

## Development of Plasma-based Simulator for Reactivity-initiated Accident (RIA) Research

Yu Yeon Kim, Sang Uk Lee, Ja Hyun Ku, and Kyoung-Jae Chung\*

Dept. of Nuclear Engineering, The Seoul National Univ., 1, Gwanak-ro, Gwanak-gu, Seoul 08826, Republic of Korea

\*Corresponding author: jkjlsh1@snu.ac.kr

### 1. Introduction

Reactivity-initiated accidents (RIAs) are design-based accidents that have a significant impact on the safe operation of nuclear power plants [1]. In the event of an RIA, the major causes of damage to the nuclear fuel cladding are the pellet cladding mechanical interaction (PCMI) and high temperatures due to deterioration of the nuclear fuel [2]. The damage caused by PCMI early in the accident results from the physical contact between the pellet and cladding due to thermal expansion that occurs owing to the rapid temperature increment of the pellets [3].

It is difficult to construct an experimental reactor for RIA research within a short period because of the economic and temporal costs required for social consensus and construction. Eventually, an experimental simulation should be performed to imitate the behavior of nuclear fuel during an RIA. The experimental results of the Nuclear Safety Research Reactor in Japan indicated that, in the case of specimens with a hydrogenated layer, damage to the cladding occurred approximately 25 ms after the pressurization started, and the pressure was less than 100 MPa [4]. Thus, it is essential to generate a transient high pressure considering the hydrogen embrittlement of the cladding for simulating PCMI in an RIA.

We constructed an equipment that can simulate the physical contact between the cladding due to PCMI and the transient high pressure generated by pulsed plasma. This paper describes the design and initial experimental results of the device for simulating an RIA event.

### 2. Plasma-based RIA simulator

The proposed plasma-based RIA simulator uses the instantaneous phase change and heating of a thin metal wire by fast high-energy transfer. To heat the metal wire up to tens of thousands Kelvin, high energy must be applied to the metal wire within a relatively short duration [5]. In this study, we utilize a capacitive discharge circuit, where the capacitor charges the electrical energy supplied by the DC power supply for a long duration and thereafter discharges to the metal wire within a millisecond. By controlling the width and amplitude of the pressure pulse through the adjustment of electrical parameters, short and strong pulse pressures of hundreds of microseconds can be simulated during an RIA.

The plasma-based RIA simulator consists of two parts: a pulse power system and a pressure generating system (high-pressure load), as shown in Fig. 1.

The main capacitive discharge system consists of a capacitor bank, mechanical switch, and switch with a silicon-controlled rectifier (SCR). The capacitor bank can connect up to eight capacitors with a capacitance of approximately 850  $\mu\text{F}$  in parallel, with a charging voltage of up to 3 kV. The SCR switch can block the inverse current that may impair the integrity of the equipment.

In the pressure generating system, the long anode sealed in the insulator was connected to the cathode by a metal wire. The lower part of the system was designed to have a cathode and anode. In addition, the upper part was made with a pressure probe to measure the pressure and its holder. The experiment was conducted using a copper wire with a diameter and length of 125  $\mu\text{m}$  and 45 mm, respectively. To simulate the cladding, a sealed container was made by welding stainless steel tubes with length, inner diameter, and thickness of 40 mm, 8.4 mm, and 1 mm, respectively. These tubes could be replaced by hydrogen embrittlement zircaloy-4 to simulate PCMI.

The current and voltage waveforms were measured using a current monitor (3025, Pearson Electronics Inc.) and a high-voltage probe (P6015A, Tektronix), respectively, at the coaxial cable output. A pressure sensor (109C12, PCB Piezotronics) was installed 25 mm from the top of the anode.

