Drying Model for Fukushima Fuel Debris - 17489

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ABSTRACT

The FATE™ code is a well-established software tool for simulation of processing, shipping, and interim storage of damaged spent nuclear fuel (SNF) that was used for process design and safety analysis for the Hanford Spent Nuclear Fuel Program (SNFP). This paper describes new model developments that allow FATE to be used for simulation of drying of damaged LWR fuel and, in particular, for simulation of processing, shipping, and interim storage of Fukushima fuel debris. The model is capable of quantifying important tradeoffs in the debris chunk size, process conditions such as temperature and pressure, container size, etc. to optimize process design. The model is also capable of demonstrating proof-of-dryness and to demonstrate the link between observed quantities such as pressure and the amount of residual water.

INTRODUCTION

Remediation of damaged fuel material at the Fukushima reactors will draw on previous experience in drying damaged fuel from commercial reactors as well as severely degraded legacy fuel stored at DOE facilities. This experience has involved the use of FATE [1] (the trademark symbol will be dropped hereafter), a commercially available tool originally created to quantify process safety and source terms for fuel cycle facilities including high level waste tanks, vitrification, and spent nuclear fuel. FATE's predecessor software was used for design and safety analysis of the original Hanford SNFP.

Technical benefits of applying the FATE models to Fukushima fuel remediation include consideration of both surface water and pore/crack water, flexibility for different physical forms such as fuel, particles, and sludge, and the integrated combination of thermal, fluid, and aerosol models. Of specific relevance for Fukushima fuel remediation are the ability to model proof-of-dryness by quantification of residual water and the ability to create specifications for proof-of-dryness testing. Practical benefits include justification of reduced drying temperatures (below 100 °C), the use of air as a process gas alternative to nitrogen or helium, and clear understanding of the tradeoffs between piece size and drying time so as to guide retrievals and size reduction requirements.

This paper provides an example application of FATE models to Fukushima fuel drying. The model was initially developed to simulate drying behavior and proof-of-dryness for damaged LWR fuel as part of the technical basis behind the Westinghouse Quiver product. Just as LWR fuel with failed cladding can contain water within fuel cracks, fuel debris pieces from Fukushima will contain water embedded in cracks.

A model allows process parameters such as temperature, vacuum pumping rate, and injection gas supply rate to be chosen for an efficient drying process. The example results demonstrate the basic features of vacuum drying operations including how decay power and stored energy play roles in water removal. Future work to apply FATE to Fukushima fuel will benefit from extending the model to multiple dimensions for flow and heat transfer, just as successfully done for the Hanford spent fuel and sludge, and also by incorporating models for variable crack and pore water parameters.

FATE OVERVIEW

FATE stands for Facility Flow, Aerosol, Thermal, and Explosion model. FATE is owned and licensed for use by Fauske & Associates, LLC (FAI), a wholly-owned subsidiary of the Westinghouse Electric Corporation. Development of the software and applications described here were conducted under the FAI Nuclear Quality Assurance program, in compliance with ASME NQA-1.

FATE is an integral plant thermal-hydraulic and aerosol analyzer with capabilities similar to that of the MAAP code for severe accident analysis, but with generalizations to consider chemical phenomena for applications to general fuel cycle and waste treatment facilities. FATE was originally developed under different names for analyses of several different types of non-reactor facility, and the key predecessors for damaged fuel and sludge analyses were HANSF and HANSF/SLUDGE.

HANSF [2], which stood for HANford Spent Fuel, was a predecessor code to FATE used for process design and safety analysis for shipping, vacuum drying [3], and interim storage of 2000 tons of metallic SNF. Key model features included reactions for uranium metal and uranium hydride in a variety of atmospheres, and multi-dimensional modeling of heat flows in fuel and scrap baskets within the fuel container, known as a Multi-Canister Overpack (MCO) container.

HANSF won a US DOE Silver Award for Technology Innovation presented to Dr. Phillip Loscoe, the DOE director of the Hanford SNFP [4]. Later, HANSF/SLUDGE and FATE were also used for process design, safety, and licensing of programs to remediate metal-bearing spent nuclear fuel sludge and highly reactive fine metallic fuel particulate [5].

