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Experimental studies on eutectic formation between metallic fuel and HT-9M cladding in a single-pin core structure of a sodium-cooled fast reactor

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A B S T R A C T

Metallic fuel relocation experiments were conducted in which molten uranium was dropped into the cladding of a single fuel pin where eutectic interaction between fuel and cladding led to the release of eutectic fuel mixture into a narrow sodium channel. The thermal hydraulic relocation behavior of the molten uranium was analyzed in a previous study. Here, the extent of the eutectic formation was evaluated by scanning electron microscopy and energy-dispersive spectroscopy (SEM/EDS). The SEM/EDS analysis confirmed that cladding failure was caused by eutectic penetration. The eutectic penetration initiated around the boundary between cladding and uranium fuel, progressed into the cladding, and caused the cladding failure. Near the cladding failure region, the original cladding shape was unrecognizable, and many cracks, breakthroughs, and partial losses of the cladding were observed. The main components of the cladding failure region were UFe_2 and U_6Fe, which are the key components in the eutectic penetration.

1. Introduction

A sodium-cooled fast reactor (SFR) was the first nuclear fission reactor in the world to produce electricity, and the reactor type used in the first commercial nuclear power plant. Although it has not been widely commercialized, SFR technology is appealing because of its improved safety, spent fuel disposal, and utilization of uranium resources. Active research and development of SFR technology continues in several countries, including the United States, Korea, Japan, China, India, and Russia. The Korea Atomic Energy Research Institute (KAERI) is developing the Prototype Gen-IV Sodium Cooled Fast Reactor (PGSFR), which is a metal-fueled pool type SFR, with support from Argonne National Laboratory (Argonne). The PGSFR construction target date is 2028. Passive shutdown and heat removal experiments conducted in the Experimental Breeder Reactor-II (EBR-II) demonstrated the inherent safety of metal-fueled pool-type SFRs [1,2]. The evaluation and understanding of hypothetical core disruptive accidents (HCDAs) that could occur under very conservative assumptions will be required in the licensing process of the PGSFR and other SFRs.

Research on the relocation behavior of metallic fuels under HCDAs has been continuous [3–13]. Many researchers have studied the fragmentation behavior of molten metallic fuels in open sodium pools [3–9]. Recently, studies have been conducted on the discharge behavior of metallic fuels in sodium coolant channels [10–12]. Kim et al. studied the relocation behavior of molten uranium in a single-pin core structure using Argonne's Metallic Uranium Safety Experiment (MUSE) facility [12]. In their experiments, metallic depleted uranium was used to simulate fuel material and HT-9M was used as a cladding material to evaluate the extent of eutectic formation between the fuel and the cladding. These experiments confirmed that there was significant cladding disruption, and some of the uranium injected into the narrow sodium channel after the cladding rupture was found to be fragments due to the sodium boiling. The cladding disruption identified in the experiment was assumed to be due to the eutectic formation between the fuel and the cladding.

The eutectic penetration and pin plenum overpressure have been suggested as two major causes of cladding failures in metal-fueled SFRs [13–15]. Bauer et al. conducted M-series tests to

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study the behavior of metallic fuels in transient overpower (TOP) accidents at the Transient Reactor Test Facility (TREAT) [13]. Their experiments showed that cladding failure is caused by total eutectic penetration in the low-burnup range (less than 2 at%), by the combination of partial eutectic formation and pin plenum overpressure in midrange burnup (more than 2 at% and less than 7 at%). They also discovered that pin plenum overpressure was the main cause of the failure in the high-burnup range (more than 7 at %). In particular, for cladding failure to occur, the cladding temperature should be at or near the threshold temperature at which eutectic formation begins to accelerate. Walter and Kelman quantitatively evaluated the penetration rate of molten uranium and iron [16,17]. Their experimental results showed that the threshold value where the penetration rate became rapid was about 1080 °C. They concluded that UFe_2 formation was intimately associated with the eutectic penetration rate. They also concluded that the reason for the accelerated penetration rates above 1080 °C was that the UFe_2 formed from two liquids.

In the present study, metallic fuel relocation experiments were conducted in the MUSE facility. Molten uranium was dropped into the clad of a single fuel pin, where eutectic interaction between fuel and cladding led to the release of a eutectic fuel mixture into a narrow sodium channel. The thermal hydraulic relocation behavior of the molten uranium was analyzed in a previous study [12]. Here, the extent of the eutectic formation between the fuel and the cladding was evaluated using scanning electron microscopy with energy-dispersive x-ray spectroscopy (SEM/EDS) analysis of the test sections of the single pin core structure used in the metallic fuel relocation experiments.

