# Testing of Seismic Isolation Bearings for the PRISM Advanced Liquid Metal Reactor Under Extreme Loads


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## INTRODUCTION

This paper presents the results of a series of tests performed to evaluate the response of high damping natural rubber seismic isolation bearings subjected to extreme horizontal displacements. Bearings of this type were included in the design of the reference U.S. advanced liquid metal reactor (ALMR), PRISM, to mitigate horizontal seismic loads and to enhance structural margins. The purpose of the tests was to determine the maximum shear strains and vertical load that the bearings could sustain before failure, to characterize the stiffness and damping of the bearings when subjected to extreme horizontal displacements representative of beyond design basis earthquakes, and to assess available performance margins.

PRISM is a compact standardized ALMR reactor installed in blocks consisting of three reactor modules per 465 MWe power block (Berglund et al., 1988). Each reactor module incorporates a horizontal isolation system to isolate the reactor module with its key safety functions of reactor shutdown, shutdown heat removal, and containment systems from potentially damaging ground motions. The entire isolated structure is housed in an underground silo as shown in Fig. 1. The small diameter of the PRISM vessel provides sufficient intrinsic resistance in the vertical direction to minimize amplifications in vertical ground motions which makes vertical isolation unnecessary. The total weight of these structures is approximately 9000 kips and is supported on 20 large diameter high damping steel laminated elastomeric bearings (Kelly, 1987). The bearings have a diameter of 52 in. and a total height of 23.1 in. and consist of thirty layers of rubber 1/2 in. thick and 29 steel plates 1/8 in. thick. The bearing dimensions were selected to give a horizontal frequency of 0.75 Hz and a vertical frequency over 20 Hz. The elastomeric compound used consists of a highly filled natural rubber with high damping. The properties of this compound were presented elsewhere (Tarics et al., 1984 and Tajirian and Kelly, 1988). Lateral loads from the isolated structure are transferred to the bearings through dowels which under large horizontal displacements would allow the top and bottom plates to bend and limit tensile stresses in the elastomer.

The design safe shutdown earthquake (SSE) for PRISM is a maximum horizontal and vertical acceleration of 0.3 g anchored to a design earthquake that envelopes the NRC Regulatory Guide 1.60 spectra. Options for siting in higher seismic zones are being investigated. Analytical results show that horizontal accelerations are substantially reduced in all the reactor components with isolation (Tajirian and Schrag, 1987). The peak spectral acceleration at the core support plate for 2 percent damping was reduced from 16.5 g to 0.25 g. Furthermore, horizontal spectral peaks above 2 Hz are eliminated. Incorporation of seismic isolation in the PRISM design results in reactor design simplification, improvements in reactor safety and facilitates design standardization for broad geographic deployment.

## SEISMIC ISOLATION BEARING TESTS

A series of quasi-static tests was performed at the University of California Earthquake Engineering Research Center (EERC) in Richmond using the test fixture shown in Fig. 2. The maximum vertical capacity of the fixture is 1500 kips. Four bearings stacked in two tiers are loaded simultaneously in the horizontal direction using two large hydraulic actuators located between the top and bottom bearings. A maximum horizontal load of 400 kips can be applied to the bearings, while producing cyclic horizontal displacements up to ± 9 in., or 18 in. in any one direction. The bearings tested so far are half-scale, have a diameter of 26 in., and consist of thirty alternating layers of rubber 0.238 in. thick and 29 steel plates, see Fig. 3. The bearings are designed for a shear strain of 50 percent at the maximum SSE displacement. A series of vertical and cyclic horizontal stiffness tests were performed to verify the bearing properties under normal design loads. The results have been previously reported in (Tajirian and Kelly, 1988). The tests verified that the bearings are capable of undergoing several cycles of varying shear strain without appreciable change to their stiffness or damping. The tests also showed that the first cycle of each test gave a slightly higher initial average stiffness. This is not expected to affect the design. Furthermore, the bearings have 10 percent damping or more for all applicable shear strains.

