Seismic Fragility Capacity of Equipment -Electric Panel Test-

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1. ABSTRACT

A seismic probabilistic safety assessment (PSA) is an available method to evaluate residual risk of nuclear plants, which are designed on definitive seismic design conditions. Seismic fragility data of components are necessary to carry out the seismic PSA, especially the components of which malfunction significantly increase the core damage frequency (CDF) are important. Our preliminary seismic PSA analysis has indicated that malfunction of electric panels, horizontal shaft pumps, control rod insertion systems and vertical shaft pumps would have significant influence on the CDF[1]. JNES has taken seismic fragility capacity tests of those components in high acceleration exceeding design levels and has evaluated seismic fragility[2],[3].

As for the electric panels, JNES has estimated the current seismic fragility at 3.6 x 9.8m/s^2 from the previous vibration test results[4] and has been applying this value uniformly to every electric panel. In recent years, there has been a growing desire to raise the reliability of the seismic PSA, to do this more detailed fragility data of each panel is necessary. JNES tested the main electric panels which were concerned with safety systems of nuclear plants and evaluated their seismic fragility. This paper describes the results of the electric panel tests.

2. OVERALL TEST PLAN

2.1 Framework of the Test

The seismic fragility capacity test consists of two kinds of tests. One is the actual equipment test and other is an element test. The main purpose of the actual equipment test was to directly investigate the critical acceleration and failure mode of the electric panels. JNES tested real electric panels which were of the same type as those in nuclear power plants under operating condition. On the element test, JNES tested many kinds of electric parts using multiple samples per one kind so that JNES not only confirmed the threshold acceleration but evaluated its dispersion. The seismic fragility of the electric panels was estimated from the results of the actual equipment test and the element test.

2.2 Test Objects

(1) Actual Equipment Test

At first, JNES selected more than ten kinds of electric panels used in safety systems and investigated the expected failure mode, influence level on CDF, the structural feature and so on. Consequently, JNES narrowed the electric panels down to eight panels as representatives for the actual equipment tests. A main control board, a reactor auxiliary control board, a logic circuit control panel, an instrumentation rack, a reactor protection rack, a reactor control center, a power center and a metal-clad switchgear (6.9kV) were tested.

(2) Element Test

Many kinds of electric parts were installed in the panels. JNES listed about three hundred electric parts such as relays, power units, switches, circuit breakers and selected about thirty different kinds of parts that performed important functions and were considered as potential weaknesses from the viewpoint of seismic condition.

2.3 Test Methods

(1) Input Wave

JNES made a basis seismic wave for the actual equipment test. It was made to fit the envelope floor response spectrum (FRS) which covered the design FRS of main electric panels.

Figure2-1 illustrates the seismic motion. As for the element tests, since seismic waves which vibrate electric parts depend on response characteristics of panels, seismic waves for the element tests were obtained by response analyses of the panels.

(2) Test Facilities

The actual equipment test was carried out in Tadotsu Engineering Laboratory of Nuclear Power Engineering Corporation (NUPEC). Maximum input acceleration for the test was intended to be 6 x 9.8m/s^2, since our preliminary seismic PSA analysis showed that if the fragility capacities of the electric panels are 5 x 9.8m/s^2 to 6 x 9.8m/s^2, the CDF value would decrease to about 50% of the current value and it would be saturated on further high fragility.

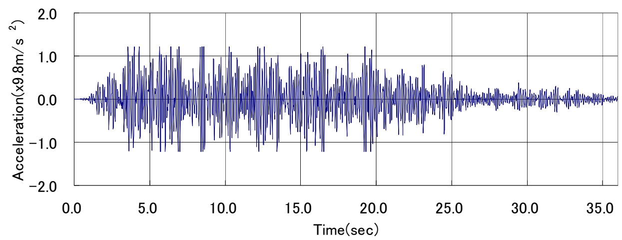

Fig.2-1 Basis Seismic Wave

The Tadotsu shaking table didn't have the capability for high-level acceleration, so JNES introduced an acceleration amplifying system. It mainly consisted of an actuator and a small shaking table (5m x 5m). They were mounted on the Tadotsu large shaking table (15m x 15m) and the actuator moved the small shaking table in synchronization with the large shaking table. The maximum loading capacity of this system was 10tons and the maximum acceleration on the small shaking table reached 6 x 9.8m/s^2. The element tests were conducted with the shaking tables of the electric panel manufacturers.

