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

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Ⅰ. Introduction

- Reactivity-initiated accidents (RIAs) are design-based accidents that have a significant impact on the safe operation of nuclear power plants.
- 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.

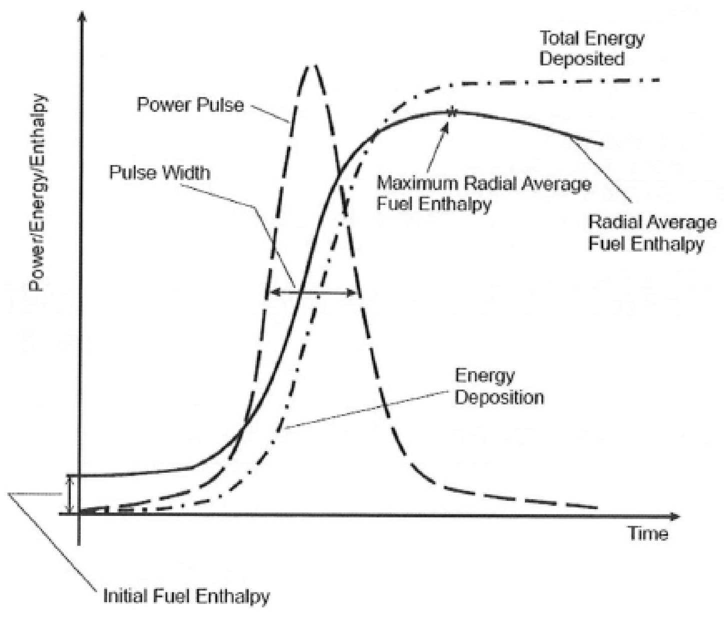

Fig. 1. Time dependent characteristics of energy change at RIA

- 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.
- 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.

➢ Example of simulation configuration

- 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
  - Time: approximately 25 ms
  - Pressure: less than 100 MPa
- 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 poster describes the design and initial experimental results of the device for simulating an RIA event.

Ⅱ. Plasma-based RIA simulator

➢ 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.
- 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 can be simulated during an RIA.

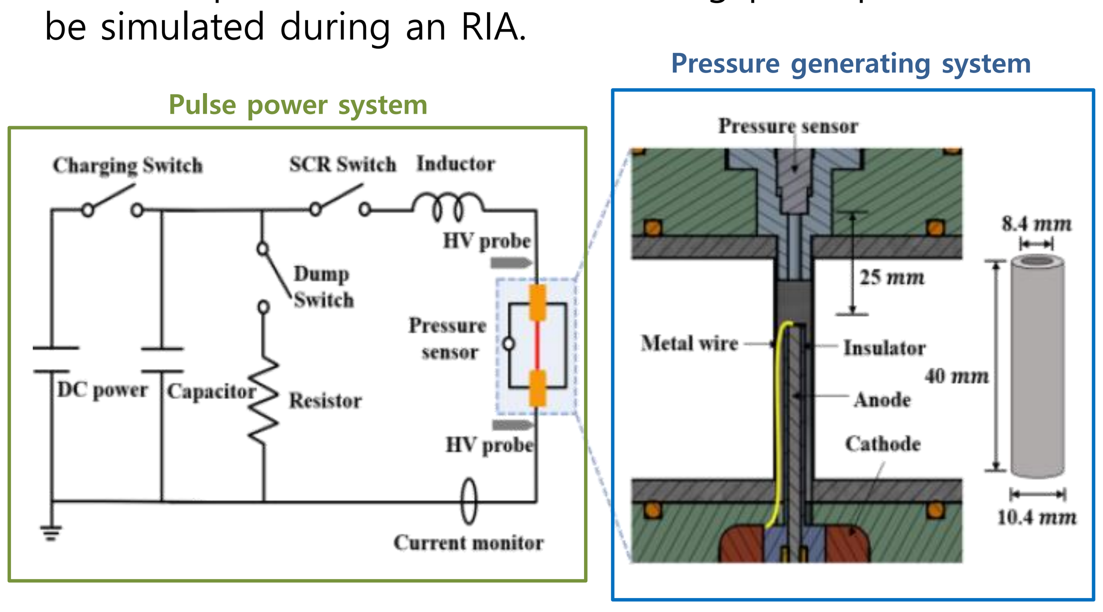

Fig. 2. Schematic of plasma-based RIA simulator

- The plasma-based RIA simulator consists of two parts as shown in Fig. 2.

➢ Pulse power system

- The main capacitive discharge system consists of a capacitor bank, mechanical switch, and switch with a silicon-controlled rectifier (SCR).
  - Capacitance: 850 $\mu F \times 8$ ea in parallel
  - Charging voltage: 3 kV

➢ Pressure generating system

- In the pressure generating system, the long anode sealed in the insulator was connected to the cathode by a metal wire.
  - The lower part: cathode and anode
  - The upper part: pressure probe and its holder.
  - Wire material: copper
  - Wire diameter and length: 125 μm and 45 mm
- To simulate the cladding, a sealed container was made by welding stainless steel tubes. These tubes could be replaced by hydrogen embrittlement zircaloy-4 to simulate PCMI.
  - Tube length: 40 mm
  - Tube inner diameter: 8.4 mm
  - Tube thickness: 1 mm

➢ Measurement equipment

- 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.

