EVALUATION OF JNES FRAGILITY TESTS FOR USE IN SEISMIC PROBABILISTIC RISK ASSESSMENT FOR U.S. NUCLEAR POWER PLANTS: AN OVERVIEW

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ABSTRACT

In seismic probabilistic risk assessments (SPRAs), high quality seismic equipment fragility data are very important in achieving accurate quantification of the risk of nuclear power plants (NPPs) during beyond-design-basis earthquakes. The need for high quality seismic equipment fragility data led to many industry and the U.S. Nuclear Regulatory Commission (NRC) sponsored research programs, the results of which are still being applied in current SPRAs. Fragility capacities and the associated uncertainties of the most critical equipment items have historically been derived from qualification test data from equipment vendors. In situations when specific qualification data may not be readily available, generic component capacity data are commonly used. However, it has been extremely rare, except perhaps in the case of relays, that fragility data is directly obtained from full-scale tests of equipment under seismic excitations that greatly exceed the design basis earthquake. The U.S. NRC and Brookhaven National Laboratory (BNL) are currently evaluating the full-scale equipment fragility tests performed by the Japan Nuclear Energy Safety Organization (JNES). This paper presents an overview of the first part of this evaluation and the corresponding major results.

INTRODUCTION

As part of collaborative efforts between the United States and Japan on seismic issues, the U.S. NRC and BNL are currently evaluating the Japanese equipment fragility tests for use in SPRA for U.S. NPPs. The full-scale equipment fragility tests used in this evaluation were performed by JNES. The unique advantage of this particular collaborative effort is obvious because of the rareness of full-scale high-level seismic equipment fragility data.

The JNES equipment fragility test program is a multi-year program to obtain realistic equipment fragility capacities for use in SPRAs of nuclear power plants in Japan. This test program started in 2002 and is planned to continue until 2012. The purpose of this test program is to improve the quality of the seismic fragility capacity database by determining realistic equipment fragility capacities from full-scale shaking table tests, and consequently to allow more accurate SPRAs to be performed to quantify the risk of NPPs during beyond-design-basis earthquakes. This test program reflects a philosophical shift from the design-proving test in the past that was intended to demonstrate the success of equipment during design basis or slightly larger earthquakes, to the current fragility test that determines the (ultimate) seismic capacity under beyond-design-basis earthquakes. This program consists of the test of a series of safety significant equipment, which are scheduled in two phases. Phase I includes large horizontal shaft pumps, large vertical shaft pumps, electrical panels, and control rod insertion capability and Phase II includes fans, valves, tanks, support structures, and overhead cranes.

The NRC/BNL evaluation study compares the JNES fragility results with the fragility data typically used in current U.S. SPRAs and assesses the impact that the new test results may have on current SPRAs and how this data can be utilized for future SPRAs. The quality of seismic fragility capacity directly affects the quality of SPRAs in quantifying the risk of NPPs during beyond-design-basis earthquakes. The need for high quality seismic equipment fragility data led to many industry and U.S. NRC sponsored research programs, the results of which are still being applied in current SPRAs. Fragility capacities and the associated uncertainties of the most critical equipment items have historically been derived from qualification test data from equipment vendors. However, in situations when specific qualification data may not be readily available, generic component capacity data are commonly used.

Albeit the amount of the generic fragility data is large, it has been extremely rare, except perhaps in the case of relays, that fragility data is directly obtained from full-scale tests of equipment under seismic excitations that greatly exceed the design basis earthquake. In the equipment qualification tests, from which some high quality equipment fragilities have been derived, the input seismic waves are only at or slightly higher than the design basis earthquake. The prohibitive cost associated with full-scale seismic fragility tests is the major reason for the

unavailability of high excitation level test-based fragility data. The JNES equipment fragility test program is a very comprehensive and conscientious effort to determine realistic seismic equipment fragility capacities based on full-scale high-level shaking table tests.