WATER REMOVAL AND PROOF-OF-DRYNESS

A key issue for process design for drying of damaged nuclear fuel and debris is the quantification of residual water. The typical test for dryness requires that the container pressure should not increase beyond a criterion value over a specified dwell time. However, a measurement of pressure rise is only a measurement of the moles of gas released during the dwell time, and not a direct inference of the residual quantity of liquid water.

The link between measurement and quantification of the mass of residual water was made for the Hanford SNFP [6]. This link quantified the release rate of water from cracks in fuel, and it was confirmed by tests with fuel element specimens.

Our recent work [7] extended the SNFP model with a rigorous solution for the transport of water vapor through cracks in fuel debris, and it is applicable to damaged LWR fuel with failed cladding as well as to pieces of fuel debris such as would be retrieved from Fukushima Daichi Units 1, 2, and 3. The model considers simultaneous molecular diffusion and convection.

The physical mechanism for efficient removal of water from fuel debris is to establish a water vapor pressure gradient from the fuel debris interior to its exterior, which can be accomplished by a vacuum process. Note that for fuel debris with sufficient decay power, a temperature gradient develops between the interior and exterior. The temperature gradient therefore creates a saturation pressure gradient, and this by itself can provide the driving force for water removal without the need of a vacuum process. Therefore, a passive vented interim storage system could be sufficient to guarantee that fuel debris loses water naturally over a reasonable period of time, after which the containers could be sealed. Without a pressure gradient, drying relies upon molecular diffusion which is a relatively slow process.

The key parameters required by the model can be estimated and measured for fuel debris surrogates. Debris porosity quantifies the water volume that could be retained in a piece of debris. Debris permeability quantifies the resistance to flow. Good fuel debris simulants could be obtained from the remains of experiments to examine molten core debris interactions with concrete (MCCI), such as the MACE test series [8]. Alternately, simulants with more metal and control material content could be created from specially formulated thermite mixtures. Bench-scale experiments could be conducted to quantify the pertinent range of porosity and permeability.

FUKUSHIMA FUEL DRYING AND PROOF OF DRYNESS EXAMPLE

The FATE damaged fuel drying model is applied here in a simple example for Fukushima fuel, which requires that we specify an example container, example fuel pieces and properties, and example process conditions. This example is not intended to demonstrate optimize system behavior, or to prescribe a container or fuel chunk size. For simplicity, a piece of highly damaged and perhaps formerly molten fuel-containing debris will be called a “fuel chunk.”

The model uses a finite-difference formula for the temperature and water inventory distributions within a fuel chunk, which is crucial to correctly predicting the location of the evaporation front. These distributions are tracked separately for chunks of different size, properties, or decay power.

Fuel debris is assumed to be loaded into a canister as shown in Figure 1. The canister has a 0.5 m inner diameter, 2 m inner height, and 0.01 m wall thickness.

These dimensions were chosen based upon experience with drying of Hanford fuel, and the practical consideration that the container length need not accommodate an intact fuel assembly, and a shorter container is easier to handle.

Fig. 1. Canister with fuel Chunks for Vacuum Drying

The canister is assumed to be filled halfway with 0.1 m diameter Fukushima fuel chunks and an overall porosity of 50%, so that 25% of the total canister volume is occupied by fuel debris. The important inputs for the fuel chunks, described below, are the decay power and values that affect water inventory and its removal.

The container is heated while it still contains water because this was shown to be an efficient technique for Hanford fuel drying; this step in the process is not modeled. After the water is drained, the vacuum pump begins operation and also a purge gas is injected. A purge gas was shown to be effective for Hanford application, and this is a practical design feature because it prevents the vacuum pump from damage by dead-heading at a low pressure.

Drying phenomena within a fuel chunk are illustrated in Figure 2. All fuel chunk cracks are initially filled with water after residual water is drained from the container. As the vacuum pump draws down the pressure in the canister, the low pressure is propagated into the cracks in the fuel and the trapped water starts to boil and flow through the cracks to the container gas space. The latent heat of evaporation is supplied by the decay heat and heat conducted from the fuel surface. The narrow and tortuous paths in the crack make it hard for steam to flow out of the interior of fuel chunk.

