Scram Characteristics of Control Rods of Pressurized Water Reactor Under Seismic Conditions*

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Control rod drop verification experiments of pressurized water reactor under seismic conditions are performed to confirm the insertion function of control rods into a core. To evaluate these tests, computer simulations are performed. A fuel assembly, control rods, a guide tube and other associated structures are immersed in a water tank, and shaken by four hydraulic shakers. The scram time of control rods under seismic conditions was measured, and confirmed to meet the scram function. Moreover, the vibrational response characteristics of core structures and the dropping behavior of control rods in consideration of collisions are calculated by using a finite difference method. The behavior of the dropping control rods and the scram time obtained by computer simulation show a very good agreement with the verification experimental results.

Key Words: Vibration, PWR, Control Rods, Earthquake, Verification Experiment, Scram Time, Collision, Finite Difference Method

1. Introduction

Pressurized water reactors (PWR Type) are so structured as to shut-down the operation of the reactor in the event of a large scale seismic condition by automatically inserting the control rods into the core by their own gravity. A standard schematic of the PWR nuclear reactor is shown in Fig.1. Inside the reactor vessel, there exist approximately 200 fuel assemblies, all supported by the upper and lower core plates, of which 20 control rods per assembly are designed to be inserted into each of 50 fuel assemblies. The control rods are combined in a cluster at the top

edge with the vane which is connected to the drive rod to facilitate raising and lowering the control rods as actuated by the control rod drive mechanism located on the lip of the reactor vessel.

By this mechanism, the control rod is set in motion to perform operation, stoppage and power supply control of the reactor. Further, upon the occurrence of a large scale earthquake, and when the acceleration exceeds the preset limit, the reactor's trip signal from the seismometer is actuated to allow the control rods to be systematically and automatically inserted into the reactor's core:

During a seismic condition of large scale, the pawl to secure the drive rod of the drive mechanism disengages, enabling the control rods to be automatically inserted by their own gravity into the fuel assembly, in which case, the control rods and the drive rods will fall down repeatedly colliding against the fuel assemblies and other structures because of the structural members being in a seismic condition. For consummate maintenance of the aseismic safety-proofness of the nuclear power plants, it is taken for granted that it is indispensably important to keep the insertion function of the control rods on a satisfactory level,

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even under these strong seismic conditions.

For confirming the reliability of large sized facilities such as the insertion function of control rods in nuclear reactors, reduced scale model tests, verification tests on the basis of the experimental prototype for the control rod drive mechanism in actual size, and computerized analytical simulations are considered effective. These experimental tests by means of the scaled model and the verification tests of insertion function have been already applied to a Canadian deuterium uranium heavy water reactor (CANDU Type) where the insertion of the control rods was performed by utilizing the gravity of the rod itself, and the time was evidenced as being less than the target value even under vibratory excitation 1.2 times as strong as the designed seismic level, as reported by Kuroda, et. al.⁽³⁾⁽⁴⁾.

With respect to the analytical simulation, there exist studies⁽⁵⁾⁽⁶⁾ using a model for considering the non-linearity of collision by the finite difference method, treating both the guide thimble in the fuel assembly and the control rod as the elastic beams.

In this paper, the experimental results of the verification test and the analytical simulation, which was enlarged to an actual size, using the same model as a reference (5) are described in order to ascertain the insertion function of a PWR-type reactor's control rod at the time of an earthquake. The purpose of this verification test is to confirm the insertion function of the control rods by exciting a set of specimens at the actual size, such as control rods and fuel assemblies etc. which are installed to a water tank simulating the reactor vessel. The purpose of analytical simulation, which is performed by replacing the system consisting

of these structural members with elastic beams using the finite difference method, is to substantiate the verification test by actual scale specimens and to establish an evaluation technique.

2. Verification Test

2.1 Control rod insertion mechanism

A schematic drawing of the PWR type nuclear reactor is shown in Fig. 1 (a). There exist the upper and lower core inside the reactor vessel which supports a total of app. 200 fuel assemblies, of which about 50 fuel assemblies will have the control rods inserted. As shown in Fig. 1, about 20 control rods are combined in a cluster and are connected to the drive rod. During the operation of the reactor, these control rods are drawn out of the fuel assembly and held inside the control rod cluster guide tube and are either raised or lowered by the control rod drive mechanism located on the lid of the reactor vessel. The power source of the control rod drive mechanism will be cut off during an emergency such as a large scale earthquake, and the control rods will scram into the fuel assemblies by their own gravity.