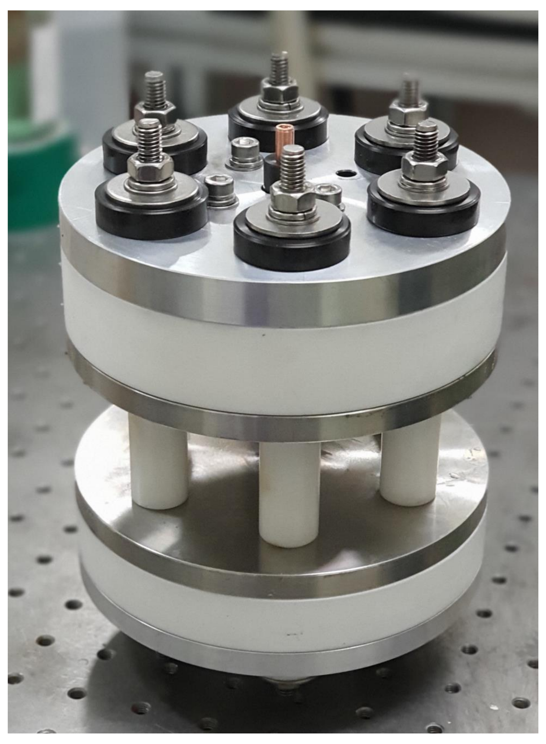

Fig. 3. Pressure generating system

Ⅲ. Experimental results and discussion

➢ Voltage and current measured at the load

- 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 μm.

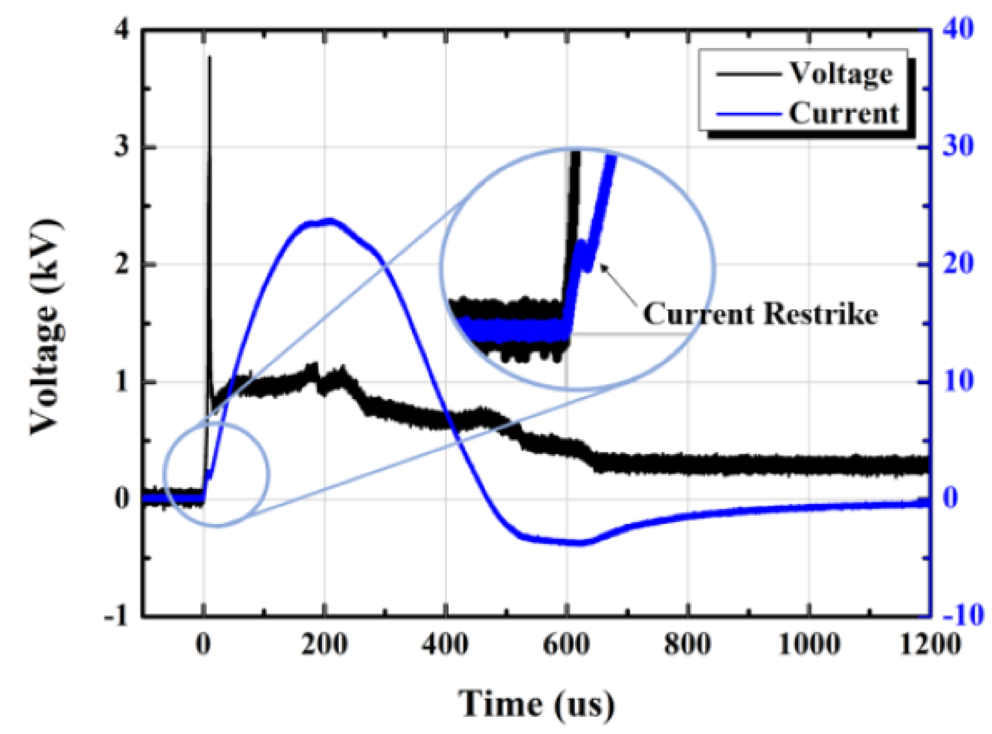

Fig. 4. Voltage and current waveforms measured at the load

- Fig. 4 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 μs, a current restrike was observed. This indicates a change in the phase from gaseous to plasma. The electrical input energy applied to the metal wire was calculated to be approximately 2 kJ.

➢ Pressure inside the metal tube

- Fig. 5 illustrates the transient changes in the pressure and current.