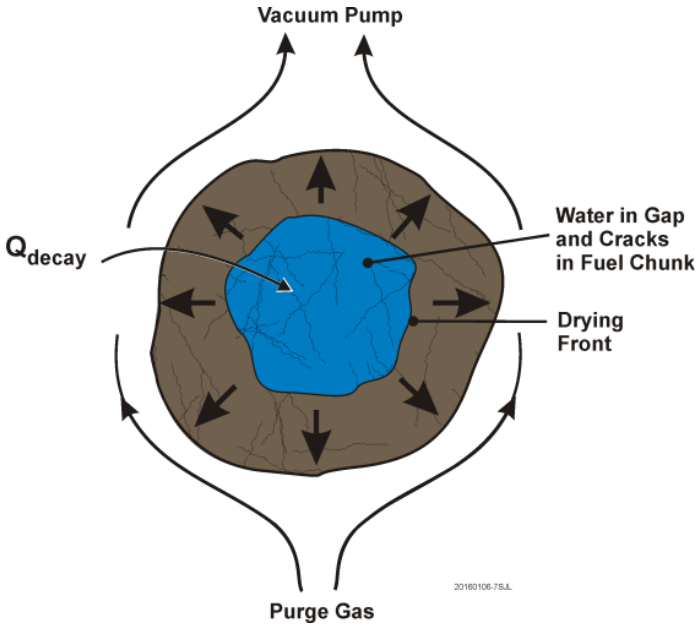

Fig. 2. Process during Fuel Chunk Drying

The important inputs for the fuel chunks are decay power and parameters that govern water inventory and resistance to water removal. For this example, decay power per unit volume of debris is estimated to be about 3200 W/m^3 given a 9 year cooling period and accounting for the presence of cladding and structural materials. In general, the decay power of a retrieved fuel chunk would be lower due to variation in burnup, presence of concrete slag, and non-uniform distribution of the materials. To demonstrate the practical impact, six groups of debris chunks are simulated whose decay power has varying fractions of the rounded figure as follows, from groups numbered 1 through 6: 80%, 60%, 40%, 20%, 10%, and 1%.

Fuel chunks were defined to have a uniform size of 100 mm diameter and a porosity of 5%. In the current model for failed LWR fuel, one average crack width and one average crack length are used because these are appropriate for a fuel pin. A crack width of 0.1 mm is used, and the chunk size of 100 mm determines the maximum crack length of 50 mm. A tortuosity (factor for increase of crack length) of 10 was used to be conservative for water removal. Given that chunks occupy 50% volume fraction of the bottom half of the container, the rounded number of chunks is 190, and the total water inventory is about 4.8 kg.

The initial temperature of the container and contents is 50 °C because this operating temperature was successfully used for the Hanford process. The saturation pressure at this temperature is 12 kPa. The vacuum pumping rate is chosen as 0.01 m^3/s in order to remove this water in about one shift. A small nitrogen purge is introduced to prevent the vacuum pump from dead-heading.

The example demonstrates three phases of operation: (1) Initial vacuum drying for water removal, (2) “Thermal reset”, which is the first step of a proof-of-dryness test, and (3) A “Pressure rebound” test which is the final step for proof-of-dryness. During vacuum drying, the vacuum pump and gas supply are set as described

above. After 5 hours (18,000 seconds) the gas supply rate is increased by a factor of 100 while keeping the vacuum pump on. This restores the pressure in the container and allows the fuel to warm up. After 10 hours (36,000 seconds), the gas supply rate is reduced to 1/10 of the flow rate during the vacuum cycle. Finally, when the pressure falls below 1000 Pa, the vacuum pump and gas supply are turned off, sealing the container. Subsequently, the pressure response is observed and is related to fuel dryness.

During the vacuum drying phase, pressure is quickly reduced to the saturation value, and then gradually declines as fuel cools as shown in Figure 3. During the thermal reset gas flow period, pressure increases to atmospheric again, but when the gas supply is reduced to 1/10 of the flow rate during the vacuum cycle, the pressure decreases quickly to the saturation pressure of water at fuel temperature. Pressure then decreases more gradually as the residual water on the fuel boils. After the fuel becomes completely dry the pressure reaches a plateau where the constant volumetric pump flow rate matches the gas supply rate.

Figure 4 shows the dryout front temperature history. This is the temperature within the fuel chunk at the location of the dryout front, so its position is moving with time. The temperature decreases during vacuum drying as energy is expended in evaporation. Then, the fuel warms up following the thermal reset. When the gas supply rate is reduced, the pressure drops and boiling resumes, cooling the fuel. The fuel heats up again after the fuel becomes completely dry.