This paper presents an overview of the NRC/BNL evaluation study of the JNES Phase I equipment fragility tests. More details can be found in NUREG/CR-7040 [1]. It should be noted that the results of this evaluation may be immediately applicable to the ongoing review of the seismic margin analyses (SMAs) for design certification (DC) or combined license (COL) applications. The Phase I JNES Equipment Fragility tests will be briefly described and the major findings from this evaluation will be summarized in the following.

OVERVIEW OF JNES PHASE I EQUIPMENT FRAGILITY TESTS

The true (realistic) equipment seismic fragility capacities have not been widely available because it is prohibitively costly to determine such capacities using high level shaking tests of full-scale equipment. Therefore, in order for JNES to make the equipment fragility tests more achievable, element (device) tests, analyses, and use of some existing data are required along with the full-scale tests to establish the final fragility values. For each selected equipment category, only one or two representative full-scale equipment specimens were tested. The main purpose of the full-scale tests was to identify critical accelerations and failure modes of the equipment. The purpose of the element tests was to evaluate threshold acceleration of individual parts and the median and standard deviation of the test results. The element tests were conducted with many samples, and therefore their median capacity and the associated variation were able to be determined statistically. For some cases, the variability was specified as those reported in the industry codes and standards. Based on the full-scale test results, analyses combined with element tests were performed to calculate the fragility capacities.

Some of the JNES equipment fragility tests were conducted at the TADOTSU shaking table of NUPEC. The TADOTSU shaking table has a plan dimension of 15 m × 15 m. Some of the test results were limited to the table capacity and therefore only function confirmed (FC) capacities were achieved. For some of the full-scale equipment tests and the element tests, higher acceleration input was required to identify their seismic fragility capacity. To this end, a vibration amplifying system was installed on top of the TADOTSU shaking table, as shown in Fig. 1. The amplification table has a plan of 5 m × 5 m. The combined input acceleration capacity of the TADOTSU shaking table and the amplification table can reach about 6 g around 10 Hz [2].

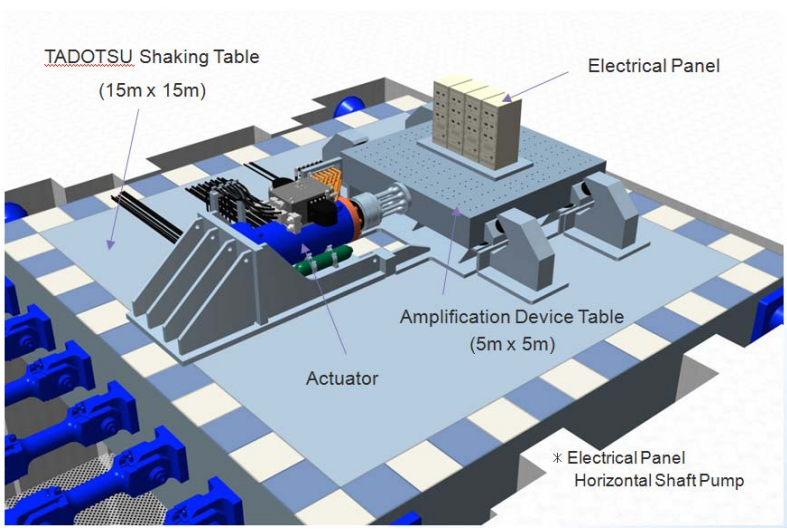


Fig. 1: TADOTSU Shaking Table and the Amplification Table

The input acceleration level was determined from JNES's sensitivity analysis of core damage frequency (CDF). For example, it was shown in a preliminary SPRA that if the critical acceleration of a large horizontal shaft pump is higher than 4g or 5g, the CDF was decreased by half. This finding was used to determine how much the capacity of the TADOTSU shaking table should be increased by an amplification table [2].

The JNES Phase I program was conducted from FY 2002 to 2005 (Japan). The JNES equipment fragility test program consists of a series of important equipment that were determined in a seismic probabilistic safety analysis (PSA) to be safety significant according to their effect on core damage frequency. The phase I test program includes large horizontal shaft pumps, large vertical shaft pumps, electrical panels, and control rod insertion capability. The fragility test equipment were typical for boiling water reactor (BWR) and pressure water reactor (PWR) plants in Japan.

