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ANALYSIS MODEL FOR SEISMIC CONTROL ROD INSERTION SYSTEM WITH TWO RODS

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ABSTRACT

An analysis model for a seismic control rod insertion system, which is composed of one hydraulic control unit that drives two control rods, was constructed and validated. The scramability of control rods plays a crucial role in the seismic-safety assessment of nuclear power plants, and the time taken to insert the rods (henceforth referred to as "control-rod insertion time") during an earthquake has been confirmed through demonstration tests. Moreover, numerical simulation models have been developed and used to study improvements and evaluate scramability of control rods under varied conditions. A conventional model has been developed for systems in which one hydraulic control unit drives two control rods and this model assumes that the piping characteristics of the scram piping and the mechanical characteristics of the control rods and fuel assemblies are identical. An analysis model was developed and applied to two control-rod insertion systems with different characteristics. Focusing on the improved control-rod insertion system, the effects of control-rod mass and pressure loss in the scram piping on control-rod insertion time were confirmed through numerical calculations. The results of the calculation indicate that the different characteristic of the two control-rod insertion systems of an advanced boiling-water reactor (ABWR) have negligible effect on control-rod insertion time to the extent that control-rod mass and pressure loss in the scram piping encompassed their respective ranges for an actual ABWR.

INTRODUCTION

As for the assessment for seismic safety of nuclear power plants, it is crucial to confirm whether the control rods, which control the nuclear reaction in the reactor, can be inserted into the reactor within a tentative criterion time (henceforth referred to as "scramability" of control rods). In case of an emergency, a hydraulic control unit generates power that pushes up the drive piston in the control-rod insertion, in manner that inserts the rods into the reactor. During an earthquake, for example, the reactor's fuel assemblies vibrate and deform in a bow shape. This deformation of the fuel assemblies causes a delay in time taken by the control rod insertion (henceforth referred to as "control-rod insertion time") due to contact with the vibrating fuel assemblies. The scramability of control rods during earthquakes is confirmed through demonstration tests.

Numerical simulation models have been developed and used to study improvements of control-rod insertion and evaluate scramability of control rods under varied conditions. Koide et al (2013) have developed an analysis model that couples two calculations: (i) calculation of frictional forces due to three-dimensional contact between control rods and fuel assemblies with (ii) calculation of transient water pressure of the hydraulic control unit and control-rod insertion. As for the conventional method for calculating control-rod insertion time, control-rod insertion time is evaluated under two assumptions: first two control rods are driven by one hydraulic control unit; second the mechanical characteristics of the scram piping after branching and the control rods and fuel assemblies are identical.

In an advanced boiling water reactor (ABWR), the mechanical characteristics of the scram piping after branching and the control rods may be different; thus, it is useful to confirm the control-rod insertion time under

that condition to further improve safety. Therefore, the purpose of this study is to develop an analysis model that can calculate the control-rod behaviour for two control-rod insertion systems with different mechanical characteristics. The analysis model was constructed by improving Koide's model calculating the transient water pressure under the condition that one hydraulic control unit is connected to two scram pipes and the control-rod insertion. The influence of parameters of control rod insertion system that may differ in the case of an actual ABWR on control-rod insertion time was also confirmed.

MODELING OF SEISMIC CONTROL-ROD INSERTION

Scram Mechanism

The internal components of an ABWR are shown schematically in Figs. 1(a) to (c): (a) pressure vessel and internal components of the reactor, (b) detailed view of the control-rod insertion system, and (c) control rod. The reactor contains several-hundred fuel assemblies, grouped in sets of four. The fuel assemblies are supported at their lower end by a fuel support and at their upper end by an upper grid. The control-rod guide tubes are positioned under the fuel support. Each control rod is housed within a control-rod guide tube, the lower end of which is connected to the drive piston of the control-rod insertion.

The control-rod insertion system is shown schematically in Fig.2. The control-rod insertion controls the nuclear reaction in the core by driving the control rods up and down. In the case of normal drive, the rotation of the electric motor is converted into vertical movement by a ball screw. Conversely, in the case of an earthquake, the scram valve opens, and allows the stored nitrogen in the accumulator to expand and generate hydraulic pressure. The working fluid passing through the scram valve is distributed to the respective scram piping, the working-fluid pressure acts on each piston of the control-rod insertion, and the control rods are rapidly inserted into the reactor core. A portion of the working fluid flows into the reactor through the labyrinth seal.