2. Experiments

2.1. Metallic Uranium Safety Experiment (MUSE) facility

Fig. 1 is a schematic diagram of MUSE facility at Argonne for the metallic fuel relocation experiments. The MUSE facility consists of a melt assembly for melting uranium to a desired temperature, a single fuel pin test section with a vertical split tube furnace, a sodium transfer system for filling sodium in the test section, instrumentation and control, and a containment box. The melt assembly consists of a graphite crucible, a plug, a rod, a pneumatic cylinder, an induction heater with a motor generator, an injection line, a diaphragm, and a melt vessel (Fig. 2). The plug at the bottom of the crucible can be pneumatically removed with a tantalum rod to allow downward injection of the fuel melt. In the experiments described here, the single pin test section represented a single flow sub-channel of the core structure of the PGSFR. The test section was installed at the injection line of the melt assembly so that molten fuel could be directed into the cladding. The vertical split tube furnace heated the single pin test section to the desired temperature. The sodium transfer system consists of a sodium supply tank, tank heaters and insulation, sodium line tubes, pneumatic valves, sodium line heaters, a sodium dump tank, and a vapor trap.

2.2. Single fuel pin test section

The single fuel pin test section consists of a containment tube, a zirconia tube, and a HT-9M cladding filled with alumina, an alumina silicate (Grade A Lava) funnel, thermocouples, and sodium level meters, as shown in Fig. 3. The containment tube was fabricated from a 316 stainless steel (SS) tube. The zirconia tube was used as the outer wall of the narrow coolant channel because zirconia is compatible with molten uranium. The fuel cladding was fabricated from a HT-9M tube with a 7.4-mm outside diameter and 0.5-mm thickness, and alumina was used to fill it to prevent sodium from flowing inside the cladding. The HT-9M, which is selected as the core structure material of the PGSFR, has more hardness than the HT-9 which is a chromium ferritic/martensitic steel being considered as FR core structure materials in Generation IV fission reactors due to their excellent void swelling resistance. A weak spot with a 3.175-mm diameter was fabricated on the fuel cladding to allow the fuel to be injected in to the coolant channel. The gap between the fuel cladding and the zirconia tube was 1.865 mm. Its hydraulic area was three times larger than that of the sub-channel of the PGSFR's core. We chose to make the gap in this experiment with a larger hydraulic area because the actual coolant channel in the PGSFR is not an annulus; it is interconnected so the molten fuel would be able to flow beyond the hydraulic area of the sub-channel. The sodium level between the container tube and the zirconia tube was equal to the height of the weak spot. The sodium level between the zirconia tube and the fuel cladding was higher than that between the container tube and the zirconia tube due to capillary action.

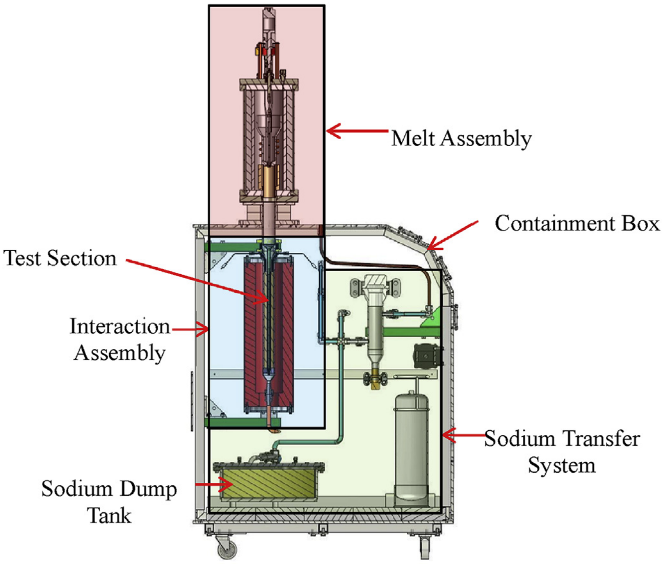

Fig. 1. Schematic of metallic uranium safety experiment (MUSE) facility.

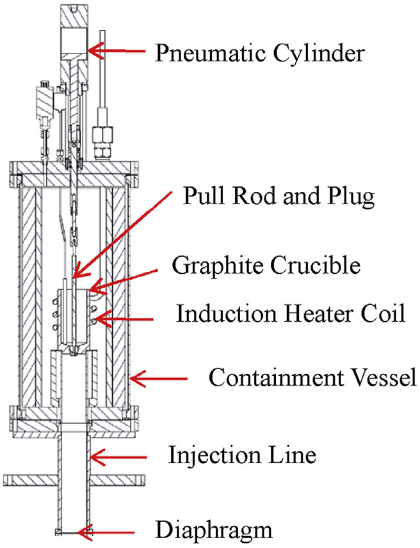

Fig. 2. Schematic diagram of melt assembly.