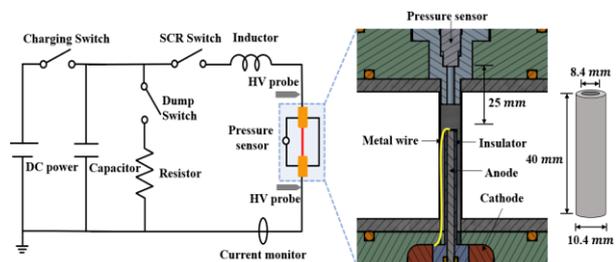


Fig. 1. Schematic of plasma-based RIA simulator

### 3. Experimental results and discussion

A series of experiments with the plasma-based RIA simulator were conducted at a charging voltage of 2 kV using a copper wire with a diameter of 125  $\mu\text{m}$ . Fig. 2 shows the current and voltage waveforms for the pulsed discharge with a capacitance of 2.62 mF. In the initial stage of discharge, 1 kV is applied to the electrode, and after the discharge, a voltage drop of approximately 0.3 kV can be observed, as the metal wire changes to the plasma state. As the voltage is applied to the metal wire and current flows, the solid metal wire instantly transforms into metal vapor. At approximately 10  $\mu\text{s}$ , a current restrike was observed. This indicates a change in the phase from gaseous to plasma [6]. The electrical

input energy applied to the metal wire was calculated to be approximately 2 kJ.

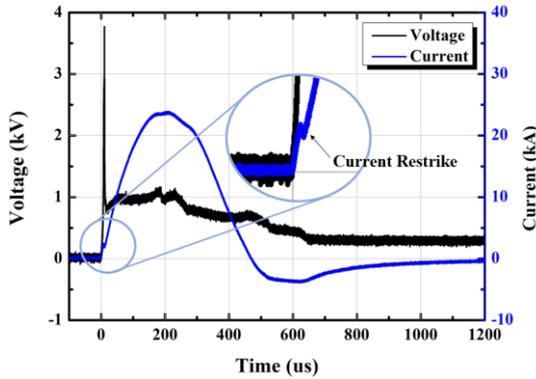


Fig. 2. Voltage and current waveforms measured at the load.

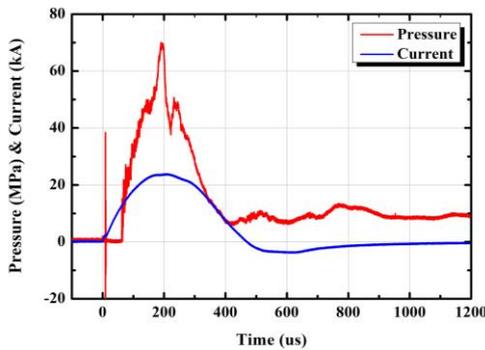


Fig. 3. Pressure waveform inside the metal tube.

Fig. 3 illustrates the transient changes in the pressure and current. As the current flows, it can be observed that the metal wire is heated, increasing the inner pressure. The peak pressure was measured to be approximately 70 MPa.

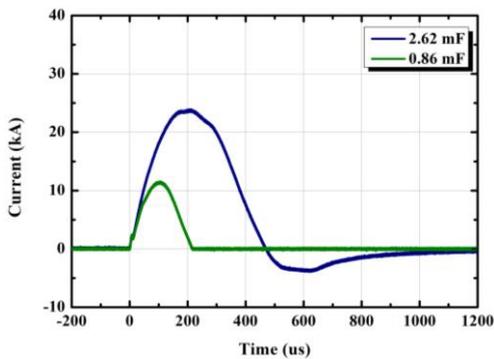


Fig. 4. Current waveforms for different capacitance values.

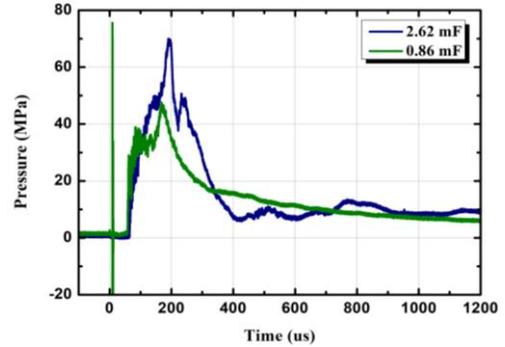


Fig. 5. Comparison of pressure at different capacitances

The changes in the current and pressure waveforms depending on the capacitance value of the pulsed power system are demonstrated in Figs. 4 and 5, respectively. The capacitance is increased from 0.86 to 2.62 mF, whereas the pulse width of the current increases as shown in Fig. 4. Accordingly, the pressure width and peak pressure increased, as depicted in Fig. 5.

#### 4. Summary

We constructed a lab-scale device to simulate PCMI in an RIA. Initial experiments yielded a peak pressure of 70 MPa, which is slightly lower than those of typical RIA events. The peak pressure and pulse width can be increased by increasing the capacitance and charging voltage of the pulsed power system.

#### ACKNOWLEDGMENTS

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