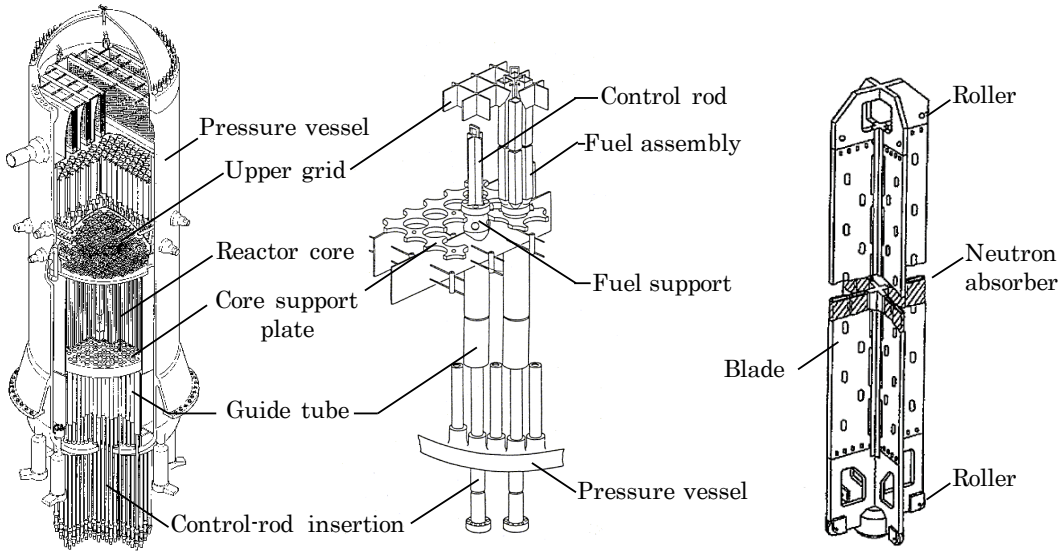

Fig. 1: Schematic representations of ABWR and control rod

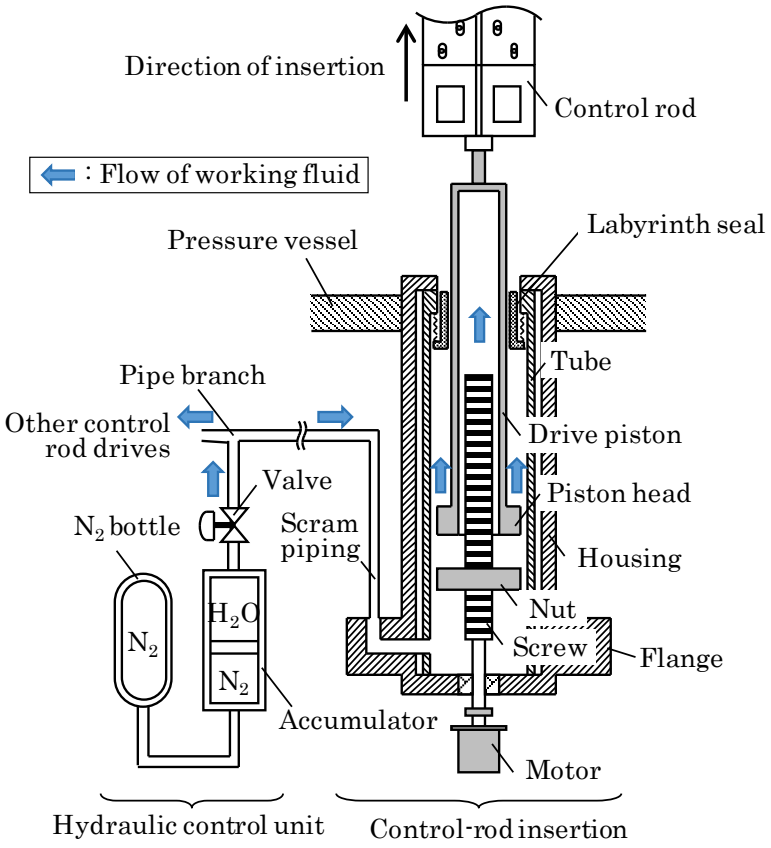

Fig. 2: Schematic representations of control-rod insertion system

Modelling of Insertion

The dynamics of the water pressure inside the accumulator and scram piping were modelled and used to simulate the driving force of the control rods. Pressure losses in the scram piping, scram valves, flow paths, and seals in the control-rod insertion are modelled by resistive elements. The capacitance effect resulting from the compressibility of nitrogen gas in the accumulator is modelled by using a lumped parameter system. The elements are interconnected in a way that satisfies the pressure- and flow-rate constraints imposed by Kirchhoff's law for a flow-channel network. Two control-rod insertion systems are created by connecting two scram pipes and control-rod insertion units to one hydraulic control unit. The analysis model was constructed by using the numerical-analysis software MATLAB® Simulink® (The MathWorks, Inc. 2023).

Modelling of Structure inside reactor pressure vessel

The three-dimensional geometry of control rods, fuel assemblies, fuel supports, and control-rod guide tubes was modelled to simulate the frictional force resulting from contact between control rod and others. The structural model is shown in Fig.3. The control rods and fuel assemblies are modelled by using concentrated mass and beam elements to calculate seismic-vibration behaviour of them. The control-rod guide tubes and fuel supports are simply modelled as rigid bodies.

