The seismic fragility of most electrical equipment is governed by the malfunction of relays. This paper discusses the combined study being performed at BNL by evaluating existing fragility test data, conducting a new relay test program and estimating the cabinet amplification at relay locations. Existing test data for relays have been collected and evaluated at BNL. The data base consists of results from a wide variety of test programs - single frequency, single axis, multifrequency, multiaxis tests. For most relays, the non-operating condition controls the chatter fragility limit. In order to characterize the effect of various parameters on the relay seismic capacity, a test program has been initiated at BNL. Selected test specimens will be tested to determine the influence of frequency of vibration, direction of motion, adjustments of relay parts, among others, on the relay capacities. The amplification study involves computing dynamic amplification factors at various device locations in motor control centers and switchgear cabinets. Fragility and high level qualification data have been used for this purpose. This paper includes a summary of the amplification results.

1.0 INTRODUCTION

Evaluation of seismic fragility of electrical equipment being performed at Brookhaven National Laboratory (BNL) and elsewhere, indicates that for most equipment the fragility levels are governed by malfunction of relays. Therefore, a special study has been undertaken at BNL for understanding relay performance. To this end, evaluation of the existing relay test data, conducting a new relay test program and investigating the dynamic amplification of relay housing cabinets are all being carried out at BNL. This paper discusses the data base, describes the testing methods and presents the cabinet amplification results.

2.0 DATA BASE TEST PROGRAMS

As part of the Component Fragility Program at BNL [1,2], a vast amount of relay test data has been collected from various sources. These tests were performed in the period 1973-1985. The test programs in the BNL data base can be grouped into two types depending on the testing methods and the available information as discussed in the following subsections.

2.1 Single Axis, Single Frequency Tests

Single axis, single frequency sine beat or sine dwell tests were performed on early vintage relays in the period 1973-75. Information is available for twenty five protective and auxiliary (including time delay) relay models. The relay specimens were tested at specific frequencies with increasing input level until they exhibited contact chatter at a pre-selected level (e.g. 1, 2 or 10
milliseconds) or until the capacity of the shake table was reached. The tests were repeated in different directions and for different electrical (i.e. energized and de-energized) and contact (i.e. normally open and normally closed) conditions. The vibration levels were measured in terms of the amplitude of the sine wave form and presented as a plot of input acceleration vs frequency. The discrete points in the plot are connected to provide a continuous fragility (or test equipment capacity) curve in the frequency range 1-35Hz. Figure 1 shows a set of typical test results for a relay model. The lower curve indicates the fragility chatter limit (2ms) for a normally closed contact of the sensing unit of the relay when de-energized and the upper curve corresponds to the shake table capacity curve which was exceeded for the energized condition. For the data base relays, the contact chatter fragility level was as low as 0.1g and as high as 3.0g sine beat input motion.

Single frequency test results reveal the frequency sensitive nature of relays. However, it is often difficult to use the input acceleration values to determine whether the data set envelops a required response spectrum, the common form of measure of the seismic demand in practice since the mid-1970's. Therefore, the use of the early test data is limited unless an appropriate conversion factor is developed.

2.2 Multiaxis, Multifrequency Tests

The data base contains multiaxis, multifrequency results from tests performed since the late 1970's. Most tests were performed with biaxial inputs - either phase incoherent or phase coherent. Triaxial input motion was used for the rest. The fragility levels due to relay chatter were determined for various electrical modes and contact conditions and expressed in terms of the test response spectrum (TRS). Some relay models did not exhibit chatter even at the shake table capacity vibration level. The multifrequency test data were of three different types and the nature of the data was also different as discussed in the following subsections.

2.2.1 Required Response Spectrum Tests

These tests were performed to meet a specific or a generic required response spectrum (RRS) and in the process the chatter fragility was reached. The corresponding vibration level was presented in terms of TRS data. These results are conservative in the sense that at some frequencies the relay may still withstand higher vibration levels.

2.2.2 IEEE Std 501 Tests

A large number of test programs were conducted following the generic procedure and the standard RRS shape recommended by IEEE Std 501 (ANSI C37.98) [3]. Since the late 1970's, the manufacturers have used this approach for seismic rating of their products. Typically, the ZPA is used as a single-valued fragility level such that the 5% damped spectral level is two and half times the ZPA. This is a very convenient and concise way of expressing the fragility limit and the seismic ratings (i.e. ZPA's) are readily available, sometimes even
Fig. 1 Single Axis Sine Beat Test Amplitude
in manufacturers' catalogs and sales brochures. Also, the fragility levels of various relay models can be easily compared and the appropriate relay can be selected. However, the TRS data used for obtaining the seismic ratings are not easily available. The database indicates a wide range of seismic ratings - from as low as 0.5g ZPA to as high as 6.0g ZPA. For many relays, the seismic rating is controlled by the capacity of the shake table rather than the capability of the relays.

