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**CORE SEISMIC METHODS
VERIFICATION REPORT**

VOLUME I

Prepared under
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for the San Francisco Operations Office
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CORE SEISMIC METHODS VERIFICATION REPORT VOLUME I

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DEVELOPED UNDER THE SUPERVISION OF B. E. OLSEN AND H. D. SHATOFF

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FOREWORD

This report, because of its size, is presented in two volumes. Volume I contains Sections 1 through 4, and Volume II includes Sections 5 through 8. Each volume contains its own detailed table of contents. Volume II includes a table of contents for the following:

- Section 5 - Element Properties and Code Parameters
- Section 6 - Correlation and Verification of the Codes
- Section 7 - Sensitivity Studies
- Section 8 - Application to Design

ABSTRACT

This report presents the description and validation of the analytical methods for calculation of the seismic loads on an HTGR core and the core support structures. Analytical modeling, integration schemes, parameter assignment, parameter sensitivity, and correlation with test data are key topics which have been covered in detail.

Much of the text concerns the description and the results of a series of scale model tests performed to obtain data for code correlation. A discussion of scaling laws, model properties, seismic excitation, instrumentation, and data reduction methods is also presented, including a section on the identification and calculation of statistical errors in the test data.

A major section was devoted to the derivation of correlation criteria which account both for errors in the test data and analytical errors due to numerical integration and code inadequacy.

The report finally describes the prototype versions of the analytical codes which will be used to provide full-scale loads for the HTGR core seismic design.

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1. INTRODUCTION AND SUMMARY

1.1. SCOPE

The high-temperature gas-cooled reactor (HTGR) core seismic program was initiated in 1970. The purpose of this comprehensive research and development effort was to predict the structural response of the core, and to adequately satisfy seismic design and licensing requirements.

In early 1974, the program was partly funded by the Energy Research and Development Administration (ERDA). Under this sponsorship, an overall core seismic verification plan was developed (Ref. 1.1-1). This plan included an expanded program for methods development and code verification, and programs for strength testing and analyzing prototype core and core support components.

The HTGR core seismic design verification program covers a combination of analysis and testing, as illustrated in Fig. 1.1-1. Special purpose one- and two-dimensional analytical models of the core and core support structures were developed since large, general purpose computer programs (e.g., ANSYS and NASTRAN) cannot efficiently model the nonlinear and discontinuous core structures consisting of over 8000 hexagonal graphite elements. These computer programs were correlated with scale model tests representing partial and full core arrays. Once verified, prototype HTGR versions of these codes will be used to calculate core design loads for the various reactor operating, life, and site conditions. These loads are then combined with other operational loads and compared with overall allowables derived from core component strength tests and design criteria. From these comparisons, the adequacy of the core component design is determined.

This report covers the core seismic methods development and verification for calculation of core seismic loads outlined by the dashed box in Fig. 1.1-1. The report documents the methods developed under this task, and presents summary descriptions and results of the seismic tests performed in support of the methods development. The results of the correlation between analysis and test data are also given and compared to specific correlation criteria established for code verification. Since the code correlation and verification task is not yet fully completed, recommendations for future work to complete this task are included. Related core design verification tasks, including core component stress analysis methods and stress criteria, are dealt with in separate topical reports.

1.2. CORE SEISMIC COMPUTER PROGRAMS

The core seismic computer programs (codes) are required for determination of the overall response and displacement characteristics of the core and to calculate design loads for the in-core and core support structures.

No general purpose codes that meet the above requirements have been found. This is the result of a number of limitations, especially the inability to efficiently treat impacts and nonlinear characteristics in large numbers. Although the programs developed are special purpose codes, they have been made as flexible and as user-oriented as possible. The only restriction is that the general physical configuration of the core remains relatively constant. Such design variables as block geometry, spring rates, damping values, number of elements, various core gaps, etc., are all user-input. The programs may be used to model either partial- or full-core arrays simply by specifying the correct input parameters.

A number of similarities exist in all the programs developed to determine the core response. For instance, none of the codes are based on finite element or finite difference formulations, but rather use lumped mass and inertia concepts. A core element, therefore, is treated as a

"rigid" body with the appropriate number of rigid-body degrees of freedom, while the element flexibilities are input as discrete springs and dampers for corner, edge, or flat-to-flat contacts, as appropriate.

Due to the inherent nonlinearity of the core response, time history integration is required. Both explicit and implicit time integration techniques have been investigated. Similarly, constant and variable time step routines have been studied, and convergence characteristics as a function of time step size have been investigated. In general, for large size problems, the central difference operator has proven most efficient, although for problems with relatively few degrees of freedom some of the variable time step methods are effective.

For all the analytical models, the PCRV is considered as a rigid boundary. For analysis, testing, and code verification purposes, input motion to the core is determined separately from an overall dynamic model that includes the amplification effects of the PCRV and containment structure as well as radiation damping resulting from soil-structure interaction. The structure is assumed to be founded on a wide range of site conditions from very soft soil to competent rock, and utilizes artificial earthquake time histories whose response spectra envelop those specified in U.S. NRC Regulatory Guide 1.60.