The fluid force generated by the accelerated motion of the fuel assemblies in the reactor water is considered as a virtual mass. The fluid force is calculated by considering the reactor water as a potential flow and obtaining the pressure distribution of the reactor water. This fluid force is incorporated into the structure model of fuel assemblies as a force element that generates a load proportional to the acceleration of the fuel assemblies.

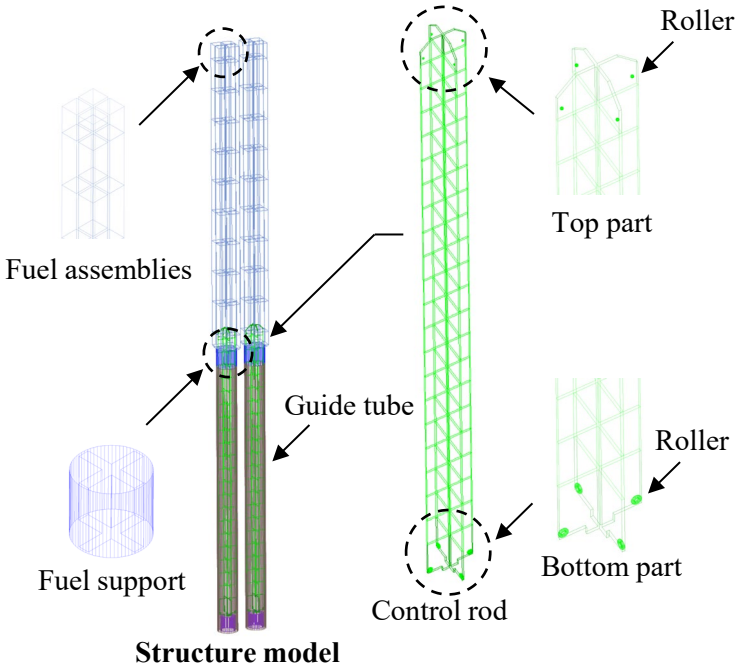

Fig. 3: Schematic model of insertion of two control rods

Analysis Model for Control Rod Insertion System with Two Rods

An analysis model for the control-rod insertion system was constructed by coupling the insertion model and the structural model. the control rods insertion analysis model is shown in Fig.4. The driving force of two control rods in the insertion model is calculated by balancing the pressure and flow within the hydraulic control unit and control-rod insertion. The calculated driving force is applied to the control rod in the structural model and then the insertion velocity of the control rod is calculated in the structural model. The insertion velocity is subsequently converted into the flow velocity of the insertion system's working-fluid hydraulic circuit and input into the insertion model. The driving force is recalculated by resolving the pressure and flow balance in the insertion model. Sequentially executing these processes, makes it possible to couple the insertion model with the structural model and construct an analysis model. This model can compute the behaviour of one hydraulic control unit driving two control rods with different characteristics in the control-rod insertion system. The specific calculation method is to convert the insertion model expressed as a block diagram into a transfer function by using MATLAB®, and then incorporate the transfer function into the equation of state of the structural-system model. The calculation using the analysis model for the control-rod insertion system runs in Adams™.

