ESTABLISHMENT OF THERMAL ANALYSIS SCENARIO OF SPENT FUEL DRY CASK ON SHORT-TERM OPERATION PROCESS

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Abstract

Short-term operation process of spent fuel means the series of steps occurring in spent fuel building, from loading of spent fuel into shipping casks before transportation. This process includes loading of fuel into shipping casks, sealing of lids, drainage inside canister, drying, and backfilling. The distribution of peak cladding temperature of spent fuel over time tends to be different for wet process, vacuum drying process because heat transfer environments and heat transfer modes are changed. The paper aims to establish thermal analysis scenario on spent fuel short-term operation process for independent verification thermal model.

1. INTRODUCTION

Spent fuel is almost universally loaded into storage casks or canisters while submerged in spent fuel pool [1]. The short-term operation process refers to the series of steps occurring in the spent nuclear fuel building, from loading of spent nuclear fuel into shipping casks to transportation. This process includes loading of fuel into shipping casks, sealing of lids, draining water within canisters, vacuum drying, and backfilling with inert gas.

The distribution of temperature over time is different for each step since heat transfer environments and heat transfer modes vary throughout the short-term operation process. During the wet process, extra caution must be taken to prevent sectional boiling of water within canisters. If sectional boiling occurs, the inner pressure of canisters will increase, making it difficult to control the amount of pressure. Further, heat transfer to the inner medium (water) will rapidly decrease and cause a sharp rise in the temperature of spent nuclear fuel. To prevent such sectional boiling, the wet process (loading and sealing of canisters) must occur before the point of boiling. Vacuum drying process is the one with the least heat removal performance from spent fuel to be removed to the outside. Since the temperature of the internal structures in canister rises the fastest, a detailed analysis is required and the integrity of the spent fuel cladding should be verified by thermal analysis. More analysis is required following the increase in internal temperature of the canister, and spent nuclear fuel cladding hulls should be examined.

Since the short-term operating process takes a certain step in time, it may be matters to carry out the heat transfer analysis focusing on one step, so it is necessary to track the temperature distribution from the beginning of the loading of spent fuel during the short-term operating process over time. Therefore, heat transfer analysis for short-term operation process requires transient state heat transfer analysis for each process. Since the boundary condition and the internal medium are changed for each process, this should be considered in the analytical model. Therefore, the heat transfer analysis model should reflect the changes of the internal medium environment and the boundary condition, and it is necessary to analyse the process step by step as initial condition of each process result. In the present work, thermal analysis scenario on spent fuel short-term operation process is established as the first stage for the independent thermal model development. We investigate the operating procedure and the working time of each process through the literature survey. Thermal analysis strategies are suggested such as methods and scenarios based on the data obtained from the previous study and thermal analysis reference model.

2. THEORETICAL BACKGROUND

2.1. Design Standards

According to NUREG-1536 [2], the temperature of spent nuclear fuel cladding should be below 400°C during the short-term operation process, which includes drying and backfilling. In addition, for each operation scenario of the short-term process (fuel loading, draining, vacuum drying, backfilling, etc.), the permitted time for cladding hulls to reach the temperature limit must be determined. During the wet process (including fuel loading), the water inside casks or canisters must not be subject to boiling. The heat-up rate and time-to-boil should be calculated for the environment within canisters. Technical specifications and limiting conditions must be specified based on these calculations.

In ISG-11 [3], for all fuel burnup (low and high), the maximum calculated fuel cladding temperatures should not exceed 400°C for normal conditions of storage and short-term operations (e.g., drying, backfilling with inert gas, and transfer of the cask to the storage pad). However, for low burnup fuel, a higher short-term temperature limit may be used, if the applicant can show by calculation that the best estimate cladding hoop stress is equal to or less than 90MPa for the temperature limit proposed. Also, during loading operations, repeated thermal cycling (repeated heatup/cooldown cycles) may occur but should be limited to less than 10 cycles, with cladding temperature variations that are less than 65°C each.

2.2. Short-Term Operation Process

Depending on the inner medium in the casks or canisters, the short-term operation process can be divided into the wet process, vacuum drying process, and dry process. With reference to the operation process of HI-STORM100 [4] and NUHOMS [5], process details can be summarized as shown in Table 1.