Two limit states were considered for the fragility analysis for the Phase I equipment: (1) structural damage should not occur; (2) loss of active function should not occur during earthquake. Examples of active function include rotation for horizontal and vertical pumps, electrical state change for electrical components, and control rod insertion.

Horizontal Shaft Pump Tests

A reactor building closed cooling water (RCW) pump used in Japan BWR plants was selected as a representative single stage horizontal shaft pump for full-scale test. This pump has a flow rate of 1250 m3/h, a length of 2.8 m, and a height of 1.5 m; and weighs 5.7×103 kg. Fig. 2 shows the layout of the full-scale RCW pump test system, which included the RCW pump, an electric motor, piping, valves, a tank, and power cabinets. It should be noted that the RCW pump and the motor were installed on top of the amplification table while other test elements were sitting on top of the main shaking table. The pump was tested in axial and transverse directions for both operating and standby conditions, with a peak acceleration gradually scaled from 2g to 6g. No damage was found up to the maximum input acceleration level of 6g, and no obvious decrease of performance was observed as well in terms of flow rate and head [3].

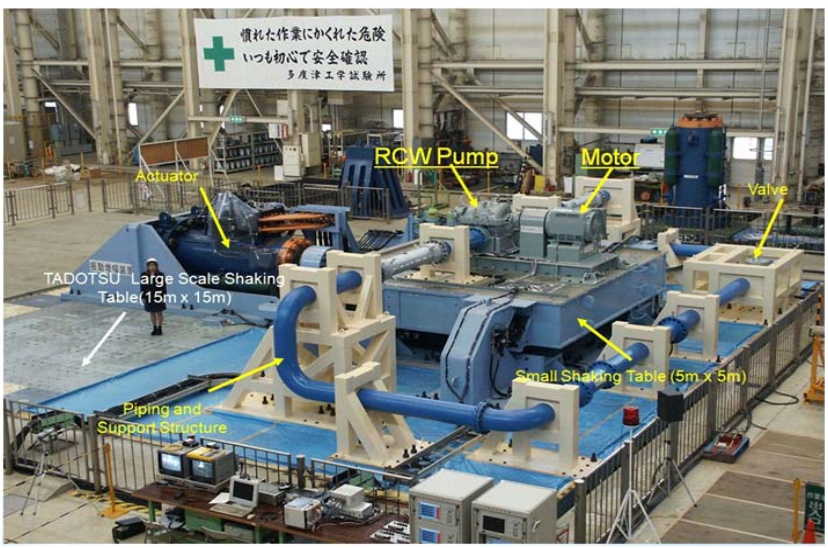


Fig. 2: RCW Pump Test Layout

Bearings and liner rings from both single stage and multi-stage horizontal shaft pumps were selected for the element tests. Liner rings were reported to have lower seismic margin than other parts and can be damaged due to impact between liner rings and the impeller during transverse vibration. Although bearings generally have high seismic margin, they are selected because they are the very fundamental parts for the pump's rotational function. Tested bearings included radial and thrust bearings of ball and slide types.

Large Vertical Shaft Pump Test

Fig. 3 shows the test setup for the RHR pit barrel pump installed on the TADOTSU shaking table. The RHR pump stands above the top of the shaking table for 7 m (mainly motor and motor stand) and below the table for 8 m (mainly the pump and pump barrel). The RHR pump has a flow rate of 1691 m3/h, a head of 92 m, and a mass of 61×103 kg (about 49×103 kg for pump and 13×103 kg for motor). The test specimen also included piping and

other components in order to simulate the operating condition. The diameter of the barrel support varied in the test such that the diametric clearance had a value of 1 mm, 2 mm, or 4 mm, depending on the test purposes. Both horizontal and vertical excitations, while applied separately, were considered for normal operating conditions and shutdown conditions. Multiple simulated seismic waves utilized in the test had different frequency characteristics to investigate different parts of the pump system, e.g., one horizontal wave for barrel without gap (16.1 Hz) and another horizontal wave for barrel body (6.4 Hz).