2.4 Schedule

This project started in fiscal 2002. The actual equipment test and the element test mainly took place in fiscal 2003, and the evaluation of test the results was conducted in fiscal 2004. Additional element tests and comprehensive evaluations were conducted in fiscal 2005.

3. TEST

3.1 The Actual Equipment Test

(1) Test Specimen

Table 3-1 shows electric panels for the actual equipment test. A main control board, a reactor auxiliary control board, a logic circuit control panel, a reactor protection rack, an instrumentation rack, a reactor control center, a power center and a metal-clad switchgear (6.9kV) were all tested. Before the fragility test, the natural frequency of each panel was obtained from a resonance curve of a random wave excitation test on low acceleration. Each of the panels indicated that the natural frequency was higher than 20Hz. Those panels are also illustrated in Figure 3-1a to Figure 3-1h. The overview of the actual equipment test is shown in Figure 3-2.

Table3-1 Electric Panels for the Test

PANEL	SIZE(m) W x H x D	WEIGHT(kg)	FREQ.(Hz)
Main Control Board	2.65 x 1.01 x 1.35	1010	44 (S-S)
Reactor Auxiliary Control Board	2.1 x 2.3 x 2.6	2580	31 (S-S)
Logic Circuit Control Panel	1.0 x 2.3 x 1.0	750	22 (S-S)
Reactor Protection Rack	1.8 x 2.3 x 0.9	2160	29 (S-S)
Instrumentation Rack	2.3 x 1.9 x 0.6	670	33 (S-S)
Reactor Control Center	0.8 x 2.3 x 0.8	640	36 (F-B)
Power Center	1.8 x 2.3 x 2.0	4050	24 (S-S)
6.9kV Metal-Clad Switchgear	2.0 x 2.3 x 2.5	5600	21 (S-S)