TABLE 1. HEAT TRANSFER MODES OF THE SHORT-TERM OPERATION PROCESS

Classification	Internal environment		
	Wet	Vacuum drying	Helium
Inner medium	Water	-	Helium
Heat transfer mode	Conduction, convection	Radiation	Conduction, Convection, Radiation

For heat transfer analysis of the short-term operation process, working hours are required for each stage. The working hours for HI-STORM100 and NUHOMS, taking into account the number of workers and exposure dose, are shown in Table 2. The time for sealing of canister lids is 4.9 hours and 9.5 hours for HI-STORM100 and NUHOMS, respectively. This difference arises from work-related variables such as the number of workers and work proficiency. In consideration of the working hours for heat transfer analysis presented in Table 2, if the working duration of each process is sufficiently increased, a conservative approach is possible.

TABLE 2. WORKING HOURS ON EACH OPERATION PROCESS

Inner environment	Process	Working hours	
		HI-STORM	NUHOMS
Wet	Lid welding of canister	4.9hr	9.5hr
Wet/Dry	Drain	1.6hr	4.0hr
Vacuum	Vacuum drying	0.5hr	
Dry	Helium filling/installation of lid	6.6hr	10.5hr

2.3. Heat Transfer Characteristics

Due to changes of the inner medium in the short-term operation process progresses, the heat transfer environment varies as well. This leads to extreme variation in temperature over time, and an external cooling device may be needed to ensure the integrity of spent nuclear fuel cladding.

As an example of change in temperature, Figure 1 presents the results of temperature change for heat transfer analysis in the FuelSolutionsTM W21 storage canister. Phase 1-2 means the transferring the cask from sent fuel pool to decontamination pit, phase 3 on drainage inside a canister, phase 4 on vacuum drying, phase 5-6 on canister inspection and if need, re-vacuum drying, phase 7 on closure plate welding, PT/NED inspection, phase 8 on vertical transfer of the cask, phase 9 on canister storage in the canister.

As shown in the Figure 1, depending on the changes of internal environment in the canister, severe changes in temperature over time are clearly observed. During the vacuum drying process, heat transfer performance becomes the worst, causing a sharp increase in temperature. At this point, the temperature limit of the spent nuclear fuel cladding may be exceeded. Cooling water should be supplied to cool the external surface of the canister and keep the temperature within the acceptable range.

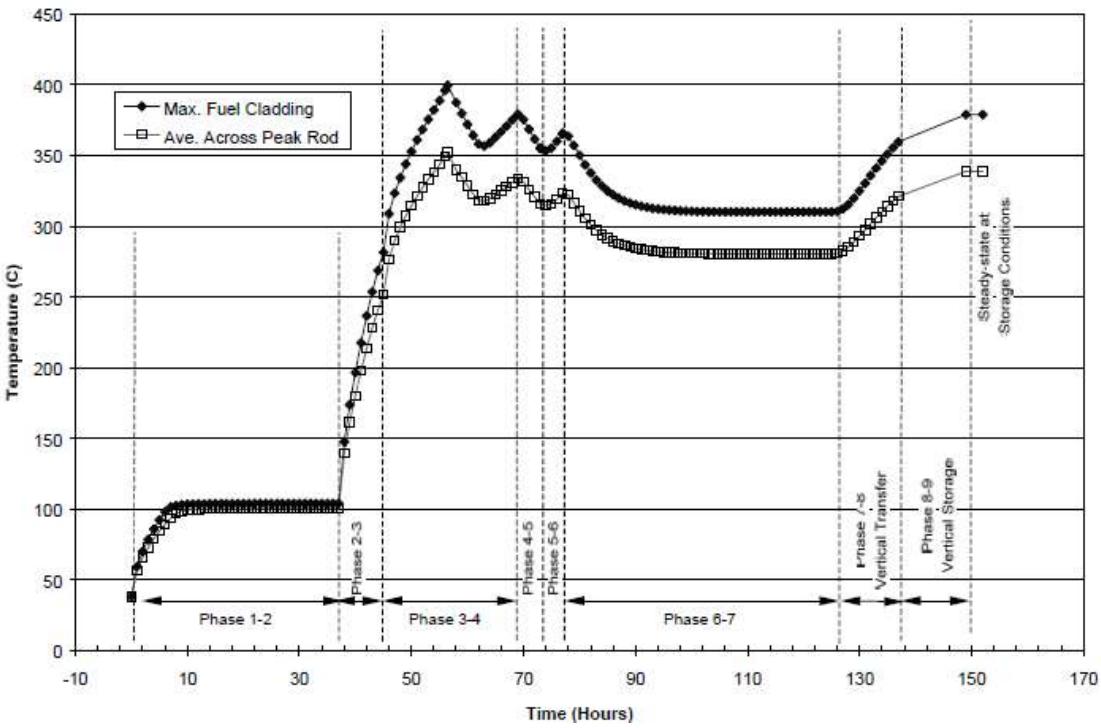

FIG. 1. Temperature variation over time on each stage of short-term operation process.