2.2.3 Panel Tests

A large number of electrical panels were tested with relays mounted in them. Since for a long time it is known in the industry that relays are the typical weak links of electrical equipment, electrical channels and accelerometers are commonly used for selected relays to monitor the electrical performance of these relays and to measure the vibration level at the device locations. Such information is an important source of relay fragility data. The BNL database contains relay information for equipment tested in the period 1977-80. The merit of the panel test data is that in application relays will be mounted in such panels and used in similar circuits. Therefore, the relay performance and the vibration level at locations recorded during panel testing are more direct, realistic and dependable, especially since the input vibration at the base of the equipment has been filtered through the cabinet structure. The limitation of the use of the panel test data is that the same relay located in another possible location in the same cabinet, or tested in another cabinet, may exhibit the fragility phenomenon corresponding to a different TRS data set due to different characteristics of the filtering medium. Another limitation of the panel test data is that since the purpose of the tests was not necessarily to determine the fragility threshold of a particular relay, the available information is most often either higher or lower than the threshold, e.g. either 20ms chatter or no chatter for a 2ms chatter criterion.

2.3 Sensitivity Parameters

The seismic fragility of relays depends on one or more parameters related to the design or the input motion. Some of these parameters are discussed in the following subsections.

2.3.1 Frequency of Vibration

Depending on the design, most relays are capable of withstanding a higher vibration level at one frequency than another. The frequency range in which a particular relay is weak may be low (e.g. less than 10Hz), medium (e.g. 10-30Hz) or higher (e.g. greater than 30Hz) as illustrated by the chatter fragility sine beat input vs frequency curves for two different relay models shown in Figure 2. One curve shows sensitivity to low frequencies and the other curve shows sensitivity to medium frequencies.

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Fig. 2 Single Axis Sine Beat Test Amplitude Frequency Sensitivity
2.3.2 Chatter Duration

Depending on the chatter duration that can be accepted for a particular application, the fragility level may change. Single axis testing indicates that for most frequencies the vibration level is higher if a longer chatter can be accepted as demonstrated by Figure 3.

2.3.3 Direction of Vibration Input

Depending on the design of the operating mechanism, relays exhibit varying capacity levels in different directions. Typically they are weak in the direction of the contact movement. Figure 4 shows single frequency capacity test data of an auxiliary relay model in three orthogonal directions, front-to-back (FB), side-to-side (SS) and vertical (V). The front-to-back (FB) vibration controls the capacity level for the relay at high frequencies.

2.3.4 Electrical Mode

Most two-state relays chatter in the de-energized electrical mode at a lower vibration level than the energized mode. This is especially true for relays with hinged armature mechanisms since in the energized state the magnetic field of the coil tends to restrain the motion of the armature. Figure 5 shows single frequency capacity results of a popular auxiliary relay with a hinged armature mechanism for both the energized (E) and de-energized (DE) modes.

2.3.5 Contact State

The moving contact of an electro-mechanical relay needs to traverse the contact gap for a normally open contact before it closes by engaging the stationary contact. On the other hand, a normally closed contact becomes open immediately by disengaging the stationary contact. Therefore, for electro-mechanical relays, normally closed contacts typically chatter at a lower vibration level than normally open contacts. Figure 5 shows the single frequency capacity levels of a normally closed (NC) contact and a normally open (NO) contact of an auxiliary relay.

2.3.6 Adjustments

In a hinged armature mechanism, the magnetic force experienced by the armature must overcome the tension of the balance spring for movement of the moving contact. An adequate spring tension is required for normal operation and engagement of the moving contact. A stronger tension value tends to press the moving contact tight against the stationary contact and thereby makes the moving contact less susceptible to vibration.

The thin shaft of a rotary disk mechanism, on the other hand, is supported by two bearings and the disk tends to jump out of plane in a vibratory environment unless the play of the vertical shaft at the bearing is properly adjusted. One popular relay model was observed to exhibit such a phenomenon in a seismic test program resulting in malfunction of the relay.
Fig. 3 Single Axis Sine Beat Test Amplitude Chatter Duration Sensitivity
Fig. 4 Single Axis Sine Dwell Test Amplitude
Input Motion Direction Sensitivity
Fig. 5 Single Axis Sine Beat Test Amplitude
Electrical Mode and Contact State Sensitivity
Thus, for different operating mechanisms, certain adjustments may influence the seismic capacity of a relay.

3.0 CURRENT TEST PROGRAM

Primarily, in order to further study the effect of parameters on relay fragility levels, BNL has initiated a relay test program. Establishing the correlation between single frequency fragility test inputs and multifrequency test response spectra, and confirming the similarity of relay models within a group are also objectives of the test program.

