Design of a Borated Aluminum Cask for Onsite Used Fuel Storage

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INTRODUCTION AND MOTIVATION

Used fuel cooling is needed for either a once-through nuclear fuel cycle or one that employs reprocessing. A cooling period of up to several years allows for radioactive decay to lessen the heat load on the fuel prior to recycling or direct disposal. Currently, used fuel is stored in pools. Monitoring water levels and ensuring a readily available water supply in the pool is extremely critical. Indeed, during the tsunami and earthquake leading to the accidents at the Fukushima nuclear power plants, loss of water in the pool resulted in damage to the fuel.

The University of Idaho has entered into a collaboration beginning in January 2018 with Boise State University, Idaho National Laboratory, and Sakae Casting, Co., LTD (Sakae) from Tokyo, Japan to model and design a used fuel cooling cask as an intermediate back end management strategy for onsite used fuel storage, in order to alleviate used fuel accumulation in the pools. Casks will be constructed of borated aluminum with internal piping in order to provide subcriticality and occupational safety. The cask is intended to be a dry design and backfilled with air, or another gas, which will be considered in this modeling effort. The material was selected due to Sakae's unique aluminum casting capabilities. Based on the modeling results, prototype designs will be selected for manufacture and performance testing. Based on the performance testing, the casks commercialization plan will be formulated. Research consists of several directions: (1) neutronics modeling and cask design, (2) materials science and engineering, (3) heat transfer modeling and experimentation, and (4) regulatory analysis [1]. Here, we discuss (1) and (2).

BACKGROUND

Used Fuel Storage

In a nuclear reactor, the fuel is replaced about every 18 months because the fissionable material becomes depleted. Additionally, the formation of fission products strongly absorb neutrons and therefore greatly inhibit fission. The used fuel that is removed from the reactor is highly radioactive and emitting significant quantities of heat. It is stored in large pools of water inside the nuclear power plant site that are about 40 feet deep for up to 20 years in order for radioactive decay to occur and the heat load to lessen, where the industry mean is about 10 years [2]. The water provides both cooling for the used fuel as well as radioactive shielding for occupational safety. Pumps circulate the water to provide consistent heat removal. The fuel must be precisely placed in the pools to maintain subcriticality. However, space is limited onsite, and the pools are becoming filled. Saturation of the available volume in the pools is a growing concern.

Currently, after the cooling period in the pools, the used fuel is transferred to large, dry cask storage, outside, also onsite. Used fuel pools can lose water in a severe accident, and the fuel can melt and possibly release radioactive materials. This occurred at the Fukushima Daiichi nuclear power plant in Japan in 2011. The tsunami and earthquake caused a loss of water in the used fuel pools and the partial reactor meltdown. While this type of accident has not occured in the United States and is unlikely, our proposed storage cask is intended for widespread use in the United States to alleviate the burden of pool overcrowded, but it also is intended for use in countries like Japan and Korea, where curren dry cask storage is not as widespread and storage space itself is limited. Therefore, this storage cask is envisioned as as an intermediate management option prior to current dry cask storage.

Prior to the March 2011 Fukushima accident, Japan generated 30% of its electrical power from nuclear reactors [3]. Nuclear energy was a national strategic priority. The combination of the earthquake and tsunami resulted in the evacuation of more than 140,000 residents within 12 miles of the plant. The natural disaster caused loss of onsite power at the nuclear plant, and, with the backup diesel generators flooded, there was no power source to remove heat from the reactor or circulate water in the used fuel pools. This caused a partial meltdown of the reactor core, which was contained by the existing containment structure. However, in the pools, the water evaporated, leaving some of the used fuel exposed to the atmosphere. The resulting partial melting of the fuel caused some fission product gases to be released to the atmosphere.

The best estimates for quantities of metric tons of heavy metal of used fuel are 13,500 in France, 19,000 in Japan, 10,900 in the Republic of Korea, and 69,000 in the USA [4]. These quantities have continued to increase due to yearly accumulation of used fuel. The Republic of Korea has the least physical space to store used fuel with a quickly diminishing capacity [5]. While France and Japan reprocess used fuel, the Republic of Korea and the United States currently employ a once-through fuel cycle with direct disposal. Regardless of the fuel cycle, however, used fuel still requires a cooling period prior to either reprocessing or permanent storage.

The United States is the world’s largest producer of nuclear power with about 805 TWh of electricity generation per year [6]. The national share of electricity generation due to nuclear is about 20%. Nuclear power plays a major role in generating electricity in the USA. With just under 100 commercial nuclear power plants located in 30 states, and no long-term disposal policy in place, storage space is a growing problem. Building more pools can be politically sensitive issue and induce regulatory burden. Additional pool construction requires both a substantial amount of space and of water. For safety and security, the pools must be located indoors. Monitoring water levels in the pools and ensuring a readily available water supply for a possible emergency is extremely critical. The used fuel storage cask therefore offers an intermediate back-end management option to the nuclear power industry. Use of the cask can optimize onsite, existing storage space. An intermediate storage option for used fuel offers potential risk reduction from potential accidents and can enhance criticality safety in the pools.

