represent cladding temperatures based on analyses in [EPRI, 1986].

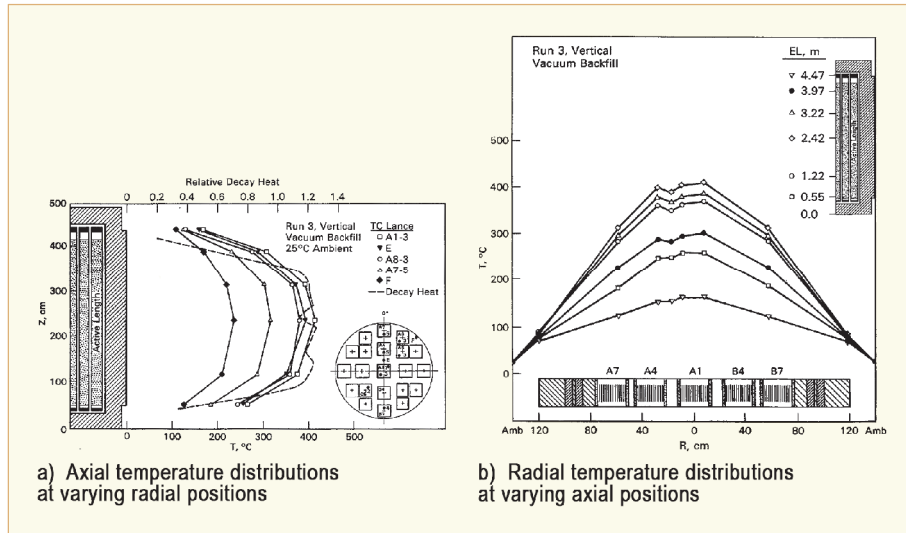


Figure 3-5: Temperature measurements in CASTOR-V/21 cask in a vertical orientation with PWR fuel assemblies in a vacuum, [EPRI, 1986].

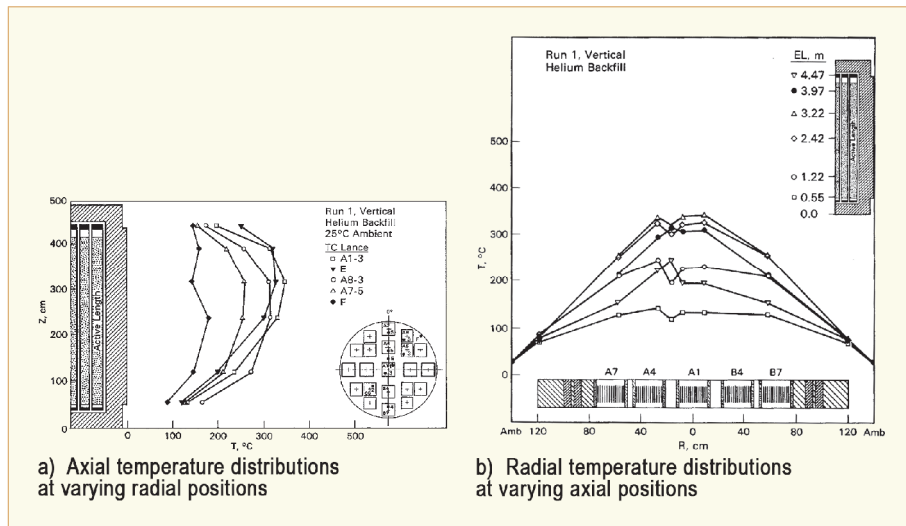


Figure 3-6: Temperature measurements in CASTOR-V/21 cask in a vertical orientation with PWR fuel assemblies in helium, [EPRI, 1986].

Temperature measurements at the beginning of the Surry test are projected over time in Figure 3-7 on the assumption that the increment above ambient temperature varies with decay heat. In the analysis by [Einzig et al, 2003], temperature is assumed to vary with time according to

$$\text{Eq. 3-1: } T_t = T_{\text{ambient}} + (T_{\text{initial}} - T_{\text{ambient}}) \exp(-\lambda t)$$

in which

$T_{\text{ambient}}$  = Ambient temperature, 38°C (constant),

$T_{\text{initial}}$  = Peak temperature at the beginning of storage, 344°C (measured) and

$\lambda$  = Thermal decay constant.

Two values of the thermal decay constant are used. In one case, the radioactive decay of  $^{137}\text{Cs}$  is used to approximate a slow rate of temperature falloff; i.e.,  $\lambda_{\text{slow}} = 0.023/\text{y}$ . In the second case, a thermal decay constant was determined by fitting Eq. 3-1 to pre- and post-storage temperature measurements, which gave  $\lambda_{\text{fast}} = 0.064/\text{y}$ . *The motivation for assuming temperature variations based on the decay of  $^{137}\text{Cs}$  rather than on one of the established decay methods (ORIGN or approximations such as those developed by [Malbrain, 1982]) or on the detailed thermal analyses that were performed at the time (HYDRA and COBRA) is unclear. The choice appears to be based on the secular equilibrium of  $^{90}\text{Sr}$  and  $^{137}\text{Cs}$  (both with  $\sim 30\text{y}$  half-lives) and their respective daughter products  $^{90}\text{Y}$  (64h) and  $^{137\text{m}}\text{Ba}$  (2.52m), the decay of which are significant contributors to heat generation in the interval of about 10-50 years. The choice also seems to be based on a desire to address potentially higher storage temperatures. The use of pre- and post-storage temperature measurements is a more rational approximation of the time variation of temperature, but was affected by the absence of thermocouple probes, which necessitated post-storage measurements after removing the cask lid and is believed to have contributed to lower temperatures.*

For perspective, Figure 3-5 also contains a third temperature estimate based on the decay heat calculated with the computer program ORIGEN-2.2 as in Figure 3-3. Estimates of decay heat from ORIGEN-2.2 suggests temperature changes based on the decay of  $^{137}\text{Cs}$  decrease too slowly relative to time. They also suggests those based on the observed temperature drop are closer to the likely behaviour, even though measurements after 14.8 years were made in an open cask. Note that lower temperatures based the post-storage measurements relative to those based on ORIGEN-2.2 are consistent with a downward temperature bias in the open cask.

Reviews of the effects of temperature on cladding behaviour later in this report use the approach of [Einziger et al, 2003] in Eq. 3-1Eq. 3-1 for bounding (high and low) temperature estimates. An average of these two approximations is also used for “best-estimate” conditions; viz.,

Eq. 3-2:

$$T_t = T_{\text{ambient}} + (T_{\text{initial}} - T_{\text{ambient}}) \left[ \frac{\exp(-\lambda_{\text{slow}} t) + \exp(-\lambda_{\text{fast}} t)}{2} \right]$$

As noted in later sections, both equations are used with temperatures that approximate current dry-storage conditions; i.e., higher peak temperatures ( $400^\circ\text{C}$ ) and lower ambient temperatures. These time profiles of temperature constitute a framework for assessments of the contributions of hydrogen diffusivity, hydrogen concentrations, hydrogen-concentration gradients and solvi for the hydrogen flux estimated by the hydrogen flux equation.