Fig. 3: Test Setup for Vertical Shaft Pump

The element tests included large and small size carbon bearings, solid lubricant distributed oilless bearings, resin bearings, rubber bearings, Kingsbury type thrust bearings, parallel plane type thrust bearings, and liner rings of two sizes.

Electrical Panels

Eight electrical panels were selected for the JNES full-scale tests: (1) main control board (BWR), (2) reactor auxiliary control board (PWR), (3) logic circuit control panel (BWR), (4) instrumentation rack (BWR), (5) reactor protection rack (PWR), (6) reactor control center (PWR), (7) power center (PWR), and (8) 6.9 kV metal-clad switchgear (BWR). The fundamental frequencies of these electrical panels were in a range of 21 Hz to 44 Hz. Fig. 4 shows the electrical panels sitting on the amplification table. The electrical panels were shaken in both front-to-back and side-to-side directions. Each panel was tested in the simulated operating condition, with some being tested with smaller current for safety reasons.

There were extensive element tests for electrical panels, including more than 30 different types of electrical parts (devices). Most of the tested devices performed normally up to the maximum input accelerations, which were mostly about 10g. Malfunction occurred for eight types of devices during the test.

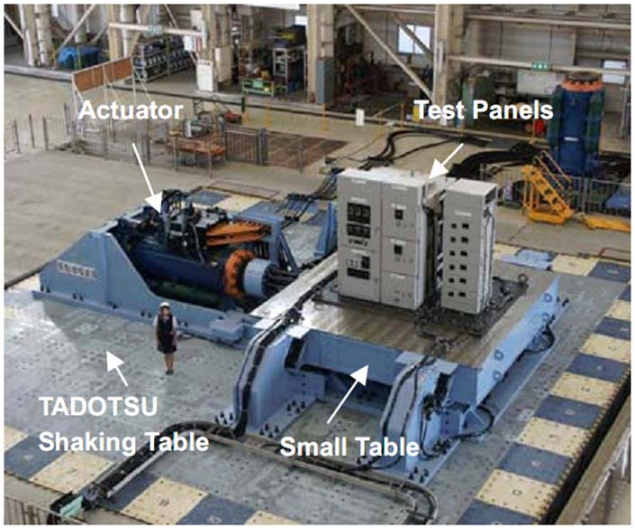
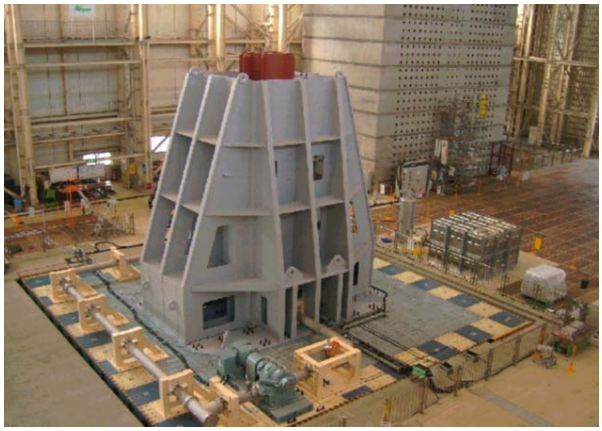


Fig. 4: Test Setting for Electrical Panels

Control Rod Insertion Capability

Both PWR control rod insertion capability and BWR control rod insertion capability were tested in full scale, as shown in Fig. 5. For the PWR control rod insertion capability test, the main test components included the fuel assemblies, control rod, and control rod drive mechanism (CRDM), which were all manufactured with the same specification as in representative 3/4 loop PWR plants except for the material of the fuel pellets. The test specimen stands above the top of the shaking table for 10 m (mainly the CRDM) and below the table for 6.3 m (mainly the fuel assemblies and control rod). The fuel assemblies and the control rod were enclosed in a cylindrical vessel, which was supported by tie rods connecting to a very sturdy frame above the shaking table and to the shaking table under the table. A pump flow loop was installed for the investigation of the effect of core flow on the control rod insertion.