### Extreme Displacement Tests

The bearings were then subjected to a series of extreme horizontal loads to determine the maximum shear strain that the dowelled bearings could sustain before delamination or other types of failure such as geometric instability would occur. The tests consisted of half cycles to maximize the achievable displacement with the actuators. Increasing horizontal loads were applied under a constant vertical load. The tests were performed for the vertical loads and shear strain levels defined in Table 1. It should be noted that the vertical load at the higher strains was increased beyond the design load to prevent rollout of the bearing and to induce failure of the elastomer in shear. The relationship between average horizontal bearing stiffness and shear strain is shown in Fig. 4. The average bearing stiffness at 50% strain is about 11.5 kips/in. and is reduced to 9.5 kips/in. at the higher strains. The stiffness is highly nonlinear at low strains, but is fairly constant for strains above 30%. The high stiffness at low strains is sufficient to resist strong wind and small earthquakes without movement. It can also be seen that the average horizontal stiffness is not sensitive to the vertical load.

The maximum shear strain achieved was 200 percent which corresponded to a maximum horizontal displacement of 14.4 in. which is four times larger than the displacement computed for the SSE (actual displacements are equal to the scaled displacements times the scaling factor of 2). Fig. 5 shows a bearing under a vertical load of 420 kips and displaced 14.4 in. There is substantial warping of the bearing end plates and disengagement of the dowels; however, even under these extreme conditions failure could not be induced. The hysteresis loops for 161, 176, and 200 percent shear strain are shown in Fig. 6. It can be seen that the stiffness of the bearing starts increasing at high strains due to stiffening of the elastomer. Additionally, the area of the hysteresis loop at higher strains is larger. This is caused by bending of the steel end plates beyond yield point and represents an increase in damping. This deformation of the end plates should produce an overall reduction of the horizontal stiffness of the bearing since the deformable system should be less stiff than a system with rigid elements but the increasing shear modulus of the elastomer at high shear strains more than compensates for the reduction in stiffness due to yielding of the plates. This provides an inherent stabilizing effect for controlling displacements in extreme events in contrast to other systems which soften with increased shear.

Even after several cycles of extreme displacements no damage could be observed in the bearings. To verify this, each extreme test was preceded and followed by a 50 percent nominal shear test and the hysteresis loops were plotted, see Fig. 7. No change in the stiffness or the hysteresis loops was observed. Larger loads could not be applied to fail the bearings due to load limitations of the test machine. Tests in Japan performed on 1/11 scale bolted elastomeric bearings with large aspect ratios have shown that the elastomer does not fail unless the shear strain exceeds 400 percent (Kurihara et al., 1987). For the PRISM half-scale bearings, this would correspond to a horizontal displacement of 30 in. Additionally, half-scale bearings with bolted type connection instead of dowelled connection were tested to compare the failure mechanism of the two systems and the results are currently being evaluated. The base PRISM design, which currently uses dowelled connections will be reassessed depending on the outcome of these tests.

### Ultimate Vertical Load Test

To assess the ultimate load capacity of a single bearing under vertical load, one bearing out of the four previously used in the shear tests was tested in the four million pound Southwark-Emery test machine at EERC. The bearing was loaded at a rate of around 400 kips per minute. The vertical displacements were measured at four points equidistantly spaced around the periphery of the bearing. The bearing was loaded to the limit of the machine, 4000 kips which corresponds to 7500 psi pressure, without causing any apparent damage to the bearing. This corresponds to a margin of safety under direct vertical load of around 32. The load deflection curve for this test is shown in Fig. 8. It can be seen that the vertical stiffness is fairly constant even at high levels of vertical loading. On unloading and removal of the bearing from the machine it was found that the steel layer at the bottom of the dowel holes, which has a thickness of 1/16 in. was permanently distorted. No evidence of any damage to the elastomer or the internal steel shims was apparent. It is anticipated that the mode of failure under the ultimate load would be tensile bursting of the internal shims. To determine the actual failure pressure it will be necessary to use a smaller bearing and scale the results.