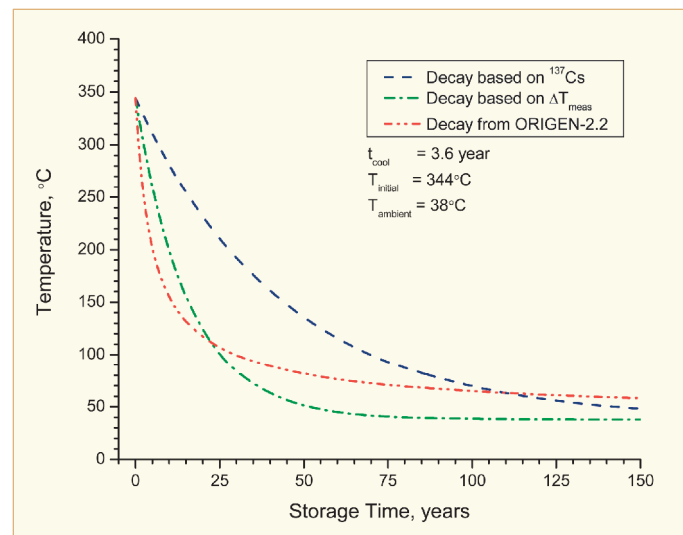


Figure 3-7: Comparison of temperature estimates based on evaluations of the Surry 15x15 PWR rods in the CASTOR-V/21 cask demonstration program and based on decay data from ORIGEN-2.2, after [Einziger et al, 2003] and [Carter et al, 2012].



As shown in Figure 3-6, temperatures at any point in time vary with position in the fuelled region of a cask. For casks in a vertical orientation, the temperature of the ends of fuel rods located in the centre of a cask are about half of the temperature difference between the peak (centre) temperature and the external, ambient temperature. This variation is approximated as a simple linear form in assessments of axial gradients in assessments of hydrogen diffusion. For casks in the horizontal orientation, the axial temperature variations differ slightly from those in the vertical orientation, but are also significant. Axial temperature variations in horizontally oriented casks are assumed to be bounded by the temperature distributions of vertically oriented casks.

### 3.2.3 Calculated storage temperatures

Calculations of dry storage temperatures usually involve a combination of empirical and numerical methods; i.e., finite element or finite difference methods. These computer models are validated relative to data from instrumented cask tests such as those discussed in the preceding section. As shown in Figure 3-8, fuel assemblies are typically treated numerically as a distributed mass; i.e., equivalent solid or porous solid with or without interface conductance gaps in each basket cell and smeared properties based on finite element models which ignore rod, grid or assembly detail. Such equivalent properties, shown in Figure 3-9, are used in 2-D or 3-D finite element or finite difference analyses of the inner storage container. Heat generation and thermal conductivity vary with axial and radial position in container according to either a bounding or specific SNF loading. However, heat generation is typically assumed to be uniform within each SNF basketed or through the basket face at a given radial and axial container position – details such as local fuel rod peaking, guide tubes or water rods are typically ignored. Note that convective heat transfer in the fuelled region of a storage container is commonly ignored because of the numerical complexity of such analyses and the small amount of heat transferred by this mechanism relative to radiation and conduction in a helium atmosphere.

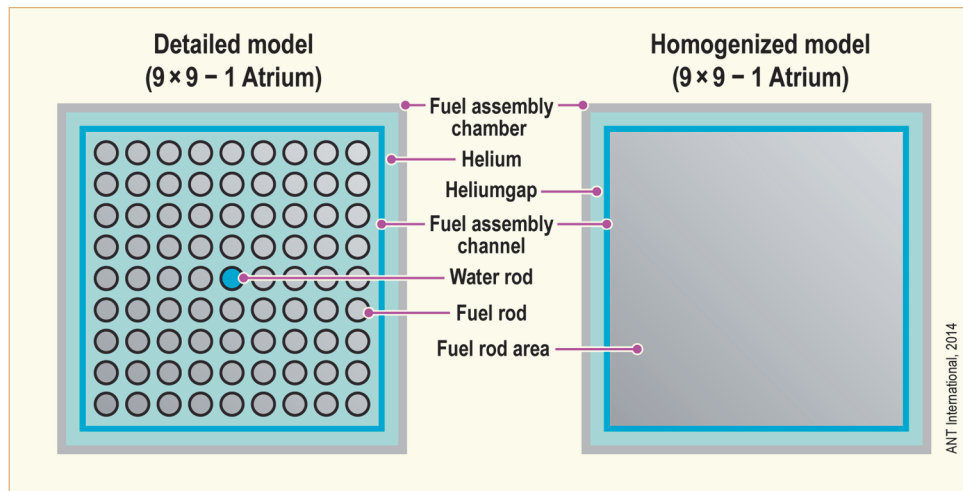


Figure 3-8: SNF assembly idealized as a distributed thermal mass, after [Leber et al, 2008].

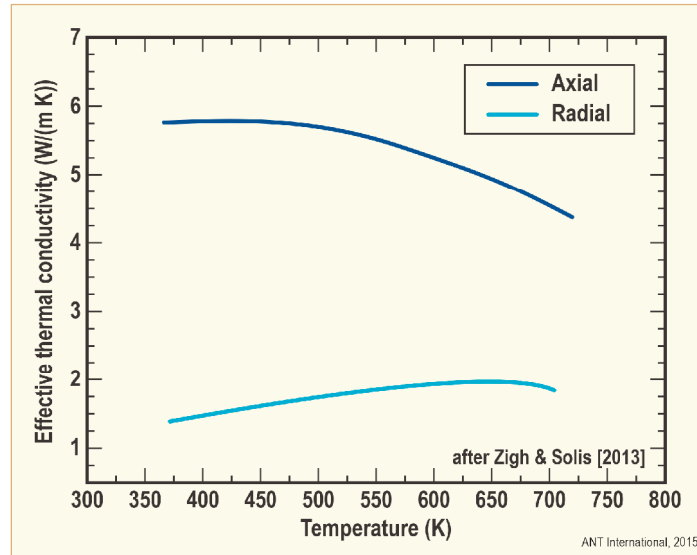


Figure 3-9: Equivalent thermal conductivity of distributed mass of SNF, after [Zigh & Solis, 2013].

Full dry-storage systems are now commonly analysed with computational fluid dynamics (CFD) models. In such evaluations, the inner container heat flux and ambient temperatures constitute the boundary conditions. Heat transfer by convection, conduction and radiation are being evaluated with computer codes such as CFX, FLUENT or STAR-CD (COBRA-SFS used as referee code by PNNL for U.S. NRC). Example of such analysis are shown in Figure 3-10 for a section of a storage cask and in Figure 3-11 for a dry storage facility. Improvements in analytic methods for dry container storage systems are largely responsible for increased thermal capacity of storage systems; e.g., from ~10kW/container to >40kW/container.