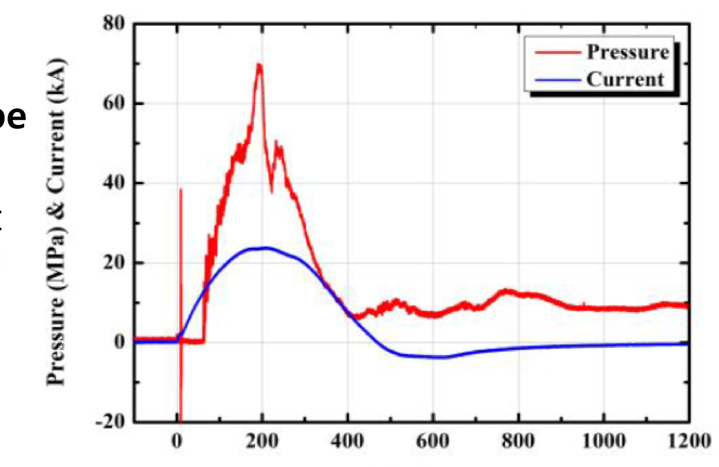

Fig. 5. Pressure and current waveform

- 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.

➢ 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. 6 and 7, respectively.
- The capacitance is increased from 0.86 to 2.62 mF, whereas the pulse width of the current increases as shown in Fig. 6.

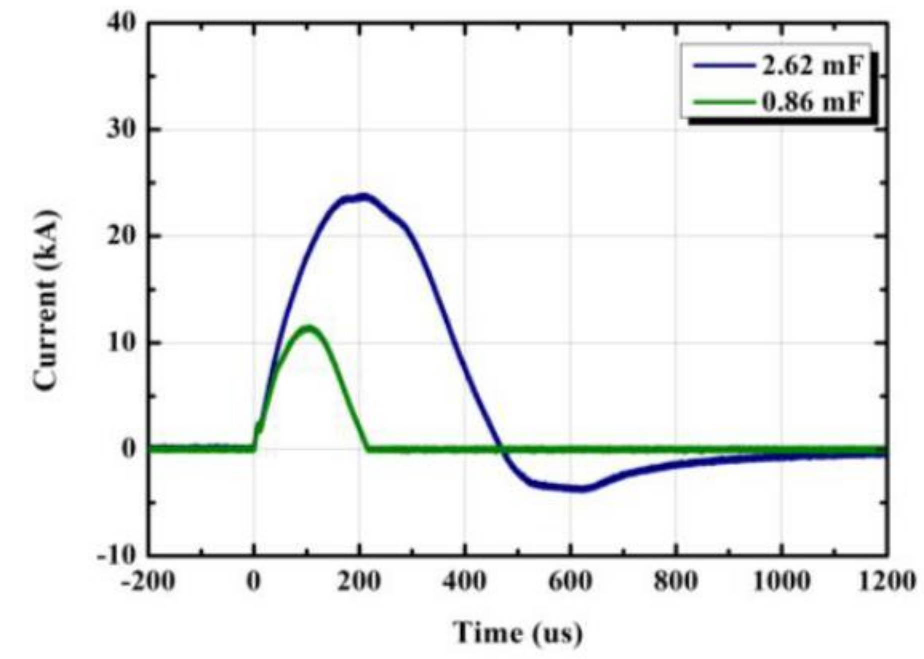

Fig. 6. Current waveforms for different capacitance values

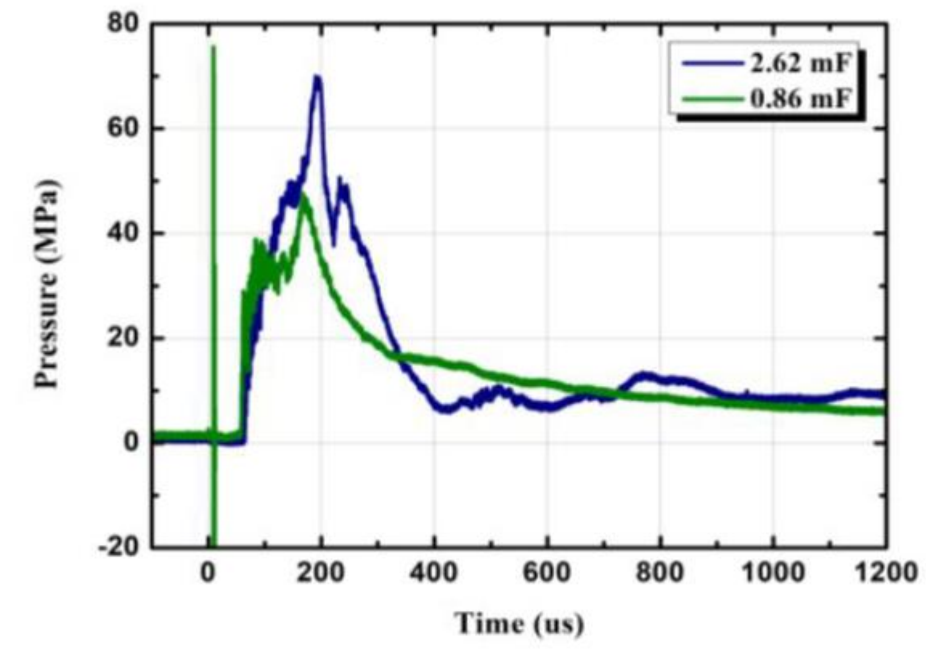

Fig. 7. Comparison of pressure at different capacitances

- Accordingly, the pressure width and peak pressure increased, as depicted in Fig. 7.

Ⅳ. 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.

Ⅴ. References

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Ⅵ. Acknowledgement

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