For the BWR control rod insertion capability test, the main test components, consisting of the fuel assemblies, control rod, and CRDM, were also manufactured with the same specification as in representative BWR plants (BWR5) with 100 mil channel boxes, except for the material of the fuel pellets. The test specimen stands above the top of the shaking table for 9.3 m (mainly the fuel assemblies and control rod) and below the table for 3.8 m (mainly the CRDM). The four fuel assemblies and the control rod were enclosed in a cylindrical vessel, which was supported by tie rods connecting to a very sturdy frame above the shaking table and to the shaking table under the table.



(a) PWR Control Rod Insertion System

(b) BWR Control Rod Insertion System

Fig. 5: Test Setups for PWR Control Rod Insertion System and for BWR Control Rod Insertion System

EVALUATION OF THE EQUIPMENT FRAGILITY DATA

The purpose of this evaluation is to compare the JNES fragility results with the fragility data typically used in current U.S. seismic probabilistic risk assessments (SPRAs) and assess the impact that the new test results may have on current SPRAs and how this data can be utilized for future SPRAs. One of the primary objectives of these JNES tests was to test full-scale components at shaking levels significantly higher than the function confirmed qualification tests to which they had previously been subjected. Therefore, these tests greatly improve the median fragility estimates for the specific components tested. In this regard, they provide a very valuable addition to the available fragility database for U.S. NPPs. However, an open question exists as to how well this JNES fragility data can be extrapolated to similar components in U.S. NPPs.

These full-scale component tests were generally limited by the shake table capability to about 6.0g zero period acceleration (ZPA). If no functionality anomaly occurred prior to reaching the upper limit of the testing, a function confirmed (FC) capacity was reported. In this case, no fragility level was actually found, and the reported median fragility was set either at or only slightly above the FC capacity. For situations where a functional anomaly was observed, the reported median fragility was set midway between the highest ZPA level for which no functional anomaly occurred, and the ZPA level at which the anomaly occurred.

It can be stated categorically that a very comprehensive and conscientious effort appears to have been performed to develop realistic median fragility estimates for the specific components being considered. Therefore, it can be concluded that the median fragilities obtained from the JNES equipment fragility tests are reasonable for the specific components considered in each of the four classes.

Of course, higher fragility capacities can generally be justified for any specific component by a detailed review of the qualification test data and/or stress analyses performed on that specific component. However, for many components included in CEUS SPRAs, this additional effort is not performed and generic fragilities are used instead. For higher seismic sites, these generic fragilities are generally not used. Generic fragilities in CEUS SPRAs are defined in terms of a broad frequency 5% damped spectral acceleration (SA) at the base of the component. The comparison of generic fragilities (in SA) to the JNES fragilities (in ZPA) utilized an approximate relationship: $SA \approx 2.4 \times ZPA$.

It should be noted that the response spectrum shape used in the JNES tests was very different from the broad frequency response spectrum shape used to define U.S. generic fragilities. In the JNES tests, highly amplified and narrow band response spectra were used considering the characteristics of the shaking table performance, vibrational characteristics of the specimens, and design response spectrum to get the most influencing and higher excitations. The response spectra typically peaked in the 7 to 10 Hz frequency range. The difference in spectra shapes makes it more difficult to make an appropriate comparison between the JNES test results and the U.S. generic fragilities reported. It was considered to be most appropriate, on average, to convert the JNES reported ZPA fragilities to equivalent broad frequency 5% damped SA fragilities by using the above relationship for the purpose of these comparisons.