2.2 Specimens

A mock-up of the fuel assembly, the upper and lower guide tubes, the thermal sleeve, the control rod drive mechanism including housing, the control rods, and the drive rod of the actual size as illustrated in Fig. 1 are fabricated to simulate actual structures. These structures are immersed in the water tank simulating the reactor vessel, and the whole structure is shaken by four hydraulic shakers. By regulating the output of these four shakers, the differential input of the seismic floor response due to the difference in

(a) Construction for drawing of a PWR nuclear reactor (b) Drawing of apparatus of verification experiment

Fig. 1 Consideration for experimental mock-up

elevation of the support position of the actual structure can be simulated. The water tank was suspended with steel wires in order to reduce the load imposed on the hydraulic shakers. The natural period as a pendulum consisting of the steel wires and the water tank was made to be so long that it removed any effect produced in the test. Figure 2 shows a photograph of the test apparatus.

2.3 Test method

2.3.1 Sine wave excitation test

The natural frequencies and vibration modes of the structures, such as the fuel assembly shown in Fig. 1 were obtained by exciting the sine wave sweep excitation to the whole apparatus. Next, the control rods were dropped and their scram characteristics were examined during excitation of the natural frequency of the first mode of each part of the specimen.

2.3.2 Seismic wave excitation test

Scram characteristics of the control rods at the time of an earthquake were examined by dropping the control rods when the whole apparatus was shaken with seismic waves.

2.4 Test results

2.4.1 Sine wave excitation test

Figure 3 shows the natural frequencies and vibration modes of each part of the specimen. The scram time under sine wave excitations are also shown in Table 1. When the control rods were dropped without excitation, they were inserted at a time rate of slightly over 1s. Further, the maximum relative displacement against the boundary of the members was found to be 14 mm at the center of the fuel assembly under 3.25 Hz, 350 Gal excitation; and 7 mm at the center of the housing under 19.9 Hz, 1 000 Gal excitation; and 3

mm at the upper end of the guide tube under 30.3 Hz, 7 000 Gal excitation, respectively.

2.4.2 Seismic wave excitation test

The scram time of the control rods was measured with the excitations of the artificial seismic waves called S_0 , S_1 , S_2 . The artificial seismic waves are those in which the phase of several sine waves of different frequencies are superposed randomly, and their maximum accelerations are 570, 1 700, and 2 800 Gal, respectively. As an example, the time history wave of S_2 wave and its response spectrum of 1% damping ratio are shown in Fig. 4. The scram times were respectively found to be 1.0, 1.01 and 1.21 times as long as the case when the control rods were not excited.

2.4.3 Evaluation of insertability

From the above experimental results, a safe perspective was found to be obtainable by the following manner for estimating the reasonable scram time of the control rods for similar structural installations

Table 1 Sine wave excitation test results (four shakers excited simultaneously)

Frequency (Hz)	Acceleration (Gal)	Scram Time Ratio
No Input	0	1.0
3.25	175	1.01
	350	1.08
19.9	500	1.0
	1000	1.14
30.3	3000	1.0
	5000	1.18
	7000	1.19

Fig. 2 Bird's eye view of test apparatus

Fig. 3 Natural frequencies and vibration mode shapes

at the time of an earthquake, i. e.,

(a) To perform a seismic analysis of the control rod insertion system based on the seismic input conditions of the plant.

(b) To obtain the scram lag time against each structure's response displacement from the sine wave excitation test that causes the same displacement as a seismic response analysis.

(c) To obtain the scram time under earthquake conditions by totalling the value of each lag time which has experimentally confirmed the safe evaluation, i. e., the total of the scram lag time of the sine wave excitation test is longer than that of the seismic wave excitation test.

3. Analytical Simulation

The analytical simulation is effective to confirm the insertion function of the control rods during an earthquake without performing a test of the actual system. The simulation of the dropping behavior of the control rod in repetitive collision in narrow clearance has been reported already, with regard to the effects on the insertability influenced by both the collision and friction of the control rod and the guide thimble, in which case, the finite difference method was applied, treating the elastic rod inserted in the vibrations cylinder as a beam.