2.3.1. Wet process

Key processes in the wet process include loading of spent nuclear fuel in spent fuel pool, transfer of canisters to the decontamination pit, and sealing of canister lids. During the wet process, the inner medium of canisters is water, which results in convection or conduction heat transfer. Radiation heat transfer hardly occurs as it is uncharacteristic of water. Working hours for the wet process shall be set such that there is no boiling of water.

2.3.2. Vacuum drying process

The vacuum drying process is the stage occurring before the internal environment is completely dried. Vacuum drying is commonly used to remove moisture from the interior of storage and transport containers after

water is drained from the containers. All remaining moisture is removed. Due to the lack of an internal medium, the only heat transfer is in the form of radiation heat transfer. The conditions for heat transfer are poorest during vacuum drying, and temperature increases the most rapidly. Depending on the amount of decay heat(high burnup fuel, low burnup fuel), additional cooling water using forced method between outer canister and inner cask may have to be inserted to stabilize the internal environment. The vacuum drying process, which is shown schematically in Figure 2, varies among countries but generally consists of evacuating water vapor from the container and its contents, 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. A series of evacuations and backfilling 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. [1].

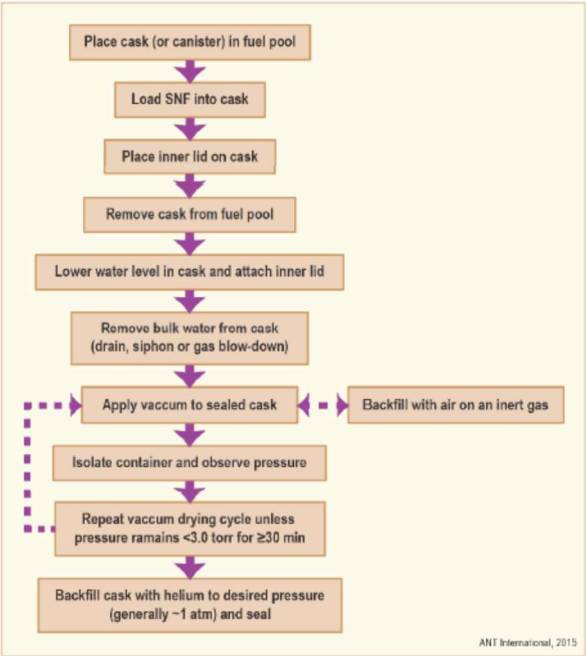

FIG. 2. Cask loading and vacuum drying flow diagram [1].

2.3.3. Dry process

The dry process occurs with the filling with helium to create a dry environment inside canisters. The internal environment is maintained to the dry state. The inner medium facilitates convection and conduction heat transfer, and radiation heat transfer also occurs within the canisters.

2.4. Overseas Case Studies on Heat Transfer Analysis Methodology

2.4.1. HI-STORM 100 Cask System

For the HI-STORM100 concrete cask [4], the canister lid is first sealed, and then the insides are dried before filling with helium. The transfer of canisters between HI-STORM100 concrete casks, and from transfer of casks to storage casks, must be carried out in a safe method. These stages are short-term events that occur no more than twice for each canister. The HI-TRAC shipping cask is the key component in the short-term operation process of the HI-STORM100 storage cask. The HI-TRAC shipping cask is crucial for the shipping of canisters. As such, it must be proven that the temperature will be kept within the acceptable range during the short-term operation process. The thermal integrity of spent nuclear fuel must be demonstrated for the scenarios (wet process, vacuum drying, inter-facility transportation, cool-down and re-flood for the unloading process). In the handling of spent fuel, some constraints may be applied to the removal of heat generated within canisters.

Additional cooling may be necessary if the temperature limit for cladding is exceeded in certain scenarios. This can be supplied by a Supplemental Cooling System (SCS).