Single frequency sine dwell tests will be performed to study the effect of vibration frequency on the fragility levels. Nineteen popular models from three manufacturers will be tested. For ten models more than one specimen will be used to study the consistency of results.

Multifrequency tests will be performed with separate single axis, biaxial and triaxial inputs on twelve relay models. Spectral shapes will be matched with the respective single frequency fragility inputs so that the conversion factors relating the single frequency test inputs to the multifrequency test response spectra can be computed.

Four relay models from one manufacturer with three specimens for each will be tested with biaxial multifrequency input motion following the IEEE Std 501 spectral shape. The test is intended to confirm the same seismic rating for all four models.

All the above tests will be performed on new (current vintage) relay models. The effect of spring tension and contact gap adjustments will be studied by varying the respective parameters of two hinged armature relay models. The effect of end play adjustments will be tested on two rotary disk relays. All adjustment tests will be performed with single frequency inputs.

The initial single frequency tests will be conducted in all three orthogonal directions for all three electrical modes (i.e. operating, nonoperating and transition) and two contact conditions (i.e. normally closed and normally open). All subsequent tests will be performed only in the weakest direction for the weakest electrical modes and contact conditions. A chatter duration of 2ms or greater will be used as the failure criterion to establish the fragility levels.

Upon completion of testing, the test data will be evaluated to draw conclusions regarding the effects of various parameters, the relation between single frequency and multifrequency results, and the similarity of relay models within the same seismic rating group. The results will be published in 1989.
4.0 CABINET AMPLIFICATION

Since relays like most other devices are mounted on electrical cabinets which tend to amplify the input motion, the relay fragility data cannot be directly compared with the seismic demand specified at the base of the cabinet. If the amplified motion at the relay location is known from testing of the particular cabinet, that can definitely be used for comparison with the relay test data. In the absence of such specific information, a "generic" amplification factor for the equipment class may be used to relate the relay test data to the input motion at the base of the housing cabinet. BNL has evaluated fragility and qualification level test data of nine motor control centers and ten switchgear cabinets and computed amplification of the input motion at various locations in the cabinets measured in terms of response spectra. The factors have been obtained at various frequencies and presented as amplification spectra in NUREG/CR-5203 [4]. The input motion is amplified at the resonant frequencies of the cabinet structure and internals. Therefore, the amplification factor at a location in the cabinet is dependent on the frequency. A typical amplification spectrum peaks at the structural resonant frequencies and dips at other frequencies as illustrated by Figure 6. The amplification factors have been computed at many device locations in the respective data base cabinets and a summary of the deterministic and probabilistic results is presented in Table 1.

5.0 CONCLUSIONS

The seismic fragility levels are to a great extent relay model specific. The existing data base provides fragility information for a large number of relay models manufactured at different periods. However, the existing data are not adequate to address certain inconsistencies in the fragility results observed in the data base, probably due to the variation of the input motions or the specimen design or both. The relay test program will focus on these issues and is expected to clarify the influence of certain parameters. Both the existing and the new test data measure the relay capacity at its location. The amplification study provides the link between the motion at the relay location in an electrical cabinet and that at the base of the cabinet. Therefore, the three studies combined together will define the parameters controlling the seismic performance of relays and allow a proper and effective use of the existing relay data base.
Fig. 6 Typical Amplification Spectra at Different Damping Values
TABLE 1
Summary of Amplification Results¹,²

<table>
<thead>
<tr>
<th>Amplification</th>
<th>Motor Control Center</th>
<th>Switchgear</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Maximum</td>
<td>Median</td>
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<tr>
<td>Peak</td>
<td></td>
<td></td>
</tr>
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<td>4-16 Hz</td>
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<td>4.8</td>
</tr>
<tr>
<td>16-40 Hz</td>
<td>8.3</td>
<td>5.3</td>
</tr>
<tr>
<td>40-100Hz</td>
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<td>5.7</td>
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<tr>
<td>Average</td>
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<td></td>
</tr>
<tr>
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<td>3.0</td>
</tr>
<tr>
<td>16-40 Hz</td>
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</tr>
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</tr>
<tr>
<td>Zero Period</td>
<td>4.8</td>
<td>3.3</td>
</tr>
</tbody>
</table>

¹ These results, are applicable only within the limitations described in chapter 3, Section 3.3 of NUREG/CR-5203
² The amplification parameters are defined in Chapter 2, Section 2.3 of NUREG/CR-5203
³ High (95%) confidence of a low (5%) probability of exceeding the listed values
⁴ Selection of the appropriate single-valued amplification factor is left to the user
REFERENCES


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NOTICE

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