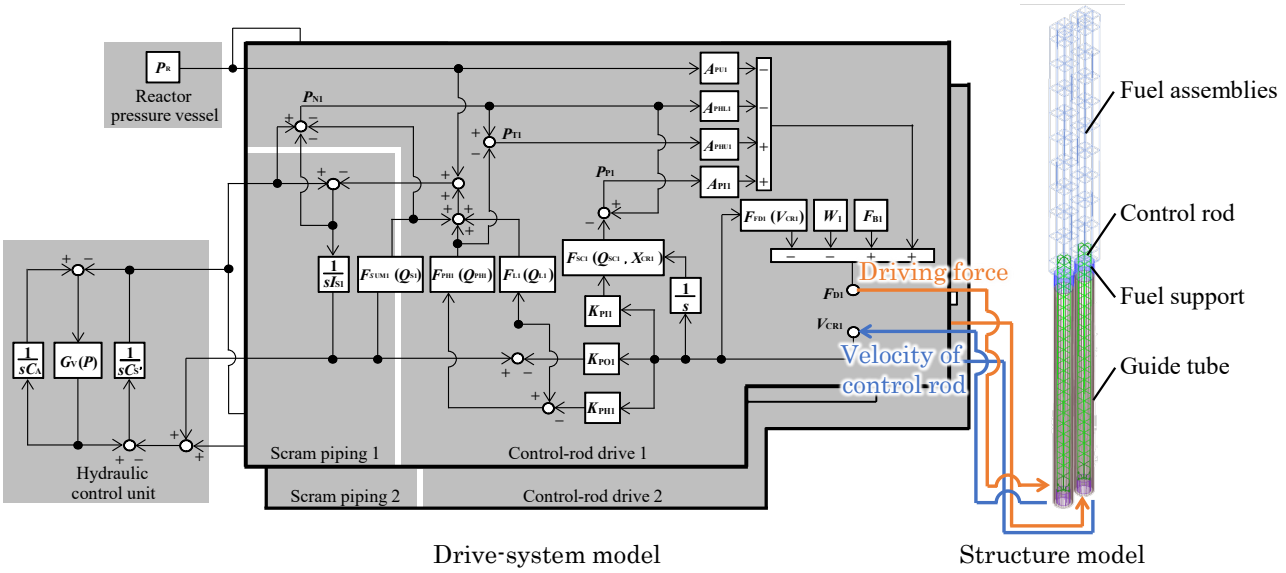

Fig. 4: Analysis model for insertion of two control rods

EVALUATION OF EFFECTS OF DIFFERENCES INSERTION SYSTEM ON CONTROL ROD INSERTION TIME

Focusing on the improved control-rod insertion system, the effect of differences in the characteristics of control-rod insertion systems on control-rod insertion time was determined as follow. Examples of two different control-rod insertion systems connected to one hydraulic control unit include differences in dead load, that is mass, due to different control-rod types and differences in pressure loss in the piping due to varying lengths, number of bends, and angles of the scram piping. Therefore, these parameters (mass and pressure loss) were varied in the analysis conditions.

Two typical masses of control rods used in an ABWR were taken as one analysis condition, and the pressure losses of the scram piping (set to 1.0, 0.8, and 0.6 times a tentative criterion value) were taken as the other analysis condition. The criterion is a tentative upper limit for pressure loss in the scram piping, including the effects of length, bends, etc., and is defined for a specific flow rate. Normalized values of control-rod mass and pressure loss in the scram piping (as respective maximum values) in each case are listed in Table 1. The parameter range for pressure loss in the scram piping was set to encompass the range in the case of an actual ABWR reactor. To examine the effect of these parameters on control-rod insertion time, two cases ("control-rod insertion systems 1 and 2") were analysed. In the first case, for systems 1 and 2, control-rod mass and scram-piping pressure loss were set to minimum or maximum. In the second case, control-rod mass and scram-piping pressure loss for system 1 were varied while those for system 2 were set to maximum. Both systems were analysed under vibration conditions. During an earthquake, the fuel assembly deforms in the first-order mode in a bow shape, and a drag force is generated during the control-rod insertion by contact of the control rod with the fuel assemblies. Therefore, the vibration condition was set to sinusoidal acceleration matching the first-order natural frequency of the fuel assembly, and the acceleration amplitude was adjusted so that the displacement response amplitude of the fuel assembly was 40 mm, which is taken as the tentative criterion (Fukushi et al, 2009). The same vibration conditions were applied to all cases.