As presented in NUREG-1536, water inside canisters must not be subject to boiling during the wet process. A rapid increase in pressure under two-phase conditions should be avoided. Such conditions are established before vacuum drying and after the spent fuel canister is transferred from spent fuel pool to the decontamination pit, with maximum working hours granted while requirements for the wet process are met inside canisters. Before this stage, the temperature of the fuel inside canisters forms equilibrium with the temperature of spent fuel pool water. When the water-filled canisters are transferred from the pool to the decontamination pit, decay heat generated from the spent fuel is absorbed by water and metallic structures inside the canisters. This leads to an increase in internal temperature, and the rate of temperature increase varies with the thermal inertia of HI-TRAC and canisters. Some conservative assumptions have been made to determine the rate of increase in temperature:

- Heat loss from natural convection and radiation occurring at the surface considered negligible;
- Maximum decay heat generated from the loaded fuel;
- Weight of water inside canisters assumed to be lighter.

To evaluate the rate of increase in temperatures, the inner weight and thermal inertia of the HI-TRAC canister were derived. The increase in temperature of the HI-TRAC shipping cask and components during the wet process can be expressed by the Equation (1). Where, Q is maximum decay heat (Btu/hr), C_h is thermal inertia of HI-TRAC (Btu/°F), T is temperature of HI-TRAC (°F), t is time after HI-TRAC is removed from the wet storage pool (hr).

$$\frac{dT}{dt} = \frac{Q}{C_h} \tag{1}$$

The maximum temperature increase of HI-TRAC is 4.99 °F/hr. From this, the maximum permitted time to prevent boiling during the wet process can be calculated as the Equation (2). Where, T_{boil} is boiling temperature of water (°F), $T_{initial}$ is intitial temperature when HI-TRAC is removed from the wet storage pool (°F), dT/dt is maximum increase in temperature (°F/hr), t_{max} is maximum permitted time (hr)

$$t_{max} = \frac{T_{boil} - T_{initial}}{(dT/dt)} \tag{2}$$

After the spent fuel is loaded within canisters, water is drained from canisters in the decontamination pit. Either Nitrogen or helium is used in this process. After draining, the canisters are filled with helium via the vacuum drying device or forced helium dehydration. The drying process for all canisters containing the spent fuel, except high burnup fuel, takes the form of conventional vacuum drying. The remaining moisture in canisters is removed in a short time by creating a vacuum. However, vacuum drying cannot be applied to canisters containing high burnup fuel or with heat leads exceeding the threshold. These canisters can be dried by the forced flow helium drying process. As vacuum drying occurs, gaseous compounds inside the canisters are removed, and heat transfer significantly decreases. The worst thermal conditions develop towards the end of the vacuum drying process, when internal pressure reaches a minimum. As the active fuel length is revealed, temperature is gradually increased from the initial condition (when fuel is completely submerged in water) of the fuel and baskets. Under vacuum conditions, the effective thermal conductivity inside the baskets is determined using the finite element method.

An axis-symmetric FLUENT heat analysis model was developed, and effective thermal conductivity (vacuum conditions) was applied as the thermal conductivity inside baskets. The thermal conductivity in the axial direction inside baskets was assumed to be the same as the effective thermal conductivity in the transverse direction. The boundary conditions applied to the vacuum drying heat analysis model are as follows.

- Heat analysis considered in the normal state with maximum decay heat;
- Low thermal conductivity within canisters;

— The temperature of the canister surface is assumed to be 232 °F(111°C) without annulus cooling, and 125°F (56°C) with annulus cooling;
  - Adiabatic conditions assumed for the upper and lower sides of canisters.

2.4.2. MAGNASTOR canister

For the MAGNASTOR canister [6], canisters loaded in shipping casks during the short-term operation process are subject to the following conditions.

— Wet conditions during sealing of canister lids;
— Vacuum drying conditions to remove moisture from canisters;
— Helium-filling conditions for complete closure of canisters and operation of cooling system in shipping casks;
— Draining of water in the shipping cask annulus, and shipping of canisters to concrete containers.

