# FRAGILITY ASSESSMENT OF ACR-1000™ NUCLEAR POWER PLANT

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**ABSTRACT:** This paper summarizes the methodology followed for fragility calculations and presents the results of the calculations for a representative structure and equipment of the ACR-1000™. Detailed fragility calculations for the containment structure of the ACR-1000 reactor building, as an example of a key structure, and for a Relay, as an example of equipment qualified by testing are presented. Two cases are used for the seismic input, a typical standard spectrum and uniform hazard spectra.

It was found that for the sample structure and equipment, the seismic margin measured in terms of the HCLPF (High Confidence of Low Probability of Failure) capacity of 0.5g peak ground acceleration is reasonably achievable for the ACR-1000 design. This compares well with the Design Basis Earthquake (DBE) of 0.3g peak ground acceleration for the standard ACR-1000.

## INTRODUCTION

A Probabilistic Based Seismic Margin Assessment (PB-SMA) of ACR-1000 nuclear power plant is planned to be performed. The PB-SMA analysis will require fragility evaluations of a list of safety related structures and components. The fragility of a structure or component is defined as the conditional probability of failure for a given Peak Ground Acceleration (PGA). The seismic capacity of structures and components are commonly defined by a High Confidence of Low Probability Failure (HCLPF) values.

The ACR-1000 standard design is developed such that many potential sites are enveloped. The seismic input is based on the standard design response spectra per Canadian Standard Association standard CAN3-N289.3 (Reference 1). Recent studies have shown that, for rock sites in Eastern North America (ENA), the frequency content of a standard design spectrum e.g. CAN3-N289.3 might be deficient for frequencies above 10 Hz. A Uniform Hazard Spectrum (UHS), in which the amplitude for each frequency corresponding to a specified target probability, should be used at these sites. The UHS is developed for a specific site based on a seismic hazard analysis that models the seismicity, tectonics and soil conditions. Reference 2 provides an approach for developing a typical UHS for ENA.

An important issue facing nuclear power plant designers in North America is the qualification of the plant to the ENA UHS because the UHS has its peak at relatively higher frequency levels than with traditionally used spectra. This paper provides the fragility calculations for a sample structure and component for ACR-1000 plant. The structure chosen is the Reactor Building (RB) Containment Structure (CS) as it is the most important structure for the plant capacity evaluation. The component chosen is a typical Relay that was qualified by testing and was used in previous CANDU plants. It is believed that Relays are one of the components that may be affected by the high frequency input of the UHS (Reference 3). This paper will assess the seismic margin of the CS and Relay versus the seismic demand imposed by the design Response Spectrum developed for ACR-1000 as well the seismic demand imposed by the UHS.

## SEISMIC DEMAND

The fragility calculations for the Containment Structure and the Relay are performed and the seismic margin is assessed for the following two seismic loading conditions:

- The ACR-1000 Ground Response Spectrum (GRS) which is based on CSA N289.3 with minor modifications. The spectrum used is the 5% damping, curve anchored to a Peak Ground Acceleration (PGA) of 0.3 g. It should be noted that this GRS is for rock sites.
- The Uniform Hazard Spectrum (UHS), Reference 2. The spectrum used herein was developed for a rock site in ENA.

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## Fragility Analysis of ACR-1000 Reactor Building Containment Structure

### Fragility Analysis Methodology

The fragility approach detailed in Reference 4 is used in this paper. The following capacity and response factors are considered in the seismic fragility evaluation:

a) Capacity Factors
- Strength Factor
- Inelastic Energy Absorption Factor

b) Structural Response Factors
- Spectral Shape Factor
- Damping Factor
- Modeling Factor
- Modal Combination Factor
- Earthquake Components Combination Factor
- Horizontal Direction Peak Response Factor
- Soil-Structure Interaction Factor

The median factor of safety and variability are calculated for each of the above factors. Variability is defined in terms of randomness ($B_R$) and uncertainty ($B_U$). The overall factor of safety (FS) is the product of all factors of safety. The overall randomness and uncertainty is the root of the sum of squares of all randomness and uncertainty values. The median capacity is defined as $A_M$

$$A_M = FS * DBE \qquad (1)$$

A commonly used value, which describes the seismic capacity of a structure or a component, is the High Confidence Low Probability Failure (HCLPF) value. It represents with a 95% confidence, that the probability of failure of a structure or component will not exceed 5%, and is calculated as follows:

$$HCLPF = A_M * \exp(-1.65(B_R + B_U)) \qquad (2)$$

### Containment Structure

ACR-1000 CS Geometry is shown in Figure 1. Three Locations A, B and C are identified to be the critical locations along the Containment wall height. The first location, A, is at the base of the containment wall. The second location, B, is chosen at the mid-height of the containment wall. The third location, C, is chosen at top of the containment wall at joint with dome. The seismic forces and moments at critical locations of containment wall are determined. Reinforcing and prestressing steel ratios at the three locations of CS are calculated. Also stresses due to dead loads and seismic loads at the three locations of containment are calculated using the results a finite elements analysis.