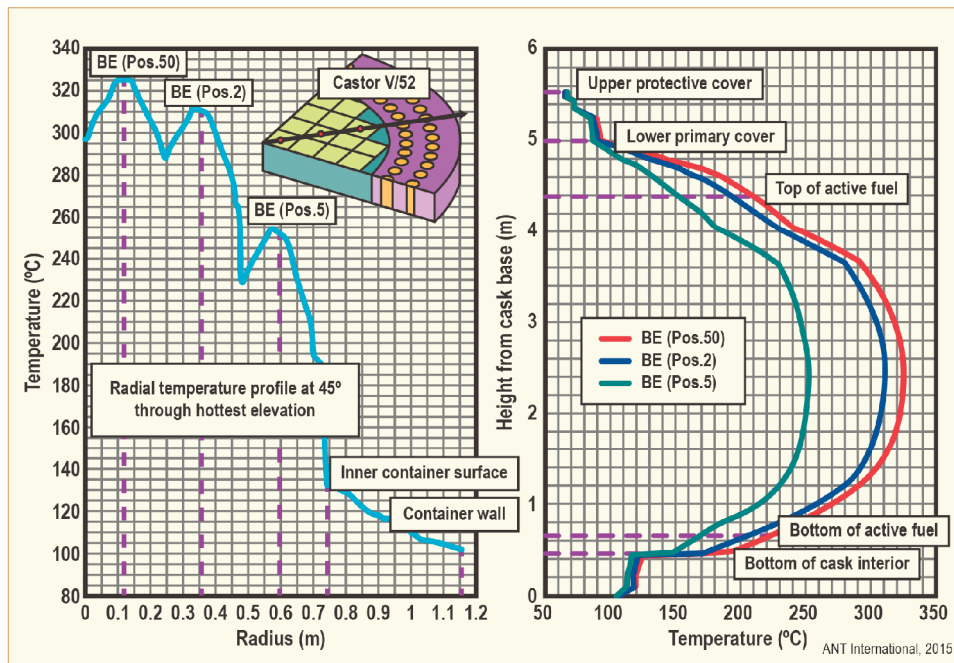


Figure 3-10: Thermal model and calculated temperatures for a dry storage cask, after [Leber et al, 2008].

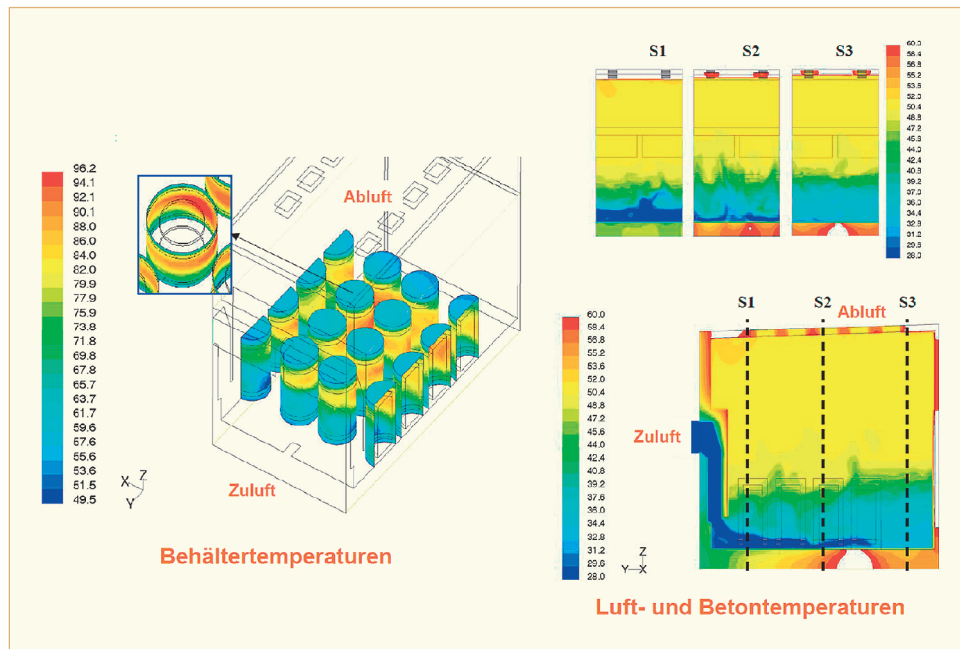


Figure 3-11: Temperatures and air flow distributions from CFD analysis of a dry storage facility [Leber et al, 2008].

The use of finite difference and finite element methods to estimate dry storage temperatures is becoming increasingly common. Early work with the computer model COBRA-SFS showed errors between calculated temperatures and measurements in cask demonstration programs of 5-10%, [Lombardo et al, 1986]. Analytic capabilities are illustrated in the comparisons of calculated and measured temperatures in the TN-24P cask test given in Figure 3-12 and Figure 3-13. Guidelines and best practices for the use of CFD in dry storage applications are now available in NUREG-2152, [Zigh & Solis, 2013].

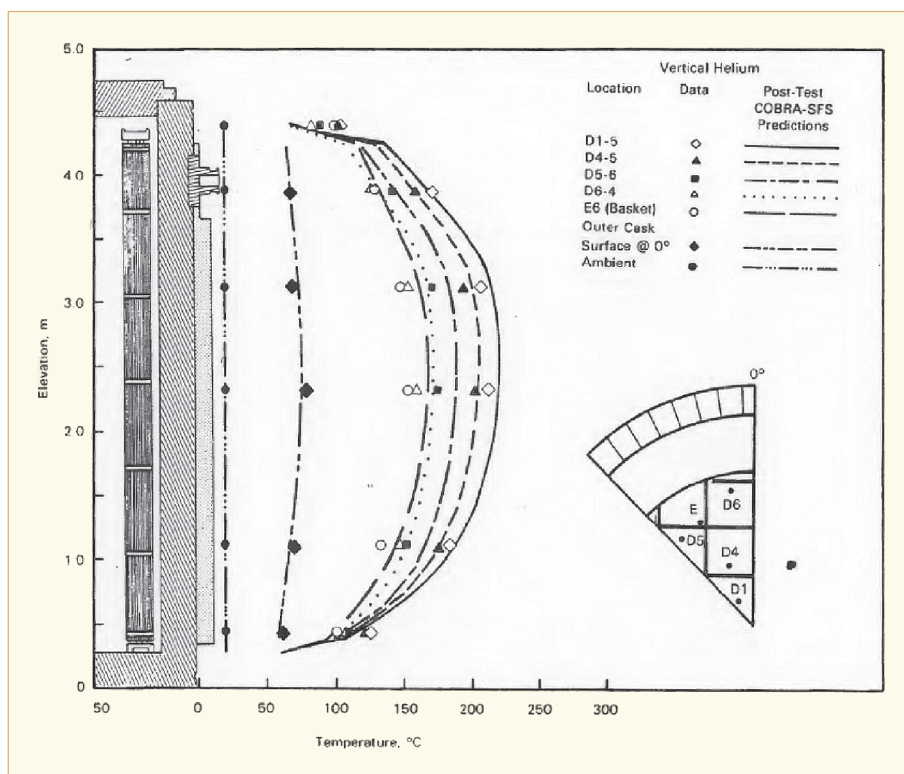


Figure 3-12: Comparison of axial temperature profiles calculated by COBRA-SFS with those measured in a vertically oriented, helium filled TN-24P cask, [EPRI, 1987].