Thermal analysis was performed to assess the validity of 24-hour cooling after the drying stage and before canisters is loaded into concrete containers. Cooling for 24-hours maximized the time for drying and shipping to concrete containers. In other words, 24-hour cooling keeps the internal temperature to a minimum and maximizes the time for drying, during which heat transfer performance is the poorest. In the first stage, normal states are considered for all heat loads. For the vacuum drying process, there are no time constraints for PWR baskets with heat loads equal to or smaller than 25kW. However, time adjustments are needed for PWR baskets with heat loads greater than 25kW.

The heat analysis model, which accounts for water inside canisters, assumes that canisters are completely filled with water. Since a slight amount of water has to be removed during sealing, the level of water in canisters is lower than that of the upper section of baskets. Holes are installed in baskets to allow water to flow from the central part of canisters to downcomers. A two-dimensional axis-symmetric model was used to evaluate the shipping process. During the wet process, he heat analysis model applied to the insides of baskets involved effective thermal conductivity. Thermal conductivity was considered, but not radiation. Since the porous medium constant is determined by the spent nuclear fuel assembly and basket frame, it takes on the same value as that derived from heat analysis under normal conditions. Because the drop in pressure inside the baskets depends on the viscosity coefficient, input data for physical properties was utilized. The maximum temperature of water inside the canisters is below 212°F (100°C). This means that the physical properties for water as a liquid should be used. The water annulus existing in shipping casks, and between shipping casks and canisters, is included in the heat analysis model. Shipping casks are represented by their effective physical properties. Although the shipping casks consist of carbon steel inner shells, gamma shield, and neutron shield NS4FR and carbon, effective physical properties are calculated to apply them as a homogeneous model. The effective thermal conductivity of shipping casks in the radial direction was calculated after assessing the thermal resistance from circuits containing series connections of four different materials. Similar calculations were made in the axial direction based on thermal resistance from circuits containing parallel connections of four different materials. The following assumptions were made for heat analysis of the wet process, and normal state analysis was performed.

— Boundary conditions at the surface of shipping casks include adiabatic conditions, but do not account for insolation;
— Entrance temperature of 100°F(37.8°C) is assumed for the annulus;
— Natural convection is assumed for water in the annulus;
— Heat generated inside canisters is considered as 15, 20, 25, 30, and 35.5 kW;
— Laminar flow is assumed inside the canisters and annulus;
— Radiation is considered negligible.

The vacuum drying system is used to dry the insides of canisters, and remove moisture and gases through the vent and drain port. During the vacuum drying stage, any convection within canisters is considered negligible. Helium thermal conductivity is used during low-pressure vacuum drying. A three-dimensional

ANSYS model was used as the shipping cask model for transient heat analysis. During vacuum drying, the annulus cooling system operates normally and removes heat from the canisters. The operation of the cooling device is for convenience, and not related to safety. In other words, shipping casks can be transferred to the wet storage tank at any time without thermal shock. The exterior temperature distribution calculated during the wet process is applied to the surface of canisters.

3. ESTABLISHMENT OF THERMAL ANALYSIS SCENARIO

3.1. Thermal Analysis Scenario

Table 3 shows the thermal analysis scenario established on short-term operation process. For heat transfer analysis, the short-term operation process was classified into wet, vacuum drying, and dry process according to changes in the mode of heat transfer. the mode of heat transfer for each stage was shown in Table 1.

TABLE 3. THERMAL ANALYSIS SCENARIO ON SHORT-TERM OPERATION PROCESS

Classification	Short-term operation	Analysis	Input variables	
Wet process	Phase 1-2 - loading, lid welding	Steady state or Transient state	- Cooling water temperature - Heat load	Thermal equilibrium with cooling water
Vacuum drying process	Phase 3 - Drainage	Transient state	- Helium flow rate and inlet temperature - Environment temperature	- Result from stage 1 - Sensitivity analysis on ambient temperature
	Phase 4, 5, 6 - Vacuum dry/re-vacuum	Transient state	- Colling water temperature and flow rate - Drying time and inspection time - Environment temperature	Result from stage 2
Dry process	Phase 7 - Welding and inspection	Transient state or Steady state	- Helium pressure - Welding and inspection - Environment temperature	Result from stage 3
	Phase 8, 9 - lift, loading, storage	Steady state or Transient state	- Environment temperature	Result from stage 4