Table 1.2-1 summarizes the core seismic computer programs currently developed and their status. CRUNCH-1D and CRUNCH-2D model one- and two-dimensional horizontal arrays, respectively. Both programs provide for modeling and relative motion between a horizontal layer of elements and the core support floor by means of linear springs and dashpots, which represent the shear and rocking constraints imposed by the core columns. Input parameters such as contact time for impact, block-to-block coefficient of restitution, etc., are obtained from tests as described in Section 1.3. Various means of energy dissipation including friction and structural damping have been investigated, but simple viscous damping has proven to be the most tractable for analysis. It also has been shown to provide acceptable correlation with the test data.

TABLE 1.2-1
SUMMARY DESCRIPTION AND STATUS OF THE CORE SEISMIC COMPUTER CODES

Code	Function	Status
CRUNCH-1D	Models a horizontal strip diametrically across the core. Effects of core column restraints and core support floor are included. Calculates in-core horizontal (flat-to-flat) impact forces and spring pack support forces.	Development completed; documentation and user's manual issued. Code correlation with test data and verification completed (Ref. 1.2-1).
CRUNCH-2D	Models a two-dimensional horizontal array within the core. Effects of core column restraints and core support floor are included. Computes the response to simultaneous two-axis horizontal ground motion. Calculates in-core horizontal (flat-to-flat) impact forces and as well as radial and tangential spring pack support forces.	Development completed, documentation and user's manual issued. Code correlation partially completed; needs further verification (Ref. 1.2-2).
COCO	Models one entire core column, core support block, and post. Computes the response to simultaneous horizontal and vertical input. Calculates fuel element impact forces with the boundary supports, dowel forces, rocking angles, and rock-down forces.	Development completed; documentation and user's manual issued. Code correlation and verification completed (Ref. 1.2-3).

TABLE 1.2-1 (Continued)

Code	Function	Status
MCOCO	Models a series of columns diametrically across the core including core support blocks and posts. Computes the response to simultaneous horizontal and vertical inputs. Calculates rocking angles, in-core element impact forces (flat-to-flat and edge), dowel forces, core support block forces, and horizontal and vertical support forces.	Development completed; documentation and user's manual issued. Code correlation ongoing (Ref. 1.2-4)
COCOROD	Models the dynamic interaction between a control rod and a core column; allows for a variation of rod insertion depth. Computes the response to simultaneous horizontal and vertical input. Calculates control rod canister impact loads and control rod shock absorber load.	Development completed; no formal documentation. Code needs verification (Ref. 1.2-5).

COCO and MCOCO were developed to treat motion in a column and in a linear array of columns, respectively. These programs consider both vertical and horizontal seismic input and provide core element dowel forces, horizontal face impact loads, edge impacts, and core support post loads, which are not available from the horizontal array programs.

Finally, the program COCOROD has been developed to investigate the dynamic interaction between a control rod and a column. The control rod is modeled as a chain-type structure that includes friction developed in the pin joint between canisters. The rod may be positioned at any location relative to the column, and models various types of impacts. In addition to determining the impact loads on the canisters, the program computes the effect of a control rod on the column response, and may also be used as an aid in evaluating the effect of an earthquake on reactor scram time.

In their present form, the two-dimensional codes MCOCO and CRUNCH-2D are very expensive to run. Accordingly, the one-dimensional CRUNCH-1D code is to be used in the design evaluation phase for parametric studies to locate the most severe environment on which the final design load calculations are based. The final design loads are then obtained with the two-dimensional codes CRUNCH-2D and MCOCO.

Sensitivity studies were performed using CRUNCH-1D because this code contains the basic features of the more sophisticated MCOCO code and is relatively inexpensive to run. The sensitivity study indicated that the random numerical error in the code results, due to integrating over impact mechanism spring and damping force discontinuities, could be as large as 20%, on a 2σ basis. This error decreases with decreasing integration time step size. The results also showed a number of cases where input parameter variations over an expected range resulted in variations of code results that exceeded the inherent error associated with numerical integration. The effects of these parameter variations on the core design must therefore be considered when subsequently using prototype versions of the codes.

1.3. CORE SEISMIC TEST PROGRAM

An extensive test program was conducted to experimentally evaluate the core seismic response. The purpose of these tests was (1) to provide basic data such as block impact spring rates required as computer code input, and (2) to provide characteristic behavior and experimental data for correlation with analytical results in order to prove the validity of the codes. The testing was carried out on 1/5- and 1/2-scale core arrays and some full-scale arrays that did not exceed the weight and size capacity of the test equipment. Table 1.3-1 summarizes the tests and their status.

Local fuel element behavior characteristics were investigated in the element collision tests and rocking tests (Tests 1 and 2). The collision tests consisted of sliding fuel elements on "frictionless" rails and producing interblock collisions with arrays of blocks ranging from two to five elements. Basic data of contact time and coefficient of restitution were obtained. These quantities varied with the impact velocity. At 50 in./sec, which approximately represents the maximum velocity during an operating basis earthquake (OBE), mean values of contact time and coefficient of restitution for a standard H-451 unirradiated fuel element were estimated as 2.3 and 0.5 msec, respectively.