S-S: Side-to-Side, F-B: Front-to-Back

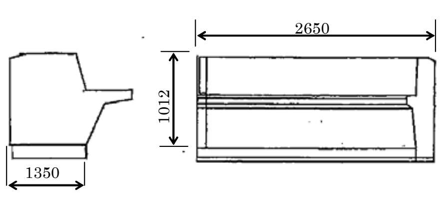

Fig.3-1a Main Control Board

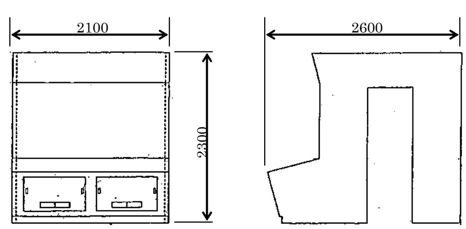

Fig.3-1b Reactor Auxiliary Control Board

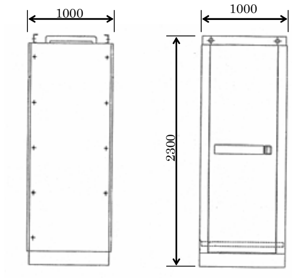

Fig.3-1c Logic Circuit Control Panel

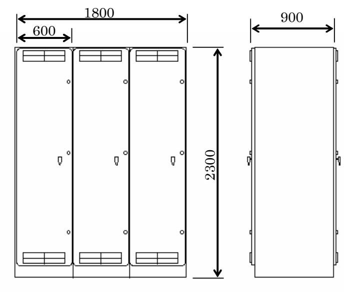

Fig.3-1d Reactor Protection Rack

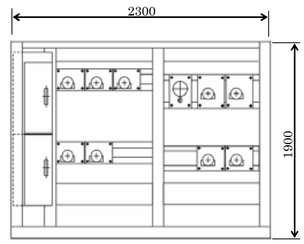

Fig.3-1e Instrumentation Rack

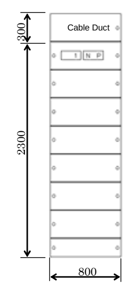

Fig.3-1f Reactor Control Center

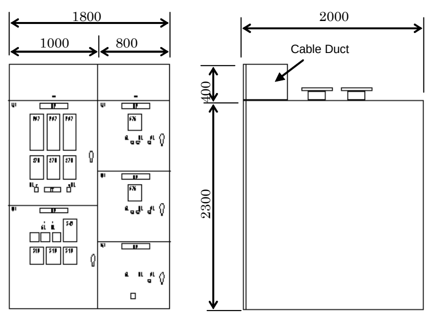

Fig.3-1g Power Center

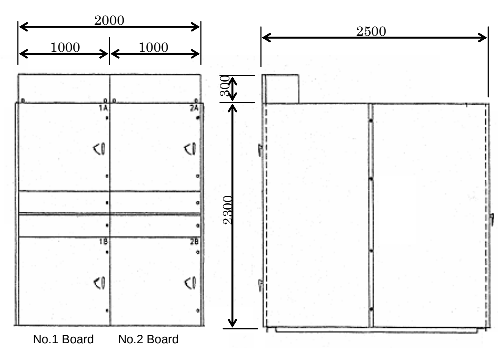

Fig.3-1h 6.9kV Metal-Clad Switchgear

(2) Test Methods

Table 3-2 shows the test conditions of the actual equipment test. Test specimens were vibrated with the seismic wave shown in Figure 2-1 in the direction of front to back and side to side, and input acceleration gradually increased from design level to 6 x 9.8m/s^2. Each panel simulated operating electrical condition but the electric power panels such as the metal-clad switchgear were tested with a smaller current in the consideration of safety.

In the test, each panel was checked whether it was able to maintain its own function or whether it acted normally during vibration.

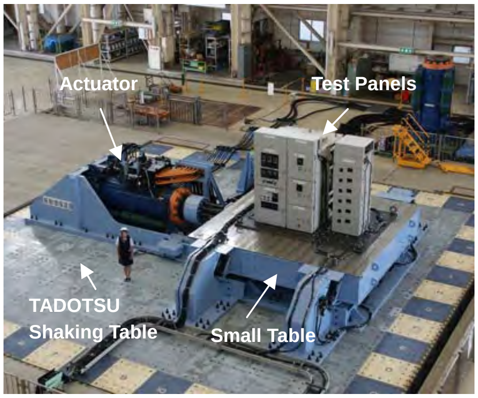

Fig.3-2 Overview of the Test

(3) Test Results

The Summary of test result is described in Table3-3. Even though the maximum acceleration rose up to 6 x 9.8m/s^2, the main control board, the instrumentation rack, the reactor auxiliary control board and the logic circuit control panel kept their functions.

Table3-2 Test Conditions

ITEM	CONDITION
Basis Seismic Motion	Fig.2-1
Input Acceleration	Maximum Acc. : Design level to 6×9.8m/s^2
Vibration Direction	Side-to-Side Front-to-Back

Loss of function occurred on the reactor protection rack, the reactor control center, the power center and the metal-clad switchgear.