Figure 5 shows the amount of residual water in the fuel. Water is lost during vacuum drying, and water loss stops when the container pressure is restored at the start of the thermal reset. The fuel heats up during this period (see Figure 4), and because of the stored heat in the fuel, boiling is effective when the pressure is reduced. By the time the pressure drops below 1000 Pa, the fuel becomes completely dry. Hence, there is no pressure rebound in this scenario, and the fuel is therefore determined to be dry.

This example demonstrates how the model can be used to establish criteria for a proof-of-dryness test.

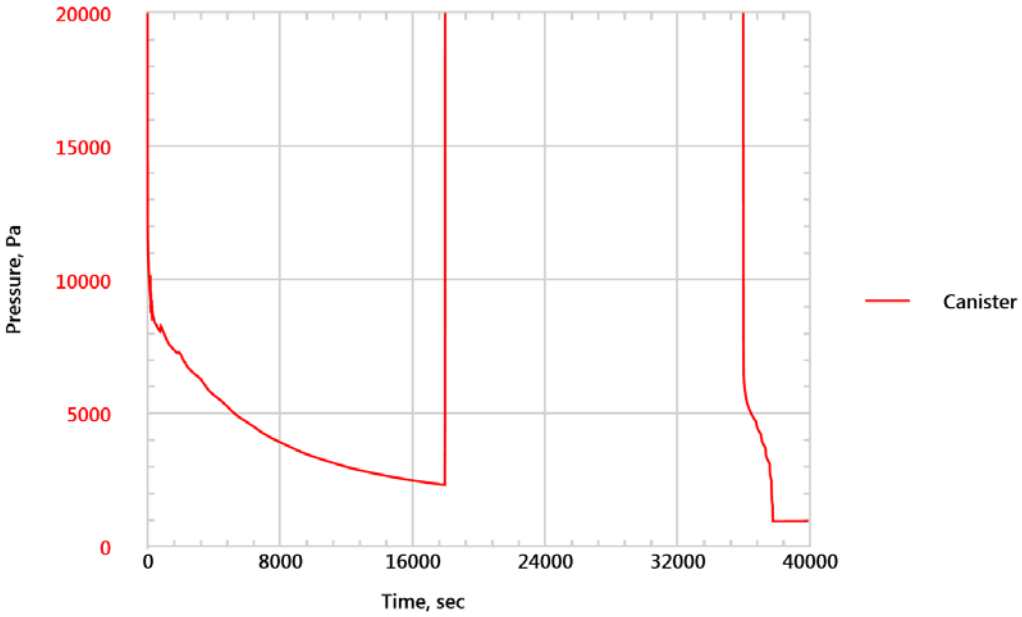

Fig. 3. Pressure History

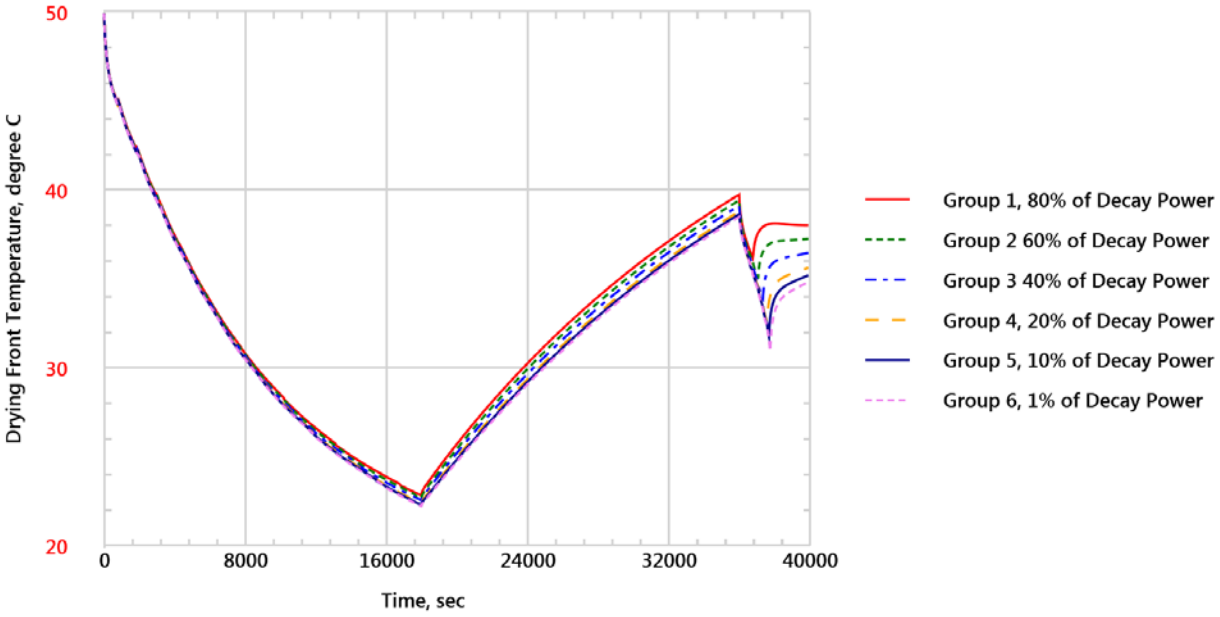

Fig. 4. Dryout Front Temperature History

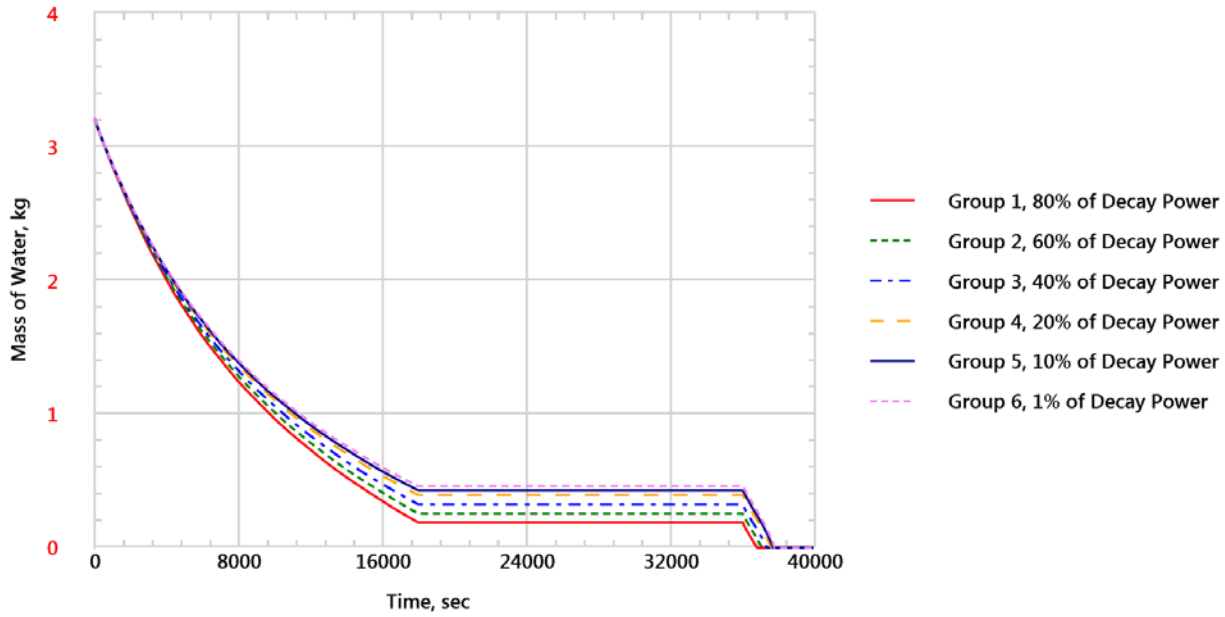

Fig. 5. Mass of Residual Water History

SUMMARY

FATE software developed for US DOE facility applications was successfully used for process design and safety analysis for remediation of 2000 tons of damaged Hanford SNF. With its improvements for residual water modeling, this software is perfectly suited to the same process design and safety applications for Fukushima fuel. Key lessons learned from US experience and discussed here are: (1) It is feasible to vacuum dry fuel debris at temperatures below 100 °C which is beneficial for cost, safety, and prevention of fission product release; (2) A proof-of-dryness test protocol can be developed and substantiated using the model, and (3) Material properties can be estimated in advance using simulant materials available from reactor safety experiments.

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