In this paper, the analytical codes which simulate the insertion behavior of the control rods are described by applying the method reported in reference (5), using the calculation model of the control rod drive mechanism, the guide tube, and the thimble of the fuel assemblies in the actual size. Further, its

(a) Time history

(b) Response spectrum

Fig. 4 Simulated seismic wave S_2

practicability will be reported by using the results of the calculation.

3.1 Dynamic model

A control rod drive mechanism and its dynamic model of the actual PWR-type plant is shown in Fig. 5. One set of the control rod drive mechanism is fabricated as a model for analytical simulation. Being long and narrow in the vertical direction, all the structural members are treated as elastic beams, considering the deflection in the horizontal direction.

As shown in Fig. 5, the housing of the control rod drive mechanism is modeled as a fixed-supported beam, the upper control rod guide tube as a cantilever and the fuel assembly as a supported beam. As the natural frequencies of other parts are sufficiently high, they are assumed to be rigid. The coupling of the drive rod and the control rods are assumed to be a pin joint, therefore, each opposite side is assumed to be a free end, respectively. In the actual reactor, about 20 control rods are coupled to the drive rod; but, in this analysis, the contact force and the friction force for one control rod and one thimble obtained after calculation shall be used for calculating the motion of the whole structure, assuming that the motion of all the control rods are the same. Collision among structural members is expressed by a spring converted into the contact stiffness. The spring itself is linear, while the collision itself is nonlinear as a whole, as shown in Fig. 6.

3.2 Equation of motion

When boundaries (supported or fixed end) of a

Fig. 5 Control rod drive mechanism and dynamic model

long and narrow beam are uniformly excited in the horizontal direction, the equation of motion is expressed by the following formula :

$$\rho_n \frac{\partial^2 x}{\partial t^2} + C_1 n \frac{\partial x}{\partial t} + (C_2 I)_n \frac{\partial^5 x}{\partial t \partial z^4} + (EI)_n \frac{\partial^4 x}{\partial z^4} = -\rho_n \frac{d^2 u}{dt^2} + \beta_n F(x_{\text{inner}}, x_{\text{outer}}, h_m, k_m) \quad (1)$$

where x : relative displacement in the horizontal from the boundary point, z : coordinate of the vertical direction, t : time, u : seismic input (displacement), ρ : mass per unit length, C_1 : external damping coefficient, C_2 : internal damping coefficient, I : area moment of inertia, h : clearance, k : contact stiffness. Subscript n denotes a number to distinguish the structural members, m denotes a number to distinguish the clearance. As shown in Fig. 6, $F(\cdot)$ denotes the reaction force of the spring determined by the relative displacement of members of the inner and the outer sides, β is -1 for the inner member and $+1$ for the outer member. Subscripts "inner" and "outer" denote the inner and outer member, respectively.

The equation of motion for the dropping of control rods is expressed by the following formula :

$$m_r \frac{d^2 z_r}{dt^2} = m_r g - F_0 - \int_0^L \mu_m |F(x_{\text{inner}}, x_{\text{outer}}, h_m, k_m)| dz \quad (2)$$

where z_r : dropped distance of the control rod, m_r : total mass of control rods and drive rod, g : acceleration due to gravity, F_0 : mean drag when control rods

drop without seismic input, μ : coefficient of friction, respectively. The integral interval L of the third term of the right hand side extends from the lower end of the control rod to the upper end of the drive rod, but the clearance and contact stiffness respectively differ depending on the location. Also, the friction force which is imposed on the control rod is used for calculating the overall drop by multiplying the number of the control rods.

3.3 Equation of finite difference

After Eq. (1) and (2) are transformed into a dimensionless form, the derivatives are expressed by the finite differences. For example, the fourth derivative of displacement is expressed by the relation formula of displacement between the five nodes as follows, i. e.,

$$\partial^4 \xi / \partial \zeta^4 = (\xi_{i+2} - 4\xi_{i+1} + 6\xi_i - 4\xi_{i-1} + \xi_{i-2}) / (\Delta \zeta)^4 \quad (3)$$

where ξ, ζ : dimensionless form of x, z of the Eq. (1) with respect to each reference clearance and the inserted total length, and i : a variable which denotes the number of the finite difference node, respectively. The derivatives of the Eq. (1) and (2) are converted into finite differences in a similar method, and delete the displacement of finite difference node ξ_i and the inserted length ζ_r of the control rod at dimensionless time $\tau + \Delta \tau$ are obtained.