Failure modes of those panels were as follows:

- Reactor control center
  Chatter of auxiliary relays caused an error of the magnetic contactor at 6.1 x 9.8m/s^2 input acceleration. (F-B)
- Reactor protection rack
  Chatter of miniature relays on AC controller caused malfunction of panel at 4.3 x 9.8m/s^2. (S-S)
- Power center
  An air circuit breaker abnormally closed due to unexpected vibration of manual close button at 3.7 x 9.8m/s^2. (F-B)
  Structural damage of the air circuit breaker occurred at 5 x 9.8m/s^2. (F-B)
- 6.9kV Metal-clad switchgear
  A grounded potential transformer (GPT or earthed voltage transformer: EVT) malfunctioned when the fuses fell out at 2.5 x 9.8m/s^2. (F-B)
  Structural damage of a vacuum circuit breaker occurred at 4.1 x 9.8m/s^2. (S-S)

Those tests showed that malfunction of the electric parts happened before damage of the panel structure. To be more precise, an error or damage happened on an electrical part when the input acceleration increased, and it caused the malfunction of electric panel.

Table 3-3 Summary of Test Results

PANEL	TEST RESULTS	INPUT ACCELERATION (×9.8m/s^2)
Reactor Control Center	Error of magnetic contactor caused by auxiliary relay chatter	6.1 (F-B)
Reactor Protection Rack	Error of AC controller card (relay error)	4.3 (S-S)
Power Center	Error of breaker closing	3.7 (F-B)
	Damage of air circuit breaker	5.0 (F-B)
6.9kV Metal-Clad Switchgear	Fall out of fuses from GPT	2.5(F-B)
	Damage of vacuum circuit breaker	4.1 (S-S)
Main Control Board	No Malfunction	6 (S-S), (F-B)
Reactor Auxiliary Control Board		
Logic Circuit Control Panel		
Instrumentation Rack		

3.2 The Element Test

(1) Test Specimen

JNES selected about thirty different kinds of electric parts which perform important functions for the panel.

Table3-4 lists electric parts for the element test. The number of the specimens was either three or nine in principle so that fragility deviation could be investigated. The specimen was located on a support structure. Installation methods of the specimen to the support structure such as the number of bolts, bolt size was prepared to be the same as with real equipment.

Table3-4 Electric Parts for the Element Test

PARTS	TYPE	NUMBER	PARTS	TYPE	NUMBER
protection relay	TUB-2-D	3	monitor module	S9146AW	3
protection relay	CO-18-D	9	Power unit	TFV	3
protection relay	VCR62D	3	Power unit	S9980UD	1
auxiliary relay	NRD-81	9	differential pressure transmitter	EDR-N6L	4
auxiliary relay	UP3A	9	pressure transmitter	EPR-N6L	1
auxiliary relay	MY4Z	9	differential pressure transmitter	AP3107	3
timer	H3M	9	differential pressure transmitter	UNE13	3
comparator card	HALN	3	magnetic contactor	MSO-A80	9
AC controller card	HASN	3	magnetic contactor	C-20J、T-20J	9
flat display	18inch type	3	molded case circuit breaker	NF100-SH	9
controller	18inch type	3	molded case circuit breaker	SH100	9
controller(CPU)	TOSMAP	3	molded case circuit breaker	F type	9
I/O unit	TOSMAP	3	module switch	SSA-SD3-53	9
test module	S9166AW	3	cam-operated switch	MS	9
power module	S9016AW	3	key switch	ACSNK	9

(2) Test Methods

Table 3-5 shows the test conditions of the element test. In general, input seismic waves which act on electric parts vary depending on the difference of panel structure or installed position. The seismic waves for the element test were obtained by response analysis of eight kinds of electric panels used for the actual equipment test. The test specimens were vibrated in the direction of front to back and side to side, and input acceleration gradually increased from design level to about 10 x 9.8m/s^2. Each electric part was checked whether it was able to maintain its own function or whether it acted normally during vibration. Regarding relays, the failure was determined when chattering time lasted more than 2ms referencing IEEE standard.