### Buckling Load Test

The boundary conditions for bearings supporting a structure have a lower boundary which is fixed to the foundation and an upper boundary which is free to move laterally. In this condition, when the vertical load on the bearing exceeds the buckling load, the bearing buckles. To determine the buckling load for a single bearing two of the bearings used in the shear tests were loaded one on top of the other in the Southwark-Emery machine in direct compression. This simulates the boundary conditions in an isolated building described above. Vertical displacements were measured at four equidistant points around the bearings. Horizontal displacements at the mid-plane were measured in two orthogonal directions since the direction of horizontal displacement was not known a priori.

The bearings were loaded in four stages; first, to 1000 kips and then increasing the load in 1000 kips increments. During the fourth stage, the bearings buckled laterally at a maximum load of 3550 kips. The load deflection curve is shown in Fig. 9. It should be noted that the vertical displacement noted in this figure is the total displacement in two bearings. The margin against buckling of a single bearing is 28. Fig. 10 shows the bearings in their buckled form.

## SEISMIC ISOLATION SYSTEM QUALIFICATION

Other programs planned to qualify the PRISM seismic isolation design include: tests of full size bearings, shake table performance tests to evaluate system performance during real earthquakes, and evaluation of the effects of input with strong long period energy, seismic hazard assessment, and the development of design guidelines (Gluekler et al., 1988). As part of this program, Argonne National Laboratory (ANL) is working with Shimizu Corporation of Japan on a joint U.S./Japanese program for testing scale size PRISM type bearings in a unique facility built by Shimizu at Tohoku University in Sendai, Japan. The features of this facility are described by Tamura et al., 1988. ANL's effort is funded by the National Science Foundation; the program is expected to last two years and the results will be reported by ANL. Additional work is in progress at ANL to develop nonlinear finite element models for the prediction of elastomeric bearing performance that can be used for optimization of the bearing geometry.

## CONCLUSIONS

Several recent technological advancements and developments are responsible for making seismic isolation a practical design alternative for earthquake damage mitigation. One important factor has been the development of large test machines which can test large scale bearings under a variety of loading conditions up to failure. The results of these tests have given designers much more confidence in selecting the necessary design parameters while ensuring satisfactory performance for the largest possible earthquakes. The high performance margins of the PRISM bearings were demonstrated by the fact that the bearings were capable of sustaining several cycles of displacements four times the SSE without failure or damage. Furthermore no loss of stiffness or damping was observed under all applicable conditions. The high available margins beyond the SSE was clearly demonstrated. The test results confirmed that both bearing horizontal stiffness and damping were not affected by changes in the magnitude of vertical load or number of cycles of loading. The results of these tests and other planned tests will be used to further optimize the design of the PRISM bearings.

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**Table 1 Half Cycle Large Horizontal Stiffness Tests**

| TEST NUMBER | VERTICAL LOAD PER BEARING (KIPS) | SHEAR STRAIN PERCENT | HORIZONTAL STIFFNESS (KIP/IN.) |
|---|---|---|---|
| 1 | 70 | 108.1 | 9.4 |
| 2 | 70 | 133.4 | 9.8 |
| 3 | 70 | 153.1 | *** |
| 4 | 140 | 107.9 | 8.7 |
| 5 | 140 | 133.4 | 9.2 |
| 6 | 210 | 108.2 | 8.4 |
| 7 | 210 | 133.0 | 9.2 |
| 8 | 280 | 107.8 | 8.5 |
| 9 | 280 | 133.6 | 9.2 |
| 10 | 280 | 158.6 | 9.9 |
| 11 | 350 | 160.4 | 9.6 |
| 12 | 420 | 161.3 | 9.4 |
| 13 | 420 | 175.9 | 9.5 |
| 14 | 420 | 197.8 | 9.4 |