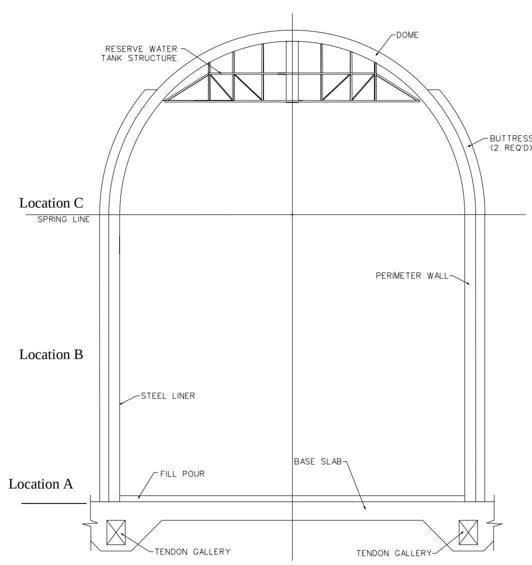


**Fig.1: ACR-1000 Containment Structure**

**Shear Capacity Evaluation**

The predominant failure mode for the CS has been determined to be tangential shearing failure rather than moment failure (Reference 5). The ultimate shear capacity based on test results has widely been used to determine the tangential shear capacity of pre-stressed containment (Reference 5):

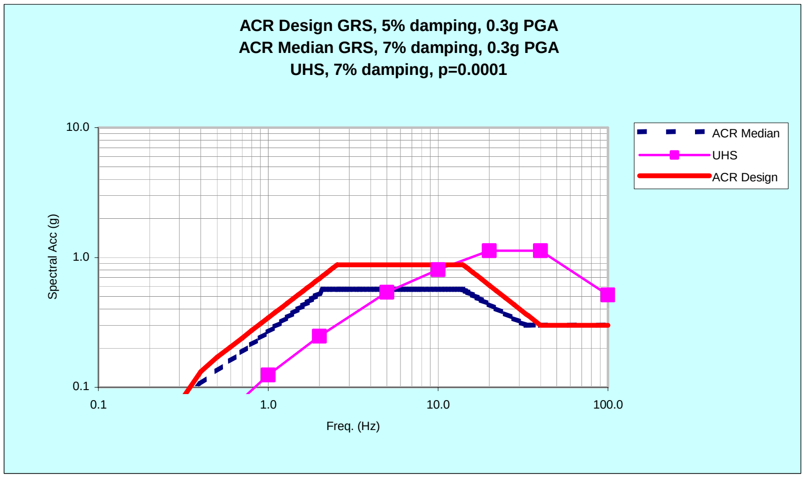



**Fig 2: Comparison Between Different Response Spectra**

**Fragility analysis Using ACR-1000 Design GRS**

The calculations are made to determine the capacity of the ACR-1000 CS using the ACR-1000 design GRS as the basis. Using the approach outlined above, each factor of safety is calculated with its randomness and uncertainty. The uncertainty and randomness values form Reference 4 are used in this study. The results of the calculations are summarized in Table 1.

**Table 1: Median Values, Randomness and Uncertainty for Structural Response Factors**

| Factors | Median Factor | $\beta_R$ | $\beta_U$ |
|---|---|---|---|
| Strength Factor | 4.9 | 0.0 | 0.21 |
| Inelastic Energy Absorption | 2.1 | 0.22 | 0.17 |
| Capacity Factor | 10.28 | 0.22 | 0.27 |
| Spectral Shape | 1.54 | 0.2 | 0.2 |
| Damping | 1.0 | 0.06 | 0.06 |
| Modeling | 1.0 | 0.0 | 0.17 |
| Modal Combination | 1.0 | 0.05 | 0.0 |
| EQ Comp. Combination | 1.0 | 0.05 | 0.0 |
| Horizontal EQ Direction | 0.9 | 0.0 | 0.0 |
| Soil-Structure Interaction | 1.0 | 0.0 | 0.0 |
| Structural Response Factor | 1.386 | 0.22 | 0.27 |
| Factor of Safety | 14.25 | 0.31 | 0.38 |