The equation of finite difference deals with a physically equivalent mass points system, as shown in Fig. 7. For convenience of calculation, the pitch of finite difference is equalized with all of the members and adjusted so the length of the members may become the integer multiple of the pitch. The spring which indicates the contact stiffness is assumed as being attached to the finite difference node of the outer side member, and, the reaction to the finite difference node of the inner side member is obtained by linear interpolation. However, as the guide plate of the guide tube does not exist on the finite difference node as shown in Fig. 8, the reaction force to the outside finite difference node of this part is also obtained by linear interpolation.

The dropping behavior is analyzed by modifying

Fig. 6 Relative displacement and reaction force

Fig. 7 Finite difference model

Fig. 8 Guide plate model

the vibration equation of the beam (1) and the equation of the downward motion (2) of the below iteration formula by finite difference:

$$\begin{aligned}
 \xi_i^{(j+1)}(\tau + \Delta\tau) = & [2\xi_i(\tau) - \xi_i(\tau - \Delta\tau) \\
 & + D_{1n}\xi_i(\tau - \Delta\tau) \cdot \Delta\tau/2 + D_{2n}\{-\xi_{i+2}^{(j)}(\tau + \Delta\tau) \\
 & + 4\xi_{i+1}^{(j)}(\tau + \Delta\tau) + 4\xi_{i-1}^{(j+1)}(\tau + \Delta\tau) \\
 & - \xi_{i-2}^{(j+1)}(\tau + \Delta\tau) + \xi_{i+2}(\tau - \Delta\tau) \\
 & - 4\xi_{i+1}(\tau - \Delta\tau) + 6\xi_i(\tau - \Delta\tau) - 4\xi_{i-1}(\tau - \Delta\tau) \\
 & + \xi_{i-2}(\tau - \Delta\tau)\} \Delta\tau/2(\Delta\tau)^4 \\
 & + S_n\{-\xi_{i+2}^{(j)}(\tau + \Delta\tau) + 4\xi_{i+1}^{(j)}(\tau + \Delta\tau) \\
 & + 4\xi_{i-1}^{(j+1)}(\tau + \Delta\tau) - \xi_{i-2}^{(j+1)}(\tau + \Delta\tau) + 2[-\xi_{i+2}(\tau) \\
 & + 4\xi_{i+1}(\tau) - 6\xi_i(\tau) + 4\xi_{i-1}(\tau) - \xi_{i-2}(\tau)] \\
 & - \xi_{i+2}(\tau - \Delta\tau) + 4\xi_{i+1}(\tau - \Delta\tau) - 6\xi_i(\tau - \Delta\tau) \\
 & + 4\xi_{i-1}(\tau - \Delta\tau) - \xi_{i-2}(\tau - \Delta\tau)\}(\Delta\tau)^2/4(\Delta\zeta)^4 \\
 & - d^2\psi(\tau + \Delta\tau)/d\tau^2 + \beta_n f(\xi_{inner}^{(j)}(\tau + \Delta\tau), \\
 & \xi_{outer}^{(j)}(\tau + \Delta\tau), \gamma_m, \kappa_m)]/[1 + D_{1n}\Delta\tau/2 \\
 & + 3D_{2n}\Delta\tau/(\Delta\zeta)^4 + 3S_n(\Delta\tau)^2/2(\Delta\zeta)^4] \quad (4) \\
 \zeta_r(\tau + \Delta\tau) = & 2\zeta_r(\tau) - \zeta_r(\tau - \Delta\tau) \\
 & + [\varphi_0 - \Delta\zeta \sum \mu_m |f(\xi_{inner}, \xi_{outer}, \gamma_m, \kappa_m)|](\Delta\tau)^2 \quad (5)
 \end{aligned}$$

where D_{1n} , D_{2n} , S_n , ψ , $f(\cdot)$, γ_m , κ_m , φ_0 are non-dimensional members, having the following physical significance. D_{1n} : external damping coefficient, D_{2n} : internal damping coefficient, S_n : bending stiffness, ψ : seismic input, $f(\cdot)$: reaction force of the spring, γ_m : clearance, κ_m : contact stiffness, and φ_0 : difference of gravity and drag, respectively.