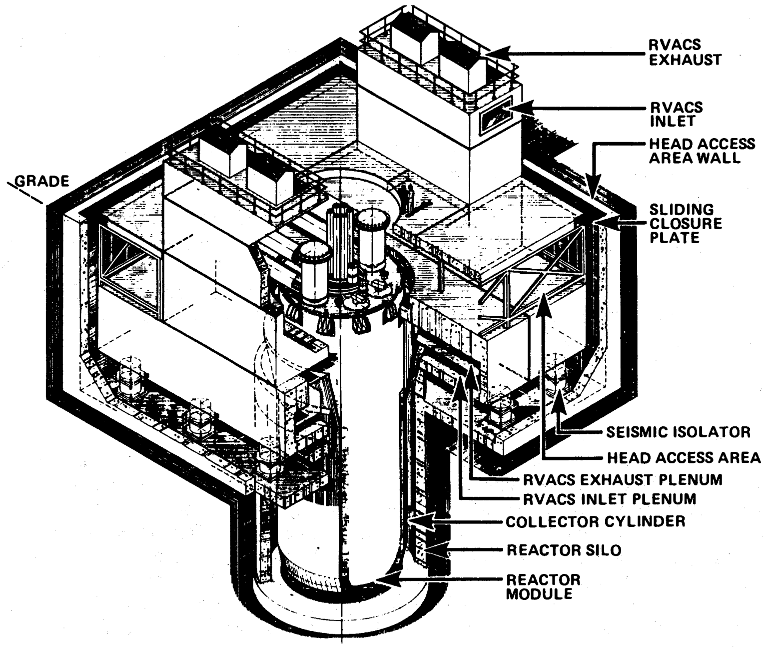


Fig. 1 PRISM Reactor Module

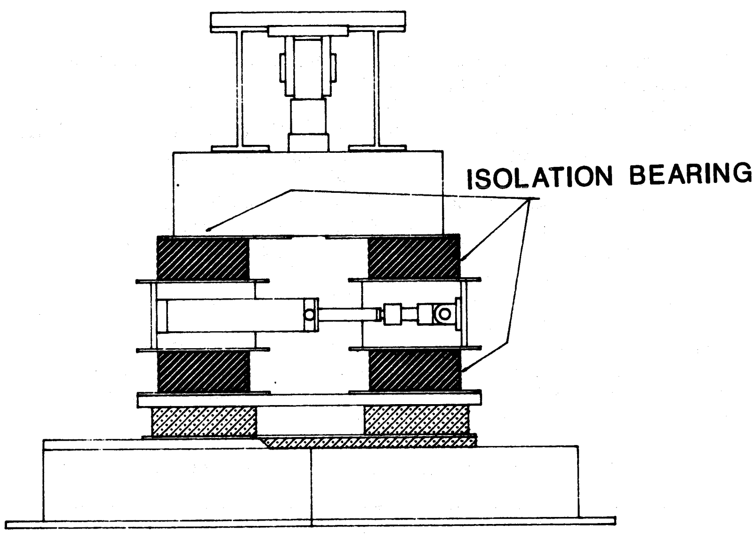


Fig. 2 EERC Test Fixture

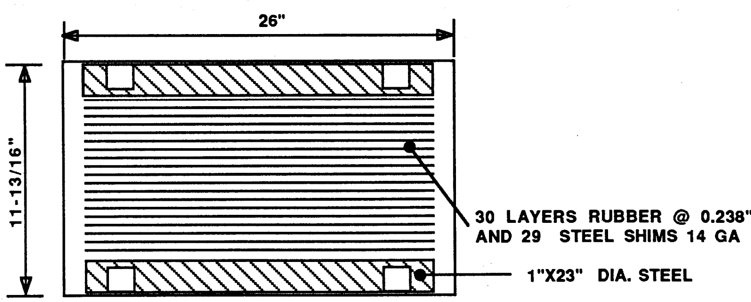


Fig. 3 Typical Half-Scale Bearing

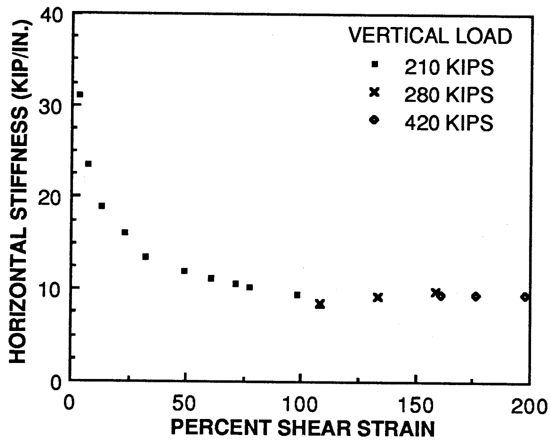


Fig. 4 Measured Horizontal Stiffness Versus Shear Strain