Casting Technology

Sakae Casting manufactures ‘Cold Plates,’ which are water-cooled, thin cooling plates that enables efficient temperature control of both the plate itself, and points and spaces in contact with the plate, by pumping coolant through pipes embedded in the aluminum casting. This system removes heat from heating elements, such as substrates, and makes use of aluminum’s high thermal conductivity. The Cold Plate design achieves a high cooling efficiency and space reduction. The Cold Plate is largely adopted for optimal performance of semiconductor equipment through direct interaction with the coolant. The design allows for a rapid decrease in temperature of integrated circuit chips and diodes while also exhibiting the ability to maintain a low temperature. Thus, energy consumption and footprint requirements are significantly reduced compared to an air-cooled system. The Cold Plate is used in various fields, including battery trays for electric vehicles, wafer production line equipment, and photolithography manufacturing companies. A notional diagram of the Cold Plate is shown in Fig. 1. The plate itself will consist of borated aluminum, and the piping material is stainless steel.

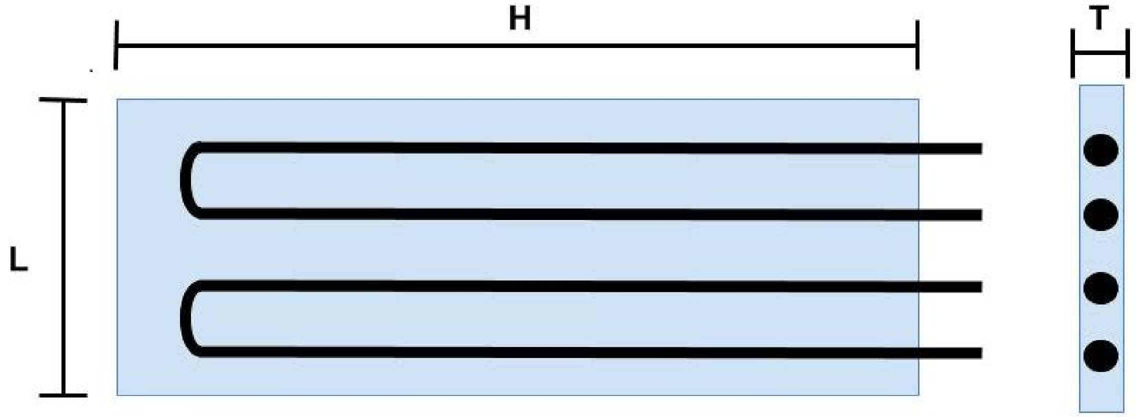

Fig 1. Notional Cold Plate for cask design. H = height; L = length; T = thickness

The height is determined based on the fuel assembly. The length varies based on the number of assemblies the cask could contain. The thickness is based on the shielding requirements. However, design constraints are largely based on Sakae's casting capabilities, including the number of cooling loops per length, and the boron-aluminum composition determined by the materials science and engineering research.

DESCRIPTION OF THE ACTUAL WORK

Used Fuel Composition

SCALE is used to simulate the used fuel composition for a typical, 17x17 pressurized water reactor assembly at enrichments from 4.0%, 4.25%, and 4.5% with burnup ranging from 40 GWD/MTU - 60 GWD/MTU. Cooling periods in the pool are assumed to be 5 - 20 years prior to emplacement in the used fuel cask. An important part of the cask design will be to determine when the fuel can be removed from the pool.

Neutronics and Design

MCNP is used to design the used fuel cask. The geometry of the cask is fairly straightforward since it is a box with embedded piping. Results from SCALE are used as the material source card. Curium is considered for the neutron source because it is the dominant source of neutrons in the used fuel with a 98% contribution after 10 years of cooling [7]. However, because the cask material is comprised of aluminum, ^{28}Al is generated due to activation by neutron emission. Therefore, the capture cross section for aluminum should be modified to include the gamma ray emission due to beta particle decay of the ^{28}Al [8]. Cask design is considered for 1, 2, 4, and 8 assemblies. This is due to limitations on the casting equipment. Cooling loops are limited to 1 loop per 80 mm of length. There is a temperature constraint of 350ºC. At this temperature, Al undergoes a phase change, and therefore, performance of the cask is affected.

Cask Materials

At the outset, the MCNP material card is run for arbitrary compositions of boron and aluminum to determine potential performance of the cask. Concurrently, experiments are being developed in order to fabricate a homogeneous solid solution of boron and aluminum.

EXPECTED RESULTS AND IMPLICATIONS

Traditional processing on borated aluminum materials for the nuclear industry includes hot pressing to form an aluminum clad cermet of aluminum and boron carbide, traditional powder processing (CIP and HIP techniques), and traditional metalworking technologies (drawing and forming). However, none of the traditional technologies allow for the integration of complex cooling channels for heat removal. Therefore, the materials development team will work closely with the MCNP team in an iterative manner to optimize the borated aluminum for casting operations, including optimum neutron adsorption and thermal dissipation capabilities in order to maintain a stable storage container. The resultant materials will be characterized for the effects of boron loading on phase and microstructure stability, thermophysical properties, and castability. MCNP results will yield a dose rate normal to the cask. The occupational dose limit of 20 mSv per year is used to determine an acceptable level to address occupational safety [9]. This corresponds approximately to 10 μSv/h for a standard year of 2000 working hours. Finally, an array of casks will be developed in order to demonstrate the maximum number that can be stored to maintain criticality safety.

UPCOMING WORK

Based on the modeling, design, and materials experimental results, Sakae will determine if a full size prototype can be manufactured. Once this is achieved, the prototype cask will undergo full scale performance testing in accordance with the regulatory analysis based on 10CFR72.

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