Table3-5 Element Test Condition

ITEM	CONDITION
Basis Seismic Motion	From response analysis of electric panels
Input Acceleration	Maximum Acc. : Design level to 10×9.8m/s^2
Vibration Direction	Side-to-Side Front-to-Back

Table 3-6 Specimens for the Additional Test

PARTS	TYPE	NUMBER
earthed voltage transformer (improved)	VTZ-E6EP	1
air circuit breaker	B10-1	1
air circuit breaker	DS-416	1
gas circuit breaker	6-SFG-40S	1

(3) Additional Element Test

JNES conducted additional element tests on the GPT (or earthed voltage transformer) and circuit breaker. On the actual equipment test of metal-clad switchgear, when it was vibrated in the direction of front-to-back, fuses on GPT slid and fell out. After the test, a countermeasure such as fuse slide stopper to prevent them from falling out was considered. And the improved GPT was tested in order to confirm seismic proof.

Since the actual equipment test suggested that the fragility capacity of circuit breaker was relatively low, additional tests were carried out to get fragility data of other circuit breakers. Table 3-6 lists the specimens for the additional element test. The listed circuit breakers are different types from those of power panels used in the actual equipment test.

(4) Test Results

The malfunction occurred on the relays, circuit breakers and GPT. Table 3-7 shows the malfunctioned parts. The table includes the fragility which was obtained from the actual equipment test. The median and the log standard deviation (β) of fragility were calculated from test results of the protection relay (TUB-2-D), the auxiliary relay (NRD-81) and the AC controller card (HASN). In the case where malfunction happened at same acceleration level, β is equal to zero. As for the circuit breakers and GPT, the medians mean average value of functioned acceleration and malfunctioned acceleration, and the deviations were not calculated because the number of specimens was only one.

Other electric parts kept their functions even though input acceleration increased to about 10 x 9.8m/s^2. The maximum input acceleration for each part is shown in Table 3-8.

In the additional test of the improved GPT, it functioned under more than 9 x 9.8m/s^2 acceleration. Regarding the air circuit breaker (DS-416), since the unexpected vibration of the manual close button caused an error of closing, a countermeasure to fix it was performed. And the improved DS-416 kept its function under about 8 x 9.8m/s^2 acceleration.

Table 3-7 Test Results (Malfunction Parts)

PARTS	TYPE	FRONT-TO-BACK		SIDE-TO-SIDE		Failure
		Median(x9.8m/s^2)	β	Median(x9.8m/s^2)	β	
protection relay	TUB-2-D	9.5	0.13	10.0[*2] (NM)		chatter
auxiliary relay	NRD-81	5.9	0	10.6[*2] (NM)		chatter
AC controller card	HASN	9.9[*2] (NM)		8.3	0.17	chatter of miniature relay
air circuit breaker	DS-416	3.8	–			error of closing
air circuit breaker[*1]	DS-840	3.3	–			error of closing
vacuum circuit breaker[*1]	VF-6M63	4.4	–	8.4	–	structural damage
gas circuit breaker	6-SFG-40S	3.5	–	6.7[*2] (NM)		structural damage
earthed voltage transformer[*1]	VTZ-E6EP	2.5	–	8.8	–	Fall out of fuses

*1; From actual equipment test, *2; Maximum test acceleration, NM ; No malfunction

Table 3-8 Test Results (No Malfunction Parts)