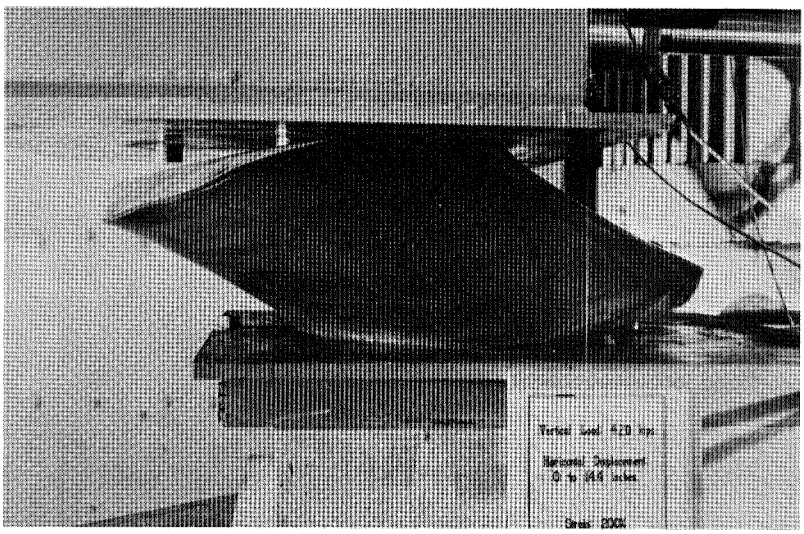

Fig. 5 Bearing Subjected to 420 Kips Vertical Load and 14.4 in. Displacement

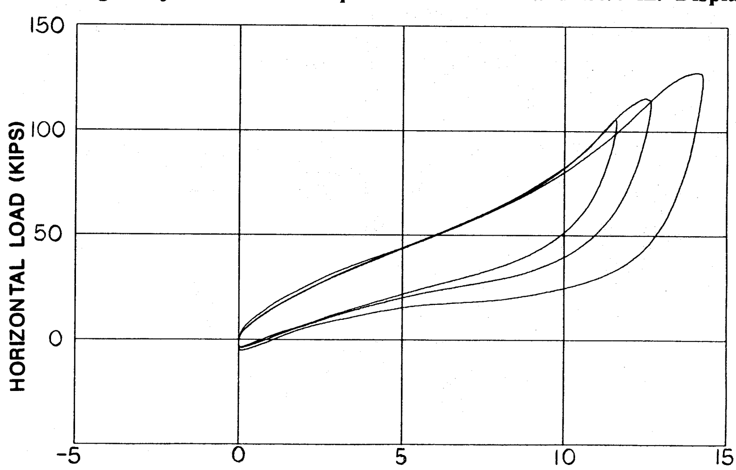


Fig. 6 Large Strain Hysteresis Loops

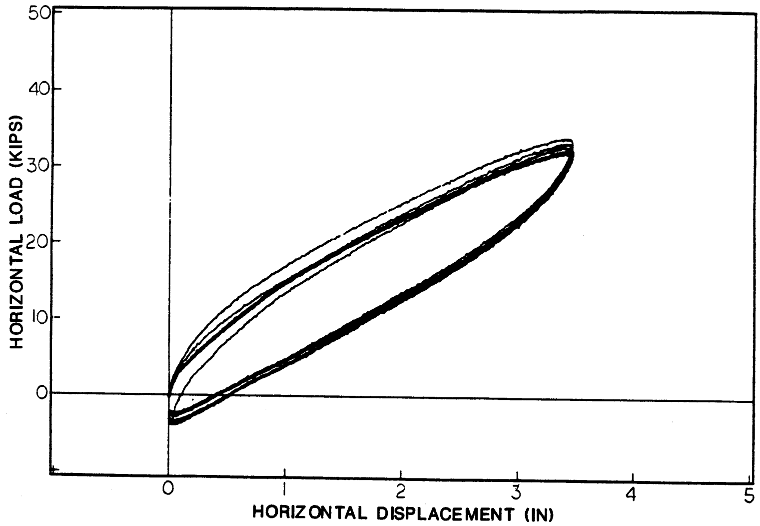


**Fig. 7 Superposition of 50% Shear Strain Hysteresis