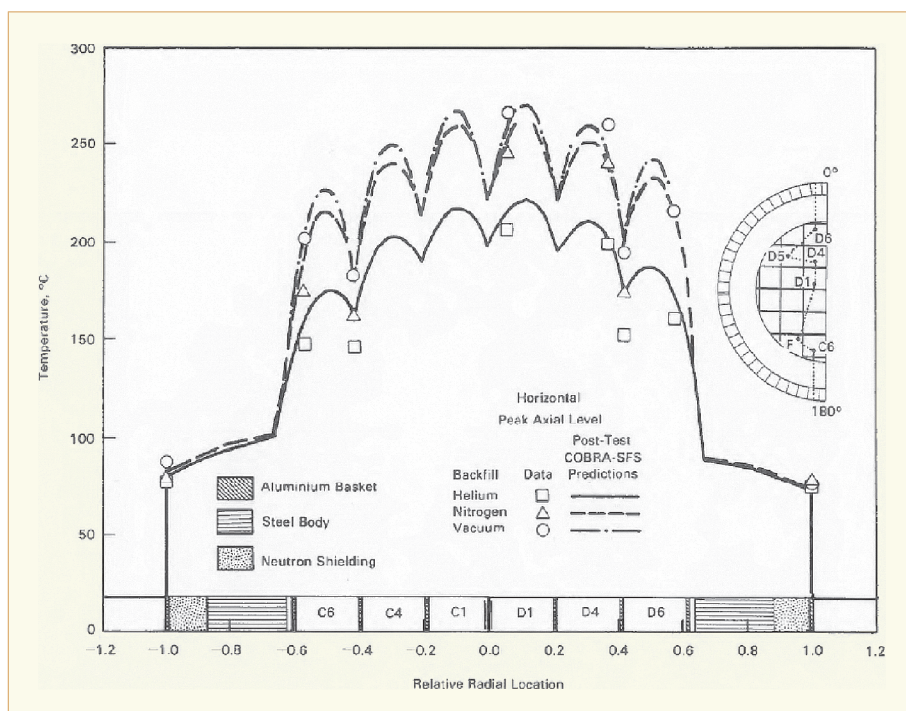


Figure 3-13: Comparison of horizontal temperature profiles calculated with COBRA-SFS with those measured with varying atmospheres in a horizontally oriented TN-24P cask.

For conditions that produce peak cladding temperatures of 400°C during vacuum drying, SNF temperatures are lower after backfilling with helium as observed in the Surry test and shown in Figure 3-14. This decrease is due to higher rates of heat transfer in helium than in a vacuum<sup>8</sup>. The time for vacuum-drying temperatures to drop to beginning-of-storage values varies with details of the drying and backfilling processes as well as with the cask and its SNF, but is typically no more than a few hours. Drying processes and the associated issues are discussed in the next section.

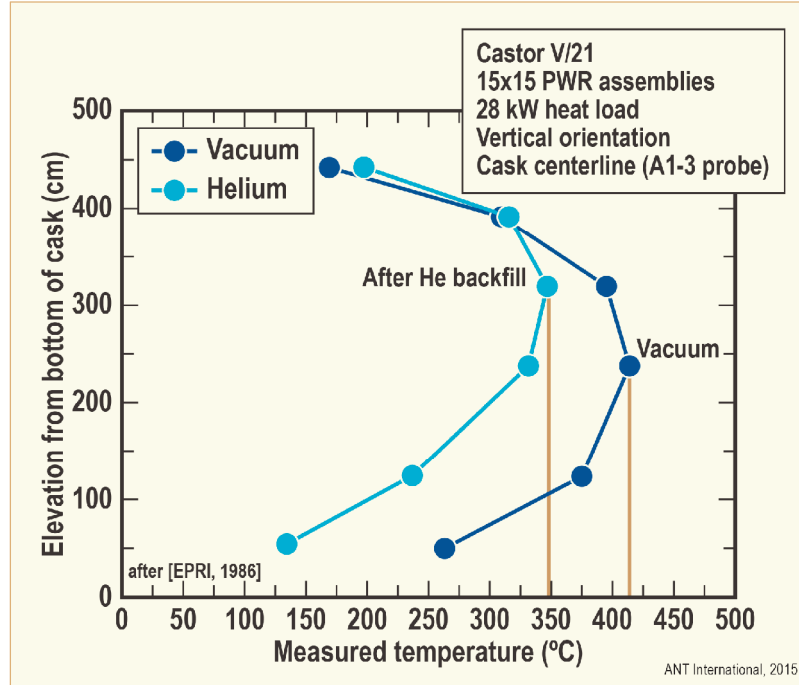


Figure 3-14: SNF temperatures in vacuum and after backfilling with helium, after [EPRI, 1986].

As shown in Figure 3-4, temperature decreases during storage at slower rates than during drying. In the model on which this figure is based, the peak temperature is calculated to decrease from 350°C after backfilling with helium to ~130°C after 40 years of dry storage and to <100°C after 120 years. Note, however, that estimates of temperature histories vary markedly with the thermal model; an alternate approach by the [IAEA, 2012b] gives temperatures of 220°C after 40 years and 160°C after 120 years. High cladding temperatures at ≤40 years of dry storage present challenges with respect to fuel retrieval for reprocessing or disposal. The low temperatures associated with extended storage introduce potential problems with respect to cladding ductility and fuel rod integrity during transportation, retrieval and handling.

<sup>8</sup> The change in the axial distribution of temperature with the addition of helium which is shown in this figure indicates heat is actually transferred by convection in a helium atmosphere. Studies of the separate effects of conduction, convection and radiation indicate, however, that the contribution by convection within the fuelled region of a storage container is small enough to be neglected relative to those by conduction and radiation in helium.

## 3.3 Drying and thermal cycling

### 3.3.1 Residual moisture

SNF is almost universally loaded into storage casks or canisters while submerged in fuel handling pools. A key issue is, therefore, the elimination of water and residual moisture from “dry” storage containers. Water in dry storage container can exist in several forms; viz.,

- Bound water
  - Chemically adsorbed water; e.g., water of hydration,
  - Physically absorbed water on free surfaces (waterlogged rods, plugged guide tubes, water rods, fuel assembly crevices),
- Free water
  - Physically trapped water,
  - Unbound water (neither adsorbed, absorbed nor trapped water).