PARTS	TYPE	MAX. TEST ACCELERATION (x9.8m/s2)	
		FRONT-TO-BACK	SIDE-TO-SIDE
protection relay	CO-18-D	10.6	10.0
protection relay	VCR62D	12.0	12.7
auxiliary relay	UP3A	11.0	11.5
auxiliary relay	MY4Z	10.1	10.0
timer	H3M	10.1	10.0
comparator card	HALN	9.9	9.5
flat display	18inch type	10.2	9.5
controller	18inch type	10.4	10.4
controller(CPU)	TOSMAP	10.8	10.9
I/O unit	TOSMAP	10.6	10.6
test module	S9166AW	10.5	10.1
power module	S9016AW	10.5	10.1
monitor module	S9146AW	10.5	10.1
power unit	TFV	11.0	10.2
power unit	S9980UD	10.5	10.1
differential pressure transmitter	EDR-N6L	10.0	10.1
pressure transmitter	EPR-N6L	10.4	10.1
differential pressure transmitter	AP3107	10.5	10.5
differential pressure transmitter	UNE13	10.0	10.0
magnetic contactor	MSO-A80	9.7	10.1
magnetic contactor	C-20J、T-20J	10.3	10.0
molded case circuit breaker	NF100-SH	9.8	9.6
molded case circuit breaker	SH100	10.4	10.1
molded case circuit breaker	F type	10.1	10.0
module switch	SSA-SD3-53	10.3	9.9
cam-operated switch	MS	10.1	10.0
key switch	ACSNK	10.1	10.0
air circuit breaker	B10-1	9.1	10.1
air circuit breaker (improved)	DS-416	7.9	
earthed voltage transformer (improved)	VTZ-E6EP	9.4	10.3

4. FRAGILITY ESTIMATE

4.1 Summary of Activity

JNES tested eight types of representative electric panels. Test results would be made available to be directly adopted to the electric panels used for current nuclear power plants but since there are many kinds of electric panels, it is more than likely that more precise fragility data of individual panels would be desired so as to have the seismic PSA carried out.

JNES proposed an evaluation method to help PSA engineers calculate the fragility of arbitrary kinds of electric panels.

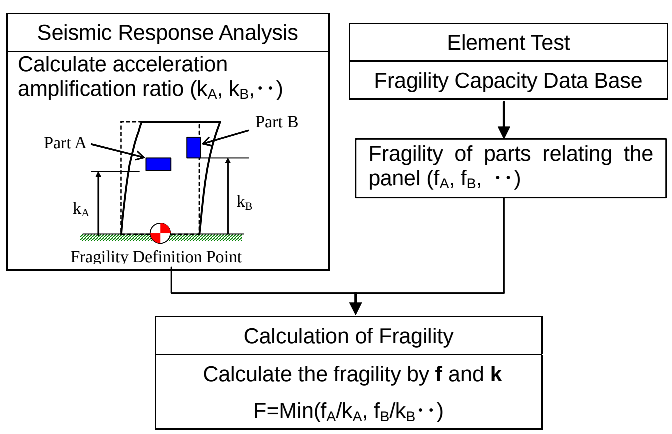

Fig.4-1 Flow of Evaluation Method

4.2 Evaluation Method

(1) Method Description

Test results of the actual panels indicate that malfunction of electric panels is caused by the malfunction of installed parts and damage of panel structure doesn't precede electrical malfunction.

Figure 4-1 conceptualizes the method for evaluating the fragility of electric panels. In our method, the fragility of the panel is defined at its foundation. The method has the feature to use fragility data of the electric parts and the acceleration amplification ratios by analysis. The fragility of the electric part is based on the element test results. The acceleration amplification ratio of the panel position in which a part installed is obtained from the FEM analysis. When the fragility of part *A* is f_A and the corresponding amplification ratio of panel position is k_A, the part *A* offers the fragility of the panel as f_A/k_A. And the fragility of the panel could be estimated at the minimum value of f / k.

(2) FEM Analysis

JNES made 3-dimentional FEM models to calculate local response acceleration of panels where critical parts were located. In the actual equipment test, most panels exhibited a decrease of natural frequency in response to an increase of the vibration level. The panel structure mainly consisted of frames and plates, but only the welded elements were under consideration for the FEM model. Bolted panels were not modeled, just the weight was being considered. We calculated response acceleration of each panel used for the actual equipment test and compared it with test results.

The analysis showed that the 3D FEM models could properly simulate vibration characteristics of the panel on high acceleration.