Loops**

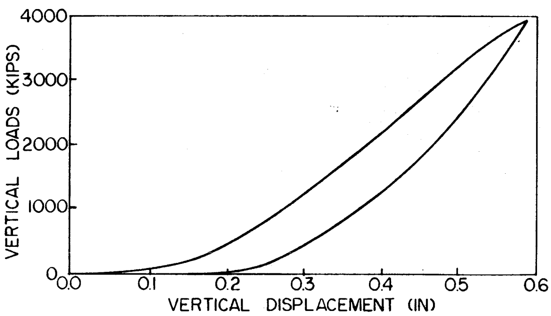


**Fig. 8 Vertical Load versus Vertical Deflection for Single Bearing**

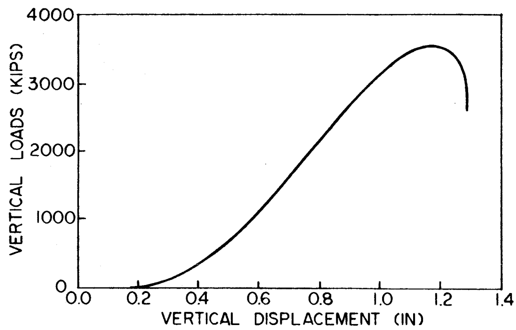


**Fig. 9 Buckling Test Vertical Load versus Vertical Deflection**

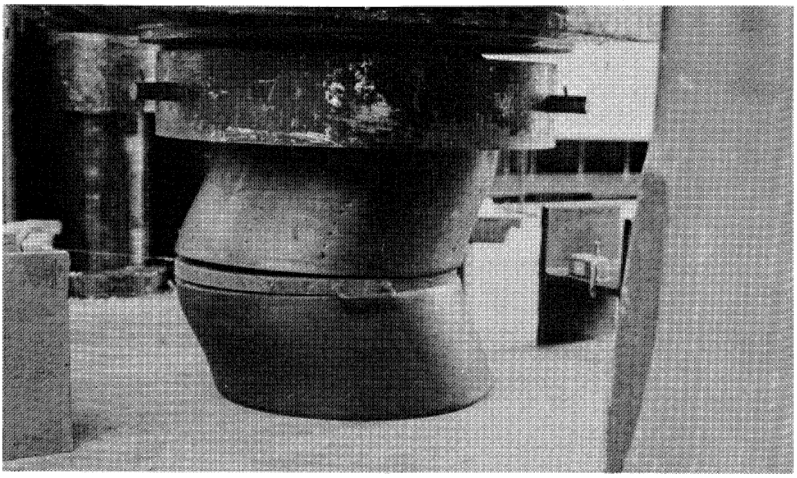

**Fig. 10 Buckling of Bearings**