Control-rod insertion time, normalized by the tentative criterion for a domestic ABWR, including maximum and minimum values, is plotted in Fig. 5. According to the figure, the maximum value corresponds to the control-rod insertion time in case 4. Conversely, the minimum value corresponds to the time for in case 1. The time history of control-rod insertion stroke, insertion speed, and time history of working-fluid flow rate in the scram piping, all in case 4, are shown in Figs. 6 to 8.

The insertion velocity of the control-rod insertion system 1 shown in Fig. 7 is zero after control-rod stroke of the system 1 reaches 100%. it indicates that the insertion stroke is maintained at 100% after the insertion is complete. The working fluid flow rate of the system 1 shown in Fig. 8 remains above zero even

after the insertion is complete. This is because the working fluid flows into the reactor through the labyrinth seal.

The insertion velocity shown in Fig. 7 and the working-fluid flow rate shown in Fig. 8 peak immediately after the start of insertion and thereafter decrease and oscillate in accordance with the contact between the control rod and fuel assemblies. The insertion velocity and working-fluid flow rate of system 1, which has a smaller pressure loss in the scram piping, is greater than that of system 2. The insertion velocity and working-fluid flow rate of system 2 increase after the insertion of system 1 is completed.

The qualitative validity of the constructed the analysis model for the control-rod insertion system was confirmed by comparing some cases of the calculated control-rod insertion time. If the characteristics of the two control-rod insertion systems are identical, the control-rod insertion times should match. This qualitative tendency can be seen in case 1 because the control-rod insertion times for systems 1 and 2 of case 1 are identical.

If the characteristics of the two control-rod insertion systems differ, the working fluid tends to concentrate in the scram piping of the system that has lower control-rod mass and smaller pressure loss. This working-fluid concentration increases the driving force applied to the control rod in the system that has lower control-rod mass and smaller pressure loss, and that increased driving force results in a shorter control-rod insertion time. The results for cases 2 to 5 indicate that control-rod insertion system 1 is faster than system 2, and that finding is consistent with the qualitative tendency. In conclusion, these results qualitatively confirm the validity of the constructed control-rod-insertion analysis model.

The effect of the differences between the control-rod insertion systems on control-rod insertion time was evaluated as follows. As shown in Fig. 5, in cases 1, 3, and 4, control-rod insertion time of control-rod insertion system 1 decreased as pressure loss in the scram piping of the system decreased, while control-rod insertion time of system 2 increased. This result can be explained by the fact that the working fluid concentrated in system 1, in which pressure loss in the scram piping is relatively small. As a result, working-fluid flow rate in the case of system 2 decreases, leading to a decrease in control-rod driving force.

Comparing control-rod insertion times in cases 4 and 5 shows that pressure-loss differences of the scram piping of systems 1 and 2 are the same in both cases. Due to the added control-rod-mass difference between system 1 and 2, it is expected that more working fluid is concentrated in system 1 in case 5. Based on the above tendency, it is expected that the control-rod driving force of system 2 will decrease and the insertion time in case 5 will increase compared to those in case 4. However, control-rod insertion time in case 5 decrease compared to that in case 4. This result can be explained by the fact that in case 5, after the control rods in system 1 were inserted earlier, the working fluid concentrated and the control-rod driving force increased in system 2, resulting in rapid insertion of the control rods in system 2.

From the above reasons, differences in the characteristics of the control-rod insertion systems have two main effects on control-rod insertion time: first, the concentration of the working fluid in one control-rod insertion system reduces the working fluid in the other system; second, the system with the concentrated working fluid completes insertion of the control rods more quickly, so the working fluid concentrates in the other system.

The control-rod insertion times was investigated as follows. The control-rod insertion times of all cases were approximately 60% of the tentative criterion time for a domestic ABWR, which has a sufficient margin. The maximum control rod insertion time (Case 4) is about 1.02 times the minimum (Case 1). These results suggest that although the differences in the characteristics of the control-rod insertion systems somewhat affect control-rod insertion time, the effect is negligible.