Water which remains in storage containers after drying (residual moisture) is postulated to contribute to a number of the technical gaps associated with long-term storage, [DOE, 2012b]. These gaps, which are listed in Table 2-1, involve the potential effects of residual moisture and the products of radiolytic decomposition on the SNF, on cask internals and on flammability of gas mixtures that could be encountered when casks are unloaded. That is, insufficient data are believed to be available regarding the amount of water that remains after drying and regarding the potential corrosion, embrittlement or cracking due to long-term exposure to such moisture and the resulting products of radiolytic decomposition. Although experience to date tends not to support the postulated relationships between residual water and potential degradation mechanisms, the composition of the gas actually present in storage containers is typically not measured during or after the drying process. In addition, the likely storage times are projected to extend beyond the current range of experience. As a result, residual moisture is considered a technical issue by several the organizations that have rated this topic in the gap-assessment process, with the highest concern expressed by the U.S. DOE, Nuclear Waste Technical Review Board and NRC and lower or no concerns by others in Asia, Europe and the U.S., [DOE, 2012b].

The amount of residual moisture is expected to be small in containers with typical, sound (unbreached) commercial SNF and the processes commonly used to dry loaded storage containers; e.g., 1moles to 5moles (18g to 90g H<sub>2</sub>O), [Jung et al, 2013]. This range is based on the pressure, temperature and free volume of a loaded cask at the end of vacuum drying; i.e., vapor density and volume. As noted above, however, concerns exist because conditions associated with the fuel, container, drying process and long-term storage can affect the amount of residual moisture. These concerns center around free water which is physically trapped in or on fuel and assembly components and on water which is chemically or physically bound to the SNF.

Bound water can be chemically adsorbed or physically absorbed on the surface of SNF and in crud and oxide deposits. Bound water is a concern in extended storage because some forms can survive typical drying processes and subsequently be released or decompose with continued exposure to temperature and radiation.



Water that is trapped in breached fuel rods can remain after drying and contribute to the residual moisture in a sealed storage container. The SNF of concern in this case involves fuel rods that develop leaks during in-core operation or wet storage, where water fills part or all of the free void volume within the breached rods. A summary by [Jung et al, 2013] of experiments with breached fuel rods shows the total amount of water collected in hot cell tests of waterlogged, full-size SNF rods (from the Bilbis PWR) heated to 160°C for 7 hours and 200°C for 24 hours ranged from 0.1moles to 0.2moles (1.9g to 3.8g H<sub>2</sub>O). An additional 0.03moles to 0.23moles (0.5g to 4.1g H<sub>2</sub>O) was collected during two months at 400°C following the initial drying. The temperature for release suggests part of this inventory was chemically or physically bound in the breached rods, [Peehs & Fleisch, 1986]. Similar observations of moisture release from a breached and waterlogged, spent BWR fuel showed the release of 0.08moles (1.5g H<sub>2</sub>O) of water under a vacuum at 325°C. In the BWR test, outgassing of water varied with temperature and time; e.g., significant evaporation of water in the first hour under vacuum at temperatures up to 130°C with continued outgassing at 325°C during the 650 hours comprising the test.

The effect of breached fuel rods on residual moisture depends on the number and nature of the failed rods in any single container. Obviously, rods that are sound (non-breached; non-failed) or that are sound at the beginning of dry storage but that subsequently develop leaks do not contribute to such moisture because they are free of internal water. Similarly, the average, in-core failure rate of LWR fuel, which has improved over early performance and is currently in the range of 80-130 failures per million rods for PWR, VVER and BWR rods in Europe and the U.S. [IAEA, 2010b], is not directly relevant because the potential inventory of residual moisture depends on the number of waterlogged rods in a single container rather than the average number of breached rods in all SNF. But, assuming cask loadings are limited to a single breached rod, which is roughly consistent with the current in-core failure rate, [Jung et al, 2013] estimate the amount of free residual water from such a rod is in the range of 1.4moles to 11moles (25g to 200g H<sub>2</sub>O).

Another potential source of residual moisture is water bound to SNF or other structural surfaces. Physisorbed water is expected to be removed by a combination of vacuum and temperature in the drying process and is not expected to be a significant source of residual moisture; [ASTM, 2008] and [Jung et al, 2013]. Less is known about chemisorbed water, which can exist as hydroxides or hydrates on the surface of Zr-alloys; e.g., ZrO<sub>2</sub>·xH<sub>2</sub>O, Zr(OH)<sub>4</sub> or ZrO(OH)<sub>2</sub>.

In an analysis of drying adequacy, [Jung et al, 2013] assumed experience regarding hydroxides and hydrates in the oxide on aluminum clad fuel is relevant to Zr-alloy cladding to infer the presence of zirconium hydroxide (ZrO(OH)<sub>2</sub>) with a thickness of 10µm and a density of 2.0g/cm<sup>3</sup>. Such hydroxides are observed to thermally decompose at rates which increase with temperature starting slightly above room temperature and extending through approximately 700°C; [Powers & Gray, 1973] and [George & Seena, 2012]. With decomposition fractions assumed to be in the range of 0.1 to 1.0 due to uncertainty on the extent of decomposition during drying and subsequently during longer-term storage, the postulated hydroxide inventory leads to 1.1moles to 85moles (20g to 1500g H<sub>2</sub>O) of residual moisture with ~600m<sup>2</sup> of SNF surface area in a typical dry storage container (Castor V/21 with 15×15 PWR fuel).

*The physical bases and likely uncertainty of the residual moisture from chemisorbed water estimated by [Jung et al, 2013] are unknown. The formation of hydrated compounds in CRUD and oxide is described by [Wikmark & Cox 2001] and in the discussion of chemisorbed water in the technical background section of the standard, vacuum-drying specification [ASTM, 2008]. The presence of  $ZrO(OH)_2$  and  $Zr(OH)_4$  on the surface of SNF is plausible but ill-defined. Studies by [Shmakov et al, 1998] and [Hermann et al, 2000] show surface water is not released below 480°C to 500 °C. Both studies were based on hot gas extraction measurements (LECO analyses) of irradiated fuel cladding. The work by [Hermann et al, 2000] involved Zry-4 cladding that operated 1 to 5 reactor cycles in a PWR. Measurements of the high burnup samples show hydrogen concentrations of 900wppm to 1160wppm in oxide that ranged from 42µm to 66µm thickness. Assuming all of this surface hydrogen is released as water (rather than hydrogen) during long-term storage gives approximately 10moles (180g H<sub>2</sub>O) of residual moisture for the cask loading considered by [Jung et al, 2013]. This amount is smaller by a factor of ~8 than the corresponding 100% release cited above, which implies the assessment of drying adequacy by [Jung et al, 2013] is probably conservative.*

As noted above, the amount of water expected to remain in a storage container with the normal conditions of vacuum drying is in the range of 1.0mol to 5.5mol (18g to 99 g) of H<sub>2</sub>O. Additional water can, however, come from breached rods and upset conditions during the drying process. A fuel rod that fails and fills with water prior to storage can release water vapor slowly and has the potential for adding 1.4mol to 11mol (25g to 200g) of H<sub>2</sub>O, [Jung et al, 2013]. The amount of residual water that could result from drying upsets is unknown. An upper bound of 55mol (~1kg) of H<sub>2</sub>O is typically assumed in assessments of drying adequacy; i.e., ~10X the normal upper bound on residual water.