Using equations (1) and (2), the median seismic capacity of the CS using ACR-1000 GRS is 4.28g and the HCLPF capacity is 1.37g

**Fragility Analysis Using Uniform Hazard Spectrum**

The calculations are repeated to estimate the HCLPF capacity of the ACR-1000 CS but using UHS as the basis for comparison. Changing the design spectrum will not have an effect on the structural capacity factor. Also, for the structural response factor, the only sub-factor affected by switching to UHS is the spectral shape factor.

Correction factors are used from Reference 2 to apply a correction factor for damping from 5% to 7%. To convert to a median curve a factor of 0.78 is used, which is consistent with the findings of Newmark in establishing NUREG-0098 median GRS (Reference 6)

Combining the structure response factor calculated for the UHS with the structural capacity factor calculated before, results in an overall factor of Safety for the CS of 22. ACR-1000 plant is designed for DBE value of 0.3g, thus the CS median seismic capacity equals to 6.6 g. The overall randomness and uncertainty calculated before are still valid.

Using equations (1) and (2), the median seismic capacity of the containment using UHS is 6.6 g and the HCLPF capacity is 2.1g.

**Analysis of Results**

An important observation is that the ACR-1000 RB CS HCLPF capacity calculated using UHS is higher than its capacity calculated using the ACR-1000 GRS. The reason for this is that the RB has a natural frequency of 4.4 Hz in the horizontal direction. The UHS has its peak acceleration values at frequency range higher than 4.4 Hz (> 10 Hz). Thus the RB CS horizontal frequency lies outside the UHS peak acceleration range.

## FRAGILITY ANALYSIS OF A TYPICAL RELAY

**Specimen**

The following section provides the fragility analysis of a sample rigidly mounted Relay, which was qualified by testing, and is commonly used in previous CANDU plants. The Relay is a solid state GE Mulitin, 269-10C-120 Motor Management Relay, GE Mulitin, MPM-HI-A20, Motor Protection Meter.

For the fragility capacity evaluation, the so-called "scaling method" was adopted. The factor of safety of various parameters that have impact on the seismic response and the seismic capacity of the equipment should be estimated based on a seismic qualification analysis report and/or test report.

In general, the seismic qualification and the seismic fragility evaluation of the equipment consist of the structural integrity and the operational functionality of the equipment, and the integrity of the anchorage system. The fragility analysis considered herein will be for the operational functionality only based on the test results documented in AECL.

**Seismic Qualification Test**

<u>Shake Table Test</u>:

This sample consists of the Relay top and the meter bottom as shown in Figure 3. The Relay was face mounted through a vertical aluminum plate using four #10 screws torqued to 17 in-lb. The meter was surface mounted using six #8 screws torqued to 8 in-lb. The Relay and meter were connected to monitor for chatter while powered to 115 VAC. With the Relay and meter powered, they were subjected to one 30 seconds seismic test.

According to the test procedures, the sample is tested on the tri-axial shaker, capable of independent motion in each axis (X-axis and Z-axis are horizontal and Y-axis is in vertical direction). Three table accelerometers are mounted underneath the table top, closely coupled to the mounting fixture.

The horizontal Required Response Spectrum (RRS) is shown in Figure 4. The vertical RRS (Y-axis) is taken as 2/3 of the horizontal RRS.

<u>Test Results:</u>

The Test Response Spectrum (TRS) are shown in Figure 5. The TRS envelop the RRS at all frequencies greater than 2.5 Hz. Acceleration levels at lower frequencies were limited by the shaker. No chatter was detected, while sampling at 10,000 Hz per monitored channel. It was concluded in the test report that this sample met the acceptance criteria.