The superscript (j) denotes the iteration time for solving vibration Eq. (4) which is a non-linear system including the clearance. This iteration method is effective since there exist possibilities of collision during the time $\Delta\tau$. Even in the term which does not contain the partial derivative with respect to time, derivatives at three nodes of time $\tau + \Delta\tau$, τ , $\tau - \Delta\tau$ are

Fig. 9 Calculation flow chart

emphasized at a ratio 1 : 2 : 1.

Figure 9 shows the flow chart of the analytical simulation. The equation of downward motion and the equation of vibration is solved separately, i. e., while dropping, the deflection is assumed invariable within the time $\Delta\tau$, and, in order to solve the equation of vibration, only the equation of vibration is sloved using the iteration method, with no regard to dropping. With this couple making a set, the drop position and deflection after $\Delta\tau$ are obtained. This method is continued until insertion is completed.

3.4 Results of calculation

In terms of elementary moments, the values of the verification experimental specimen simulating the actual reactor were used for the analytical simulation. As to the coefficient of friction and the contact stiffness, the coefficient of friction was varied for engineering consideration within the range of 0.1~0.3, and as for the contact stiffness, it was assumed to be 4.9×10^6 N/m² where the nodes collide against the control rod, and 4.9×10^7 N/m² where the nodes collide against the drive rod, respectively. The approximate values of the non-dimensional parameters used in the calculation are shown in Table 2.

Figure 10 shows the calculated results when excited by 3.25 Hz, i. e., the natural frequency of the fuel assembly, which shows a good agreement with $\mu = 0.2$ when compared with the test results. For exam-

Table 2 Non dimensional parameters

D_{21}	9.42×10^{-4}	ϕ_0	0.0031
D_{23}	2.41×10^{-4}	κ_m	3.43*
D_{25}	4.27×10^{-5}	κ_m	0.343 Δ
S_n	≤ 1.00	*: for Drive Rod Δ : for Control Rod	
r_m	0.57 ~ 1.12

Fig. 10 Comparison of calculation results and experimental results

ple, the experimental value at 350 Gal is 1.08 times as long as the experimental value without excitation, while the calculated value is 1.07 times.

Figure 11 reveals the calculated results when excited by 19.9 Hz, i. e., the natural frequency of the control rod drive mechanism housing, and the scram time excited by 1 000 Gal is 1.15 times without excitation when assuming that $\mu=0.2$. This is slightly longer than the experimental result of 1.14 times.

In Fig. 12~15, the seismic response against E1 Centro NS wave is shown. Figure 12 is for the input wave whose maximum acceleration is 340 Gal. Figures 13~15 are for the absolute acceleration at the

middle point of the housing of the control rod drive mechanism, the upper end of the upper control rod guide tube, and the middle point of the fuel assembly, respectively. In the calculation, it was assumed that the drop will start after 0.25 s when the acceleration of excitation exceeds 100 Gal. It was 1.65 s after the seismic wave was applied. The response of the members is found to be nearly the same as the excitation wave; but when collision with the control rod or with the drive rod occurred, a more sharp wave from appeared.

Figures 16~18 are for the deflection of members at the time when the drop started (7% insertion), 40% insertion and also 85% insertion, all excited by the same E1 Centro NS wave, which allow the visualization of the state of the condition as to how the control rod and the drive rod are inserted in repetitive collisions with the outer members. These figures also reveal that even in collision, the outer members are only subject to the excitation of the fundamental mode. Assuming that $\mu=0.2$, the scram time from the start of drop to 85% insertion was found to be 1.05 times as long as the experimental result without excitation.

Fig. 11 Comparison of calculation results and experimental results

Fig. 12 Excitation

Fig. 14 Response of guide tube upper end

Fig. 13 Response of middle of housing

Fig. 15 Response of middle of fuel assembly

Fig. 16 Deflection of members at the start of drop

Fig. 17 Deflection of members at 40% insertion

Fig. 18 Deflection of members at 85% insertion

4. Conclusion

(1) We have developed the test apparatus for the control rod to the reactor core under the seismic condition by employing a simulated specimen for the pressurized water reactor, and performed research on the seismic vibration which influences the effect on the scram time of the control rods to the reactor core.

(2) With the aid of analytical simulation, the substantiative verification of the insertion function

was made available, even for the extremely intricate system of the control rod insertion to the actual reactor in service.

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