(3) An Example of Application

We describe in an example application of the evaluation method to the reactor control center (RCC) which was used for the actual equipment test. In the case of this panel, molded case circuit breakers (NF100-SH), auxiliary relays (NRD-81) and other electric parts were installed and the fragility data of them was obtained from the element test. The acceleration amplification ratio of the panel structure can be calculated through the FEM analysis. Figure 4-2 shows a FEM model of the reactor control center and Table 4-1 provides the evaluation results. In this case, the minimum value of f over k is decided from front-to-back direction data of the auxiliary relay. Precisely speaking, the fragility of auxiliary relay (NRD-81) is 5.9 x 9.8m/s^2 and the acceleration amplification ratio is 1.3. Consequently, we can estimate the fragility of the reactor control center at 4.5 x 9.8m/s^2.

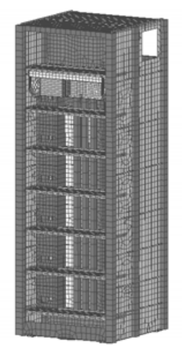

Fig.4-2 FEM Model of RCC

Table 4-1 Evaluation Result of RCC

CRITICAL PART	ESTIMATED ACCELERATION (BASE OF PANEL)
Auxiliary Relay	4.5x9.8m/s2 (F-B)

4.3 Evaluation Results

JNES applied the evaluation method to other electric panels which were tested on the actual equipment test. The fragility capacities of eight panels are shown in Table 4-2. The estimated acceleration of the malfunctioned panels is closely consistent with the results of the actual equipment test. As for the power center and the metal-clad switchgear, they were estimated on the premise of the application of the improved air circuit breaker and the improved GPT respectively. In the case of panels that kept their function, the fragility resulted in a conservative evaluation. Because the fragility of the electric parts installed in those panels was conservatively decided from the maximum input acceleration of the element tests, even though those parts didn't malfunction on the tests.

Table 4-2 Evaluation Results of Electric Panels

TEST PANELS	ESTIMATED ACCELERATION (x9.8m/s^2)	CRITICAL PARTS
Main Control Board	5.6 (S-S)	display system
Reactor Auxiliary Control Board	9.8 (F-B)	module switch
Logic Circuit Control Panel	6.7 (S-S)	power unit
Reactor Protection Rack	4.4 (S-S)	AC controller card
Instrumentation Rack	4.2 (S-S)	differential pressure transmitter
Reactor Control Center	4.5 (F-B)	auxiliary relay
Power Center	4.4 (F-B)	air circuit breaker
6.9kV Metal-Clad Switchgear	4.2 (S-S)	vacuum circuit breaker

5. CONCLUSION

JNES carried out vibration tests on the electric panels on high acceleration in order to realistically grasp their fragility capacity. Eight kinds of electric panels pertaining to the safety systems were tested. Main control board, instrumentation rack, reactor auxiliary control board and logic circuit control panel kept their functions even though the input acceleration was 6 x 9.8m/s^2. Regarding the reactor protection rack, reactor control center, power center and 6.9kV metal-clad switchgear, the loss of function occurred at below 6 x 9.8m/s^2. The testing found that errors or damage of the electric parts caused the malfunction of those panels.

JNES also tested about thirty different kinds of electric parts that were considered as weaknesses from the viewpoint of seismic conditions and obtained their fragility data. In the element test, some kinds of relays and circuit breakers malfunctioned.

Since there are many kinds of electric panels in nuclear plants and it is likely that more precise fragility data of individual panels would be desired to carry out the seismic PSA, JNES proposed a generalized method for evaluating the fragility of electric panels. The method has the feature to use the fragility data of electric parts and the acceleration amplification ratios from the FEM analysis. The evaluation method was applied to the main electric panels and calculation results were closely consistent with the actual equipment test results.

JNES obtained precise fragility capacities of main electric panels which had significant effect on CDF through the tests and analysis. Those seismic fragility capacity data is going to be incorporated into our seismic PSA, and it is expected that the reliability of the seismic PSA will increase.

Acknowledgments

This task has been performed by JNES as a national project with the review of the technical committee that is comprised of learned and experienced specialists.

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