**Fragility Methodology**

For equipment qualified by shake table test, the following formula is used to evaluate the seismic fragility capacity of the equipment (Reference 4):

$$A_m = F_{QM} * (TRS_C/RRS_C) * F_D * F_{RS} * PGA \quad (3)$$

$$TRS_C = TRS * C_T * C_I, \quad RRS_C = RRS * C_C * D_R \quad (4)$$

where $A_m$ = median capacity of the equipment in terms of peak ground acceleration

$F_{QM}$ = qualification method factor to account for the conservatism in the RRS

TRS = equipment test response spectrum capacity

RRS = equipment seismic demand in terms of required response spectrum

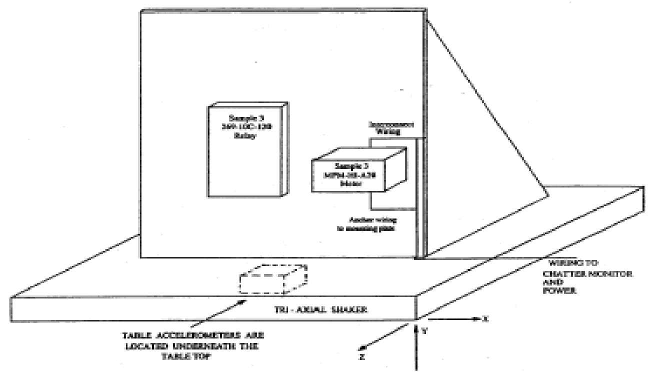
$C_T$ = clipping factor for narrow-banded TRS

$C_I$ = capacity increase factor

$C_C$ = clipping factor for narrow-banded demand

$D_R$ = demand reduction factor

$F_D$ = broad frequency input spectrum device capacity factor
$F_{RS}$ = structural response factor of the building
PGA = peak ground acceleration of the DBE design ground response spectrum.




The GE Multilin Motor Protection Relay and Motor Protection Meter shall be mounted to a vertical plate using #10-32 and #8-32 screws respectively. Through holes with flat washers shall be used. The vertical plate is mounted to the tri-axial shaker. The accelerometers located underneath the table top below the vertical plate. The Y direction is vertical.

**Figure 3: Relay Test Specimen**

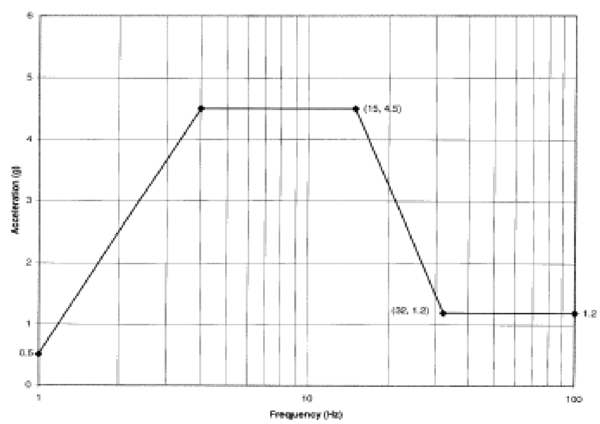



**Figure 4: Required Response Spectrum (RRS) – 5% damping**

The typical Relay qualified by testing has to be assessed for all frequency ranges of the test. This is done in two steps: First the margin between RRS and the TRS is assessed. Second step, is to assess the margin between the design response spectrum and the RRS. Generally, the design response spectrum would be Floor Response Spectrum (FRS) however because the Relay is at the ground level, the GRS is used. The product of the two margins, RRS/GRS and TRS/RRS results in the overall margin between the GRS and the TRS. As mentioned earlier the overall margin has to be calculated for all test frequency ranges. Typically two ranges are important: the peak of the RRS range (4-15 Hz for the example) and the Zero Period Acceleration (ZPA) range.

**Fragility Analysis**

Examining figure 5, and calculating all factors of safety, it is found that X-direction provided the smallest margin for both peak frequency range and ZPA range. In the RRS peak range, frequency 4-15 Hz, the ratio $(TRS_C/RRS_C)_{X1}$ calculated using equation (4) is 1.71 while at the ZPA, frequency > 32 Hz, the ratio $(TRS_C/RRS_C)_{X2}$ calculated using equation (4) is 3.49.

Figure 6 shows that the lowest $F_{QM}$ factor at the RRS peak range, frequency 4-15 Hz, $F_{QM1}$ is equal to 5.1, governed by ACR-1000 design GRS. Also, the lowest factor at the ZPA range $F_{QM2}$ is equal to 0.9, governed by UHS. For both factors, there are no randomness or uncertainty.

The median capacity of the Relay is calculated using equation (3) twice, once in the RRS peak range and once at the ZPA range. In the RRS peak range, frequency 4-15 Hz, $A_{M1}$ is equal to 4.67 g, governed by the ACR-1000 design GRS. At the ZPA range $A_{M2}$ is equal to 1.69 g, governed by the UHS. Therefore, the lowest median capacity $A_M$ is equal to 1.69g.

A HCLPF capacity of 0.73g for the Relay can be obtained from its median capacity using equation (2).