The processes currently used to remove moisture from dry-storage containers are vacuum drying and forced gas (helium) dehydration. These processes are discussed separately in sections which follow.

### 3.3.2 Vacuum drying

Vacuum drying is commonly used to remove moisture from the interior of storage and transport containers after water is drained from the containers. The vacuum drying process, which is shown schematically in Figure 3-15 and Figure 3-16, varies among countries but generally consists of evacuating a loaded container in a slow, stepwise or combined slow and stepwise manner to a low pressure and relying on decay heat and a combination of mass transport and molecular diffusion to remove water vapor from the container and its contents. A series of evacuations and back-fillings with air or an inert gas are used in some applications to increase heat transfer among components of the SNF and container and to promote moisture removal by mass transfer. Heated gas is also used in containers with limited decay heat or to reduce the overall process time (which makes this type of vacuum drying a hybrid form of gas dehydration).

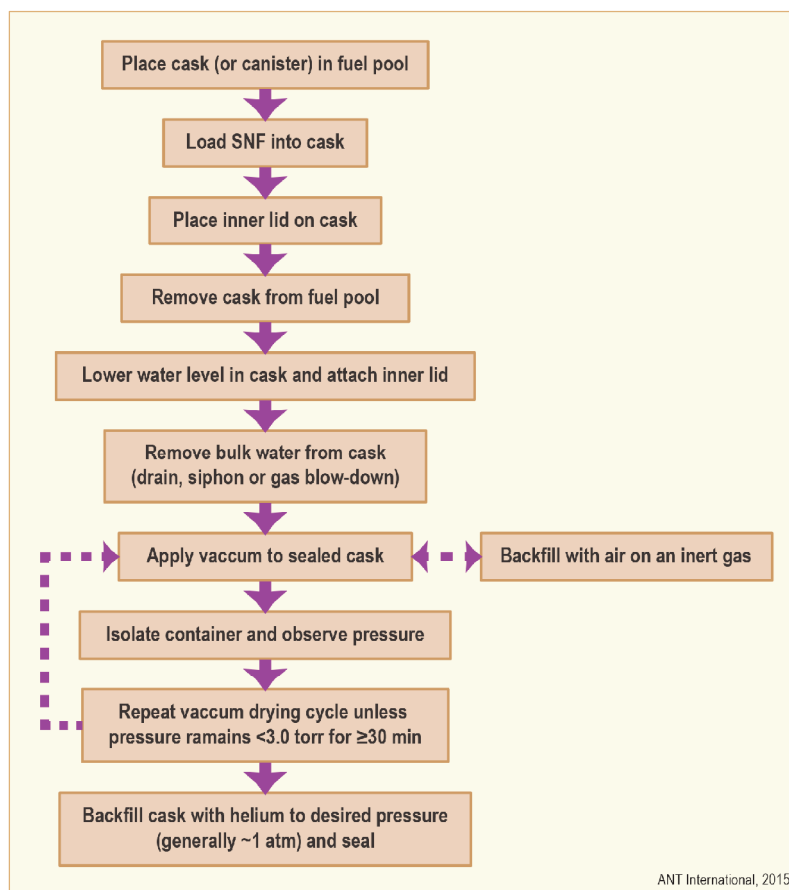


Figure 3-15: Cask loading and vacuum drying flow diagram.

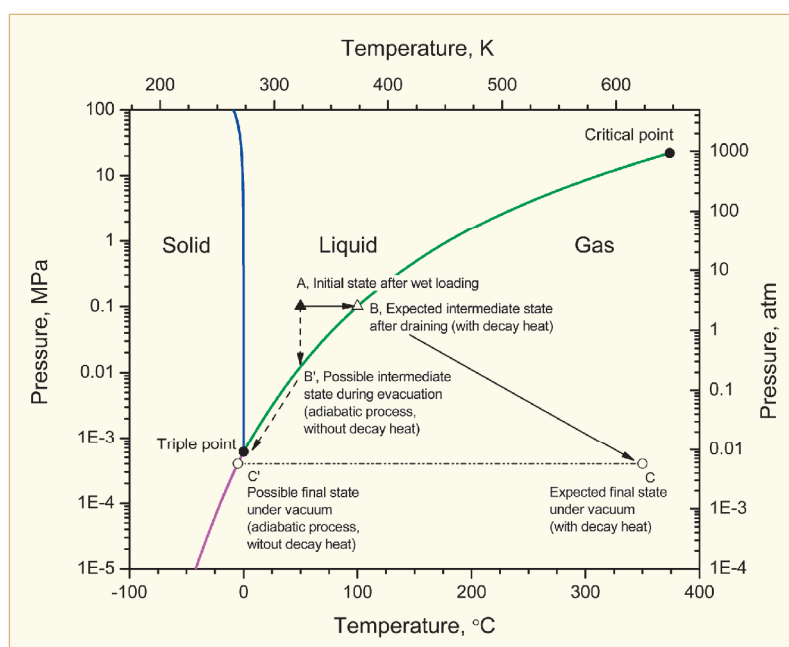


Figure 3-16: Schematic diagram of pressures and temperatures during vacuum drying, [Wagner & Pruß, 2002] and [NIST, 2011].

Moisture removal is assessed by isolating the container from the vacuum system and observing the change in pressure over a prescribed interval of time; e.g., an acceptable degree of dryness is assumed if the isolated pressure remains  $\leq 3$  Torr ( $\sim 400$  Pa) for  $\geq 30$  minutes, [ASTM, 2008]. This pressure stability criteria for dryness is based on increases in pressure due to the evaporation of any residual water that might be present during the isolation interval (assuming thermal equilibrium). The drying process is repeated if pressure rises above the limiting value.

The number of thermal cycles to which SNF can be subjected during vacuum drying has historically been limited due to issues related to the growth or reorientation of cladding hydrides in the (unfavourable) radial direction. Thermal drying cycles with changes in cladding temperature up to  $65^{\circ}\text{C}$  are commonly limited to  $< 10$  cycles, [NRC, 2003a], [NRC, 2010]. This constraint is based on observations of hydride reorientation primarily in unirradiated cladding which now seem to differ from hydride reorientation observed in irradiated cladding, [Billone et al, 2013b]. Although a fixed number of temperature cycles are still imposed in some countries, the trend is toward evaluation on a case-by-case basis.

One of the conditions that can theoretically affect the removal of free water is the formation of ice during the pressure reduction phase of the vacuum drying process. Ice can form because reducing pressure from the wet, post-drainage condition (points A or B in Figure 3-16) brings water to the liquid-vapor transformation line (points B or B'). Along this phase-transformation line, the heat required to vaporize liquid water ( $539.6\text{ cal/g}$  at 1 atm and  $100^{\circ}\text{C}$ ) exceeds the heat required to freeze water ( $79.7\text{ cal/g}$ ) and can exceed the energy available locally from ambient conditions or fission product decay.