3.1.1. Wet Process

In this process, the canisters are filled with water. Heat transfer forms an equilibrium with the temperature of water in the wet storage pool while spent nuclear fuel is loaded into canisters, so heat transfer analysis is performed beginning at the decontamination pit. The key process in the decontamination pit is the sealing of canister lids. During this process, radiation and convection occur at the surface of metal canisters. Over time, temperature rises in the water and fuel stored inside canisters. Only conductivity is taken into account in assessing such heat transfer, and natural convection is considered negligible. A three-dimensional model is applied to the analysis model for heat transfer analysis in the wet process, and ANSYS CFX is used as the analysis code. The three-dimensional model must include each component of the metal canister and should be applied in the vertical state. Heat transfer analysis should be in the form of transient state analysis with consideration of working hours, and the initial condition is set as 46°C in thermal equilibrium according to NUREG-1536. The main component to be evaluated in the wet process is whether there is boiling of water inside the canisters. Similar to the methodology presented in the safety analysis report of HI-STORM100, thermal inertia of metal canisters is first evaluated, followed by calculations for the rate of increase in temperature. In addition, the maximum time without boiling should be determined, while accounting for the rate of temperature increase.

3.1.2. Vacuum Drying Process

The vacuum drying process creates a vacuum inside canisters to drain the remaining water and eliminate all moisture. As the vacuum state is maintained within canisters, internal heat transfer rapidly decreases. Since no inner medium exists inside the canisters, there is no conduction or convection. Due to the poor heat transfer performance, the internal temperature surges, and may even exceed the temperature limit for spent nuclear fuel cladding. If necessary, cooling should be attempted through the annulus, which exists between the surface and inner walls of canisters. The HI-STORM100 and MAGNASTOR canisters require cooling through the annulus. As shown in Table 4, the cooling method and time limit should differ according to the inner decay heat.

TABLE 4. COOLING METHOD BY DECAY HEAT

Canister	Decay	Cooling method
HI-STORM 100	< 20.88kW	Cooling performed with water filled in the annulus
	>20.88kW	Cooling performed with circulation of the water-filled annulus
MAGNASTOR	<25.0Kw	- Cooling performed with circulation of the water-filled annulus - No time limit for the vacuum drying process
	>25.0 kW	- Cooling performed with circulation of the water-filled annulus - 24-hour limit for the vacuum drying process

If metal canisters are the target of analysis, the decay heat of 16.8kW is lower that of HI-STORM 100 and MAGNASTOR canisters. Thus, cooling does not have to be performed through the annulus between the canister surface and inner walls. Since an increase is temperature is expected with the change in internal environment, the temperature of spent nuclear fuel cladding should be evaluated. The analysis model for heat transfer analysis in vacuum is the same as the wet process model. One difference is that only radiation occurs due to the lack of an inner medium when in the vacuum state.

3.1.3. Dry Process

The vacuum drying process is followed by the dry process, during which helium is filled and canisters are sealed with lids. At this time, the mode of heat transfer is convection driven by the inner medium of helium, as well as radiation and conduction inside the canisters. Looking at the integrity of spent nuclear fuel cladding, results of the dry process can be seen as being included in the results of analysis performed under normal operating conditions.

3.2. Thermal Analysis Model

Based on the methodology for heat transfer analysis of the short-term operation process, a three-dimensional finite volume model was used to perform heat transfer analysis. A 1/8 symmetric model was used for the analysis model with consideration of vertical installation. Reference model for thermal analysis is considered as Holtec inc. system. Heat analysis was carried out using ANSYS CFX. The model configuration includes components such as the spent fuel rods and metal structures, container body, and lid. Components such as the canister lid bolt and trunnion were substituted with a solid model or excluded altogether since they do not affect heat transfer and thermal flow. The annulus between the canister surface and inner walls was not considered in this work.

4. CONCLUSION

This study aims to establish the thermal analysis scenario of spent fuel dry cask on short-term operation for developing the independent verification model. The operating procedure, heat transfer characteristics and the working time, issues, thermal analysis methodology on each process of short-term operation were investigated through the literature survey. Based on the data, the thermal analysis scenario for thermal analysis as further

plan was established on short-term operation process which was classified into wet, vacuum drying, and dry process according to changes in the mode of heat transfer. Also, input variables and computational thermal analysis program and thermal analysis reference model were determined.

ACKNOWLEDGEMENTS

This work was supported by the Nuclear Safety Research Program through the Korea Foundation of Nuclear Safety (KOFONS), granted financial resource from the Nuclear Safety and Security Commission (NSSC), South Korea (No. 1803015)

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