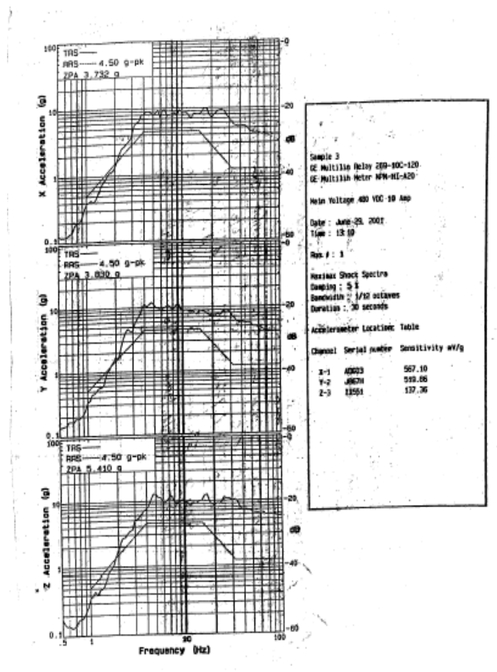



**Figure 5: TRS versus RRS Response Spectra**

**Analysis of Results**

An important observation is that the Relay seismic capacity calculated using UHS is lower than its capacity calculated using the ACR-1000 GRS. The reason for this is that the Relay has to be qualified over the entire frequency range of the TRS. The UHS has its peak acceleration values at higher frequency range (> 10 Hz). On the other hand, the ACR-1000 GRS has its peak acceleration values between 2.5 and 15 Hz.

As mentioned earlier, the capacity of the Relay is a function of two main factors. One factor is the margin between the design spectrum used and the RRS. The second factor is the margin between the TRS and the RRS. The product of these two factors determines the overall capacity of the Relay. Thus with using UHS without calculating both factors for both frequency ranges, and comparing their product, it is not possible to assess whether the ZPA range of a spectrum will govern the capacity of an equipment, or the 4-15 Hz range.

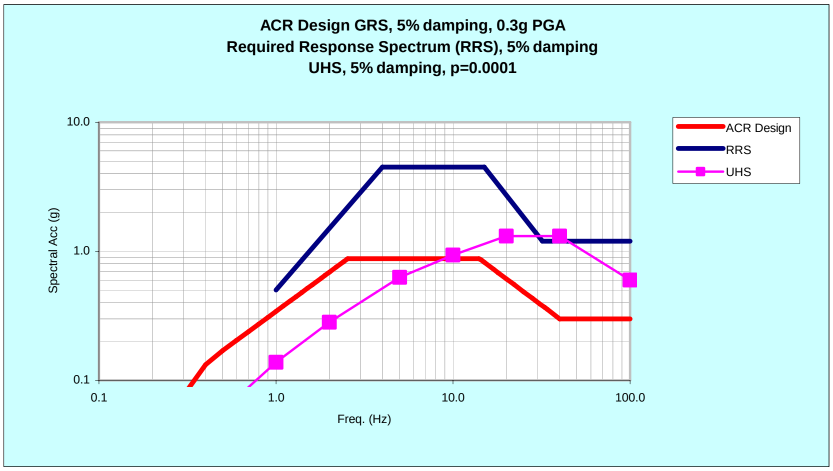



**Figure 6: Comparison Between RRS and Various Design Response Spectra**

## CONCLUSIONS AND RECOMMENDATIONS

Following this study several interesting observations are arrived at:

- The RB CS HCLPF capacity is 1.37 g when using the ACR-1000 design GRS, while it is 2.1 g when using UHS. Thus, the UHS with its peak value above 10 Hz is not critical for determining the capacity of a structure like the RB CS.
- The above observation can be generalized to all other structures in the CANDU plant, since all major structures have natural frequencies below 10 Hz.
- In the 4-15 Hz range, the seismic margin of the Relay was lower (more critical) when using ACR-1000 design GRS than when using UHS. The opposite was true for the high frequency range where using UHS was more critical than using ACR-1000 design GRS. Finally, the total margin between GRS and TRS was the least when using UHS rather than ACR-1000 design GRS.
- The Relay still had a robust design and its HCLPF (0.73 g) was well above the safety objective for the whole ACR-1000 plant of 0.5 g. However, using UHS was important, since it showed a lower margin for this component versus if only ACR-1000 design GRS was used.

It is recommended that for qualification of structures, systems and components both the UHS and the design GRS be considered for the ACR-1000 standard design.

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