Large Horizontal Shaft Pumps

The JNES tested pump appears to be very similar to RCW pumps in U.S. nuclear plants. Therefore, it is judged that this test result could be used to estimate the median fragility of RCW pumps in U.S. plants. For the tested pump, function was confirmed at a ZPA of 6.0 g, which indicates that the median fragility level should be set at a ZPA level somewhat higher than 6.0g. Based on the element tests and analyses, the following median bearing wear functionality limits (ZPA) were computed by JNES: 8.4 g for the tested RCW pump, 8.6 g for a larger RCW pump, and 17.3 g for a charging injection pump. The median capacity of the pump frame anchorage to the foundation for the three evaluated pumps ranged between ZPA=11.0 g to 28.5 g and were not controlling.

The potentially controlling fragility appears to be slip of the motor on the pump frame due to inadequate torqueing of the mounting bolts and oversize bolt holes. The reported computed (reference) values for this onset of motor slip reference fragility are ZPA=6.1 g, 5.3 g, and 2.6 g, respectively for the tested RCW pump, the larger RCW pump, and the charging injection pump. The onset of motor slip reference fragilities were based on a coefficient of friction of 0.3. There is considerable uncertainty in the coefficient of friction that should be used in these slip calculations. For a specified minimum bolt torque applied to the mounting bolts, there is significant variability in the bolt tension preload. There are limits as to how far the motor might slip due to oversized or slotted bolt holes. It is also not known how much motor slip is likely to damage the pump shaft and/or bearings. This mode may be a controlling functionality failure mode for large horizontal pumps.

For large and critical horizontal pumps such as RCW pumps and charging high pressure injection pumps, it has been common U.S. fragility practice to base their fragility estimate on a review and scaling of the qualification

stress report for the specific pump involved. In addition, the anchorage of the pump frame to the foundation and the capacity of the motor mounting to pump frame are evaluated. The degree of rigor with which motor slip has been assessed, and the parameters used in this assessment have likely varied among fragility analysts.

For lower CEUS seismic regions, and for less critical horizontal pumps, horizontal pumps have often been assigned a ground motion screening level spectral acceleration of SA_{SL} = 1.2g based on EPRI NP-6041-SL [7] screening tables. The median ZPA capacity can be estimated to be only about 2.0 g, which is much less than the function confirmed ZPA = 6.0g obtained in the JNES RCW pump full-scale test. These screening level based fragility estimates are exceedingly conservative for horizontal pumps within our experience. This screening level approach should not be used for risk important horizontal pumps.

Large Vertical Shaft Pump

The JNES tests showed that no loss of function for the tested RHR pump was confirmed at an input ZPA of 1.6 g and a top-of-moter ZPA of 14.0 g for motor, and at an input ZPA of 2.8 g and a bottom-of-barrel ZPA of 31 g for barrel/column. The JNES equipment fragility test indicates that yielding of the motor mounting bolts was confirmed at an input ZPA of 1.5g (top of motor ZPA of 12.0g) and that yielding of the barrel was confirmed at a bottom of barrel ZPA of 31.0. Similarly as for the large horizontal pumps, the lowest reported fragility is a motor slip reference fragility reported in terms of top-of-motor ZPA response (ZPA_{TOM}), which ranged 2.8 g to 6.2 g for four analyzed pumps.

In higher quality fragility analyses, the median fragility of vertical pumps is typically determined by analysis in which median capacities are based on 90% of the fully plastic moment capacity for motor mounting bolts; lower motor stand; and pump barrel, casing, column, or shaft. The JNES large vertical pump test results seem to confirm the reasonableness of this approach. Similar to the large horizontal shaft pumps, the median ZPA capacity can be estimated based on the screen level to be 2.0 g. By comparing to the JNES fragility result, this value should not be used for large critical vertical pumps. Instead, the fragility should be based on pump specific analysis.