The paths to the final vacuum state of  $\leq 3$  Torr are varied. For the fueled region of dry storage cask, the pressure and temperature are expected to move from an initial point such as A in Figure 3-16 (1 atm,  $50^{\circ}\text{C}$ ) to the vapor-liquid evaporation line, point B, as decay heat increases the temperature of water remaining in the cask following gross dewatering. Pressure and temperature will remain at point B until the remaining water transforms from liquid to vapor. Temperature in the fueled region will then progress to a point such as C with the continued generation of decay heat, container evacuation and the resulting decreases in the heat transfer capabilities of the cask atmosphere. Water at point C will be in the form of superheated steam. Alternately, with heat input that is smaller than the heat required for evaporation, temperatures can decrease so water freezes and approaches point C' in Figure 3-16. For a cask loaded with spent commercial LWR fuel, this condition is possible with rapid pressure reductions, little or no heat input and without dwell times to achieve thermal equilibrium; e.g., water trapped in vacuum lines outside of the region heated by radioactive decay. Note that such adiabatic expansions, which are sometimes cited as a basis for ice formation, are theoretically possible based on the pumping capabilities of vacuum equipment typically used in vacuum drying; i.e.,  $60\text{ m}^3/\text{h}$  to  $70\text{ m}^3/\text{h}$  pumping rates down to  $\sim 10$  Torr vs.  $2\text{ m}^3$  to  $8\text{ m}^3$  volume, [Miller et al, 2013]. So, the likelihood of forming ice in the fueled region of a storage container depends on the rate at which decay heat is generated and the actual rate of evacuation. Ice formation can theoretically be avoided by increasing the minimum pressure under vacuum to values greater than 4.6 Torr (0.61 kPa), where the saturation temperature is slightly over  $0^{\circ}\text{C}$ ; see discussion in [IAEA, 2012b].

The possibility of ice formation is well recognized and is addressed in the design and operation of vacuum drying equipment; e.g., by configuring unheated vacuum and pressure-sensor lines to prevent water retention, by slow or stepwise pressure reductions and by backfilling or flushing hot gas through a storage container during the drying process; see, for example, [ASTM, 2008]. The decay heat in a container with SNF from commercial LWRs varies with power, exposure and cooling time, but is typically great enough to prevent icing with the drying equipment and procedures now in use. For example, the decay heat from a  $\text{UO}_2$  fuel rod after operating to  $40\text{ GWd/MTU}$  in a PWR or BWR and cooling for 5-10 years is in the range of  $1.4\text{ W/kgU}$  to  $2.7\text{ W/kgU}$  [NRC, 1999]. This heat generation rate is sufficient to prevent the formation of ice in a breached, fully waterlogged rod when the evacuation time is greater than approximately 4 hours.

Assuming a loaded storage container is evacuated slowly enough to achieve thermal equilibrium, the free water in fuel assemblies and on cask internal structures is expected to evaporate and to either be transported out of the container during the evacuation or diffuse from the container while under a vacuum. The remaining water will be in the form of superheated steam at a pressure determined by the evacuation process (order of 3Torr) and an effective temperature, which is unknown but lies somewhere along line C'-C in Figure 3-16. The density of the steam under these conditions ranges from approximately 3.0g/cm<sup>3</sup> to 1.4g/cm<sup>3</sup> ( $T_{\text{effective}} = 20^{\circ}\text{C}$  to  $350^{\circ}\text{C}$ ). The high end of this density range corresponds to the residual inventory noted previously when the free volumes of loaded dry storage containers are considered.

Vacuum drying temperatures, heating and cooling rates and times vary among dry-container storage systems, container loadings and drying procedures. As noted above, cladding temperatures are limited to calculated peak values. The total drying time varies, but is generally in the range of 1-3 days; [Miller et al, 2013]; [IAEA, 2012b].

Cooling rates vary during vacuum drying and dry storage. As indicated in Figure 3-14, the temperatures after back filling a storage container with helium are lower than those during the vacuum drying operation. The cooling rates after vacuum drying are much faster than during storage; e.g., cladding cooling at  $\sim 1^{\circ}\text{C/h}$  during helium backfill versus 3-5 orders of magnitude slower due to the falloff of decay heat during dry storage. Temperatures and cooling rates are expected to affect the behaviour of hydrogen in Zr-alloys and are discussed in later sections.

### 3.3.3 Gas dehydration

The second drying process, forced gas dehydration, is summarized in Figure 3-17, Figure 3-18 and Figure 3-19. This process differs from vacuum drying in that an inert, superheated gas is circulated through a loaded cask to evaporate and transport water from the SNF and container. The gas (usually helium) is heated along path A-B in Figure 3-19 and then passed through the cask. The temperature to which the gas is heated before entering the container can be adjusted according to the SNF decay heat and cask exit temperature. The moisture concentration of the gas increases in the cask along path B-C<sub>initial</sub> at the beginning of the drying process. After leaving the cask, the gas passes through a heat exchanger and cold trap, where water is removed, path C<sub>initial</sub>-D<sub>initial</sub>-A. The cold trap temperature fixes the partial pressure of moisture in the circulating gas, which needs to be under  $-7^{\circ}\text{C}$  (at 1atm) for its vapour pressure to be less than 3torr. Gas circulation and moisture removal continues until the moisture pressure remains less than the required value, path A-B-C<sub>final</sub>-D<sub>final</sub>. An advantage of the gas dehydration process is that temperatures during drying can be lower than those in vacuum drying, thereby reducing the amount of hydrogen which is dissolved during the drying process.