Table 1: Control-rod mass and pressure loss of scram piping in each analysed case

	Control rod mass		Pressure loss	
	Type 1	Type 2	Piping 1	Piping 2
Case 1	1.0	1.0	1.0	1.0
Case 2	0.8	1.0	1.0	1.0
Case 3	1.0	1.0	0.8	1.0
Case 4	1.0	1.0	0.6	1.0
Case 5	0.8	1.0	0.6	1.0

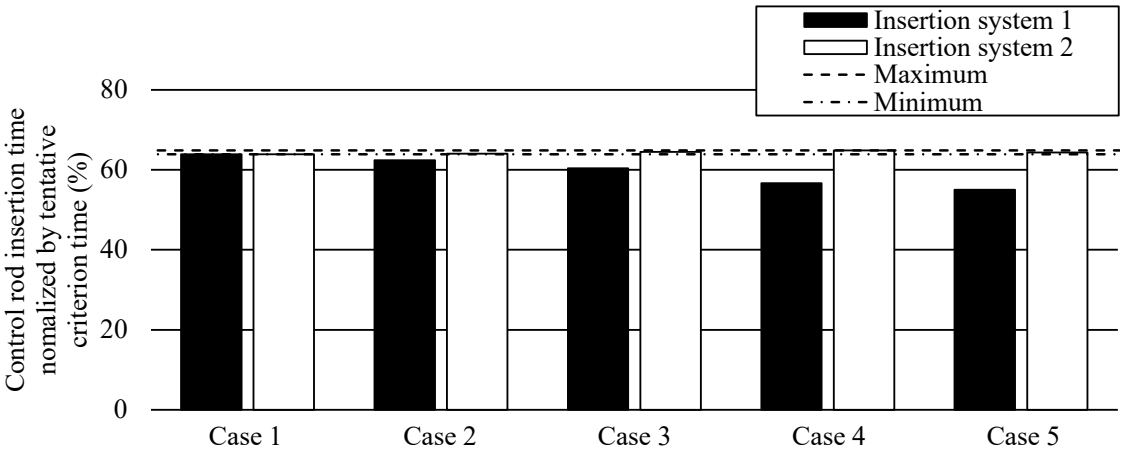

Fig. 5: Comparison of control rod insertion time, including maximum and minimum values