Lastly, JNES performed a vertical input seismic shaking on the RHR Pump. The concern is with vertical loads being imposed on the motor thrust bearing, and with lifting the shaft more than the clearance that exists between the impeller and the lower liner ring. For the tested pump, no loss of function was confirmed for a vertical ZPA level of 1.9g. To the best knowledge of the authors, this potential for failure to function of the motor thrust bearing or exceedance of vertical clearance due to vertical shaking has also not been considered in U.S. fragility analyses of vertical pumps.

Electrical Component Fragilities

The median SA fragility levels based on JNES test data for electrical components range between 5.5g and 14.2g. Generic median SA fragilities for similar electrical components range between 2.2g and 5.1g [4, 5]. This comparison indicates that generic fragilities commonly used in U.S. SPRAs for existing CEUS plants might be conservatively biased by more than a factor of two. The JNES test data median SA50% fragility levels for electrical components are comparable to the ALWR "achievable" fragilities from EPRI TR-016780 [6] shown in Table 2 7.

However, considerable caution must be exercised before extending the use of these JNES median fragilities for electrical components to existing electrical components in the U.S. plants. The natural frequencies reported in the JNES equipment fragility test report for all eight tested electrical components ranged between 20 Hz and 50 Hz. All of these electrical components tested by JNES were very stiff and not representative of most similar existing electrical components in U.S. plants. Most of these electrical components in U.S. plants exhibit local panel mode frequencies in the 4 Hz to 15 Hz range when tested at higher shaking levels.

Control Rod Insertion Capability

The input motion and resulting maximum fuel assembly displacement for the PWR control rod were a ZPA = 3.2 g and a displacement = 48 mm. The median functional limit fuel assembly displacement was estimated to be 77 mm and the associated uncertainty was estimated to be 0.19. No input motion level corresponding to the 77 mm fuel assembly displacement was explicitly defined in the JNES equipment fragility test report but can be estimated to be 3.9 g [1].

For the full-scale test of BWR control rod insertion capability, the input motion and resulting fuel assembly displacement were ZPA = 3.0 g and displacement = 83 mm. The median fragility for BWR5 fuel assembly displacement was estimated to be 91 mm and the associated uncertainty was reported as 0.1, which appears to be very low for this complex of a phenomena. The corresponding median input ZPA was estimated to be 3.1 to 3.3 g.

The JNES fragility results are applicable for failure modes associated with fuel assembly displacements. However, these results do not address structural failure modes since the entire assembly was supported by very stiff frames in the test. Within the U.S., control rod insertion fragilities are generally derived based on a detailed review and scaling of Nuclear Steam Supply System (NSSS) vendor submitted qualification reported results. For PWR plants, the derived fragilities are generally controlled by the supports of the control rod drive mechanism. During the JNES test, the control rod drive mechanism was very substantially supported by a very rigid frame. The failure modes that have typically been considered to be controlling in U.S. fragility assessments for control rod insertion could not have occurred during these tests.

CONCLUSION

This paper presents a brief summary of the Phase I equipment fragility test program performed by JNES and an assessment of the fragility data determined from these tests. The JNES Phase I equipment fragility tests included horizontal shaft pumps, electrical panels, control rod insertion capability, and large size vertical shaft pumps. The JNES tests make a valuable contribution to the overall state of knowledge of equipment fragility levels for use in SPRAs. The JNES fragility capacities were determined based on full-scale component tests and element tests under simulated seismic excitations that were much larger than the design basis earthquakes commonly used in previous qualification tests or design proving tests. The fragility levels found in the JNES tests are in general much higher than those used in current U.S. SPRAs. Additional failure modes, such as relative motor slip on pump frame and functional failure of submerged bearings, have been identified for consideration by fragility analysts. These test results should be considered by fragility analysts in performing future SPRAs. However, caution must be applied to assess the applicability of the results to the specific equipment being considered. In particular, an analysis of the component anchorage and support fragility needs to be performed as a necessary supplement to the equipment fragility data for a proper application.

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DISCLAIMER NOTICE

The findings and opinions expressed in this paper are those of the authors, and do not necessarily reflect the views of the U.S. Nuclear Regulatory Commission or Brookhaven National Laboratory.

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