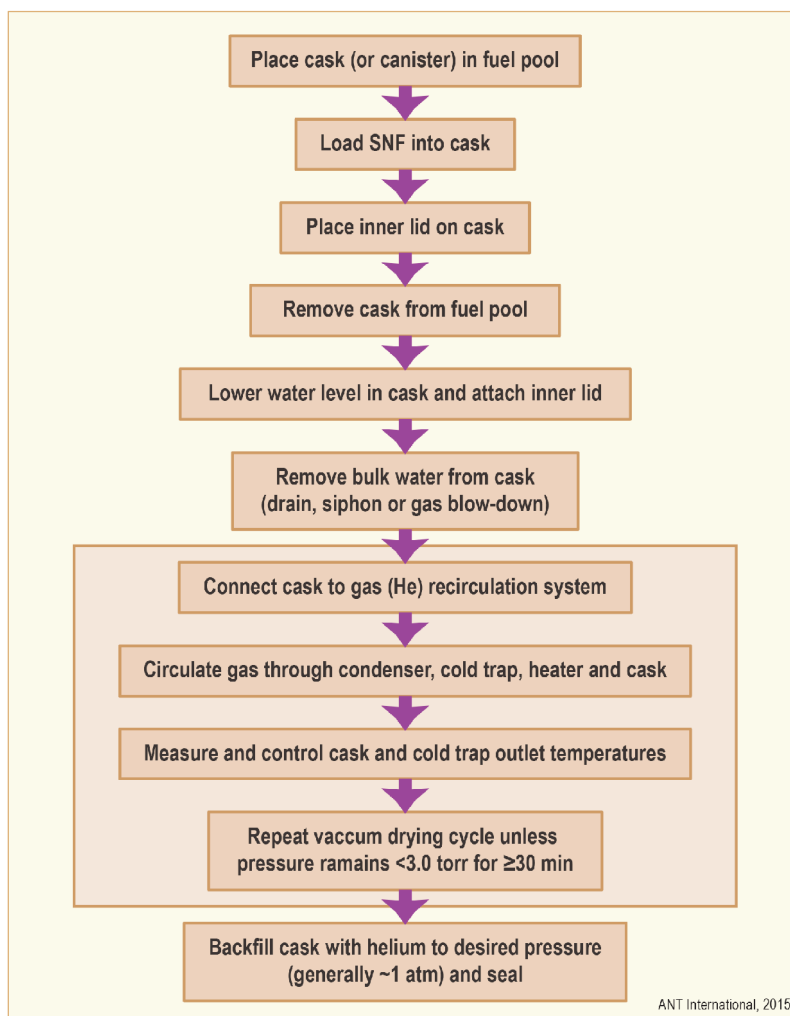


Figure 3-17: Schematic diagram of cask loading and forced gas (helium) dehydration process, after [Singh, 2004] and [Singh, 2013].

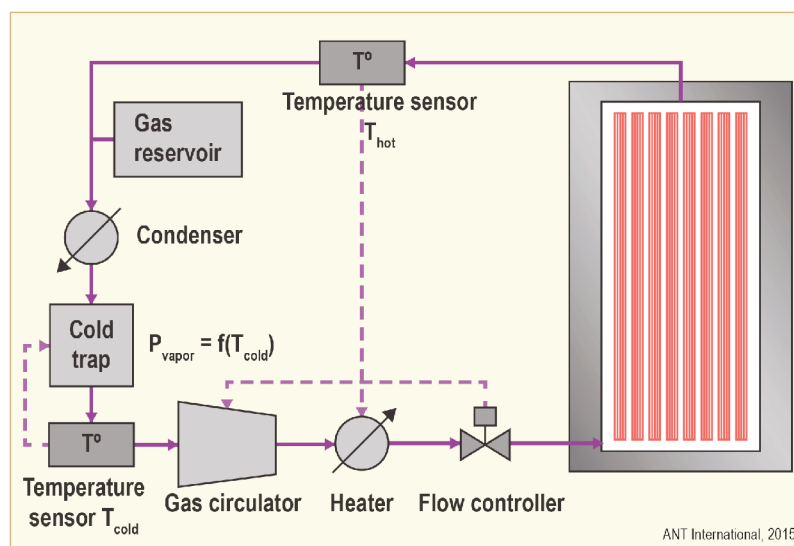


Figure 3-18: Cask loading and drying process by gas dehydration.



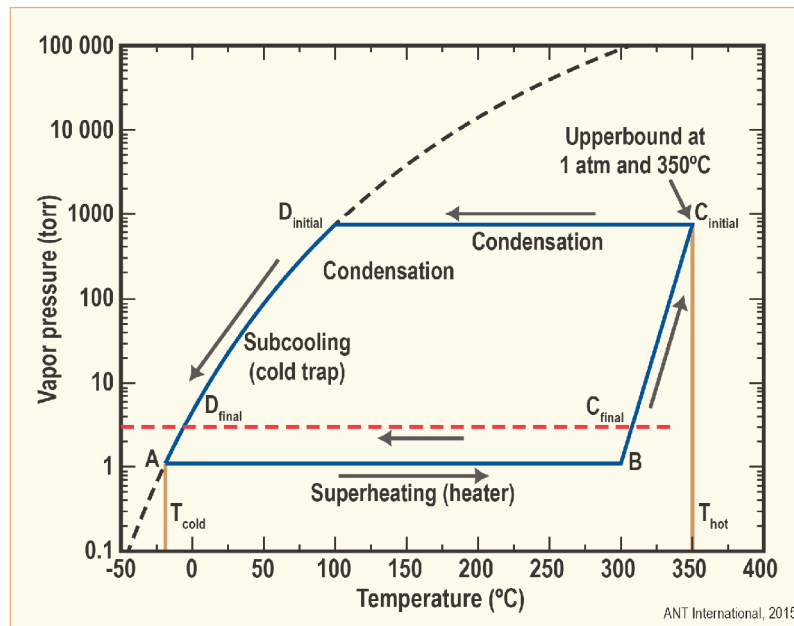


Figure 3-19: Pressure-temperature cycle of gas dehydration process.

Another potential advantage of forced gas dehydration is shorter drying times relative to vacuum drying. Although reports of cask drying experience with gas dehydration in open literature are limited, the removal of water by sweeping gas through a loaded cask is expected to be faster than by the molecular diffusion involved in vacuum drying. Assuming water can evaporate (i.e., unbound or unconfined water) and mixes fully with the sweep gas, the calculated vapour pressure is expected to drop below 3torr after six or more atmosphere exchanges. The mixing efficiency is likely to be less than 100%, so a greater number of gas exchanges is likely to be needed in practice. With this behaviour, however, drying times for a given storage container are fixed largely by the gas flow rates.

### 3.3.4 Thermal cycling during storage

The temperature of SNF will continue to vary with changes in ambient conditions during storage. The effects of changes in ambient temperatures on SNF and cask temperatures depend on the magnitude and rate of such changes. Temperature variations depend on location, with daily variations of approximately  $\pm 5^{\circ}\text{C}$  to  $15^{\circ}\text{C}$  in maritime regions [Scheitlin, 2013] and  $\pm 20^{\circ}\text{C}$  to  $30^{\circ}\text{C}$  in high, mountain desert regions (see <http://www.weatherpages.com/variety/diurnal.html>, for example). The thermal mass of loaded storage containers is large, however; e.g., cask mass  $\sim 100\text{MT}$  and SNF mass  $\sim 10\text{MT}$  to  $20\text{MT}$ . So, daily temperatures changes inside a storage container are damped by the heat capacity of the fuel and cask are expected to remain close to the daily-average value. Annual temperature changes also depend on location, but can be up to approximately  $\pm 20^{\circ}\text{C}$  to  $25^{\circ}\text{C}$  (see reference cited above). These changes are slow enough that SNF and inner container temperatures are expected to undergo similar variations.

Note that temperatures inside a dry storage container are calculated prior to loading and are neither measured, controlled nor managed during storage. Analyses of technical gaps have identified the need to improve the accuracy of temperature calculations in support of high burnup fuel and long-term storage; [EPRI, 2011], [DOE, 2012b], [Hanson et al, 2012] and [NRC, 2012]. The importance of improved analytic models is expected to increase with the higher heat loadings associated with extended exposures. The importance of methods improvements is also expected to increase with longer storage time, where the lower bounds of temperature are significant to the ductility and impact resistance of Zr-alloys, a topic which is discussed later section.