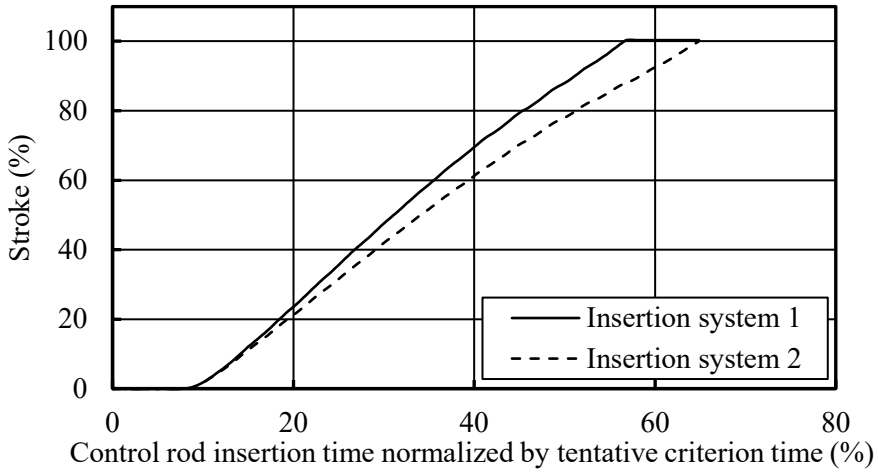

Fig. 6: Time histories of control-rod stroke

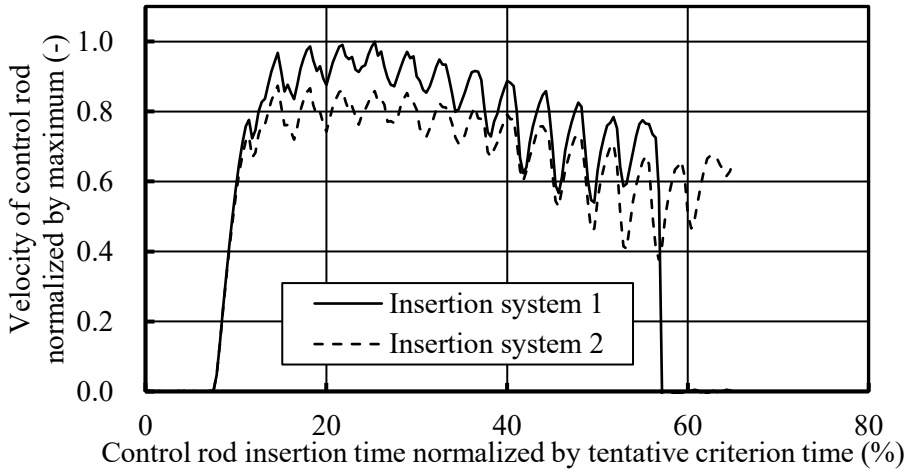

Fig. 7: Time histories of velocity of control rod

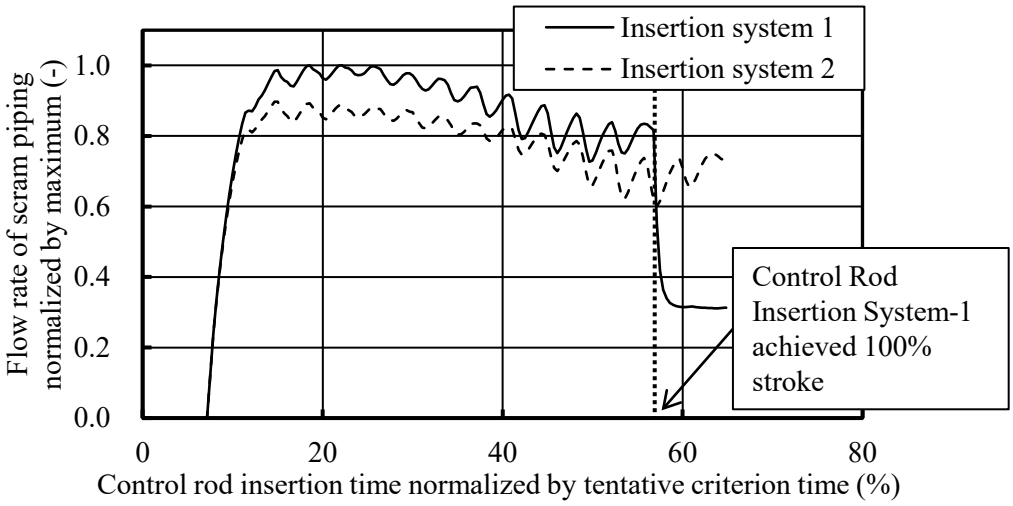

Fig. 8: Time histories of flow rate in scram piping

CONCLUSION

An analysis model that can simulate the behaviour of a single hydraulic control unit driving two control-rod insertion systems with different characteristics was developed. The model was constructed by coupling two models: (i) an insertion model, improved Koide's model, connecting the hydraulic control unit to two scram pipes and control-rod insertions and (ii) a structural model coupling the respective control-rod insertion models. The two control-rod insertion systems connected to one hydraulic control unit probably include differences in mass due to different control-rod types and differences in pressure loss in the scram piping due to varying lengths, number of bends, and angles of the scram piping. Therefore, the effects of these factors were confirmed in the parameter range that encompasses the advanced boiling water reactor (ABWR).

The constructed control-rod-insertion analysis model was validated by confirming that the calculated control-rod insertion time agrees with the qualitative tendency of the control-rod insertion time in the case that the characteristics of the control-rod insertion systems are identical and differ.

It was shown that when the characteristics of the control-rod insertion systems differ, two factors affects control-rod insertion time: first, concentration of the working fluid in one control-rod insertion system reduces the flow of working fluid in the other system; second, the system with the concentrated working fluid completes insertion of the control rods more rapidly, causing the working fluid to concentrate in the other system.

The control-rod insertion times of all cases were approximately 60% of the tentative criterion time for a domestic ABWR, which has a sufficient margin. The maximum control-rod insertion time is about 1.02 times the minimum. It is therefore concluded that the characteristics of the control-rod insertion systems have a negligible effect on control-rod insertion time.

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