The rocking tests were performed with two to four elements stacked on top of each other. The blocks were displaced to a set configuration and then released. Both the collision dynamics and basic rocking tests provided simple element motion characteristics in the horizontal and vertical planes. Analytical results were compared with the test data to assure that individual collision and rocking phenomena are treated adequately within the computer program.

A more complex series of tests was conducted on partial horizontal planar arrays of 73 elements (Tests 3 and 4) using 1/5- and 1/2-scale models. The objective of these tests was to experimentally determine the two-dimensional response characteristics of a horizontal section of the

TABLE 1.3-1
SUMMARY DESCRIPTION AND STATUS OF THE CORE SEISMIC TESTS

Test	Function	Status
1. Collision dynamics tests (1/5, 1/2 and 1/1 scale, 2-5 elements).	Study of collision behavior between fuel elements in arrays of two to five elements. Obtains contact time and coefficient of restitution. Correlation with analytical collision model.	Testing completed and test report issued (Ref. 1.3-1).
2. Basic rocking tests (1/5 and 1/1 scale, 2-4 elements).	Study of fuel element rocking behavior in arrays of two to four elements stacked in a column. Correlation with analytical collision/rocking models.	Testing completed and test report issued (Ref. 1.3-2).
3. 2D horizontal array tests (1/5 and 1/2 scale, 73 elements).	Study of effect of core gap on seismic response. Obtains in-core velocities, forces, and boundary loads. Correlation with CRUNCH-1D and -2D	Testing completed and test report issued (Ref. 1.3-3).
4. 2D, two-axis horizontal array test (1/2 scale, 73 elements).	Study of simultaneous two-axis horizontal excitation; obtain in-core velocities, forces, and support loads. Correlation with CRUNCH-2D.	Testing completed and test report issued (Ref. 1.3-4).
5. Single column test (1/5 scale, 10 elements).	Obtains core column dynamic properties and studies simultaneous horizontal and vertical excitation. Obtains rocking angles, element forces, dowel forces, and support loads. Correlation with COCO.	Testing completed and test report issued (Ref. 1.3-5).

TABLE 1.3-1 (Continued)

Test	Function	Status
6. 3D test, uniaxial (1/5 scale, full array).	Study core dynamic characteristics, effect of excitation axis direction, lateral support stiffness, and seismic wave properties. Obtains in-core velocities and forces, boundary displacements and velocities, and support forces. Correlation with all codes.	Testing completed and test report issued (Refs. 1.3-6, 1.3-7).
7. Dowel force test (1/5 scale, full array).	Obtains as an extension to Test 6, dowel forces and improved incore forces, edge and corner loads, and rocking angles. Correlation with all codes.	Testing completed and test report issued (Ref. 1.3-8).

core without the complicating effects of the core support floor and the elements immediately above and below the section of interest. The elements were supported on very low friction supports, which maintained the elements in a vertical position but provided virtually no lateral or torsional restraint. Tests were conducted for both single- and two-axis simultaneous horizontal inputs. Variations in interblock gaps were also investigated to simulate and evaluate the changes in the response that are experienced for different reactor operating conditions. These tests demonstrated the characteristic behavior of the HTGR core, which was later confirmed by full-array tests. The core behavior was characteristic of a nonlinear spring hardening system, showing a resonant frequency mainly dependent on the core gap and excitation force magnitude. Simultaneous two-axis input motion did not alter the core resonance characteristics significantly. The results from both single- and two-axis testing were used for correlation with the one- and two-dimensional codes modeling a horizontal core section.

Tests of a similar scope were performed on a single 1/5-scale column (Test 5) supported vertically on a simulated core support block and post system. The column was confined inside a rigid boundary separated by adjustable gaps on each side. These tests were performed in order to verify that the response of a single column could be adequately treated analytically before combining a series of columns into a much more complex analytical model. The column was subjected to both horizontal and vertical input motion, both separately and combined.

The horizontal and vertical resonance characteristics of the column were obtained. The horizontal resonance resembled the spring hardening characteristics obtained for the planar array test, while the vertical resonance, obtained at a much higher frequency, showed spring softening characteristics. Of particular interest was the column response to biaxial excitation. It was found that the vertical input had little effect on lateral column response such as rocking angles, impact forces, and dowel forces. However, horizontal excitation produced substantial

vertical support loads due to element rocking. Extensive correlation with analysis was undertaken to verify the modeling of column characteristic behavior.

Full core behavior was studied with a 1/5-scale model of a 3000-MW(t) HTGR core (Tests 6 and 7). The model included more than 8000 graphite elements representing fuel elements, reflector elements, and core support blocks. These tests were limited to separate uniaxial input across the flats of the hexagonal fuel elements and across the corners. Testing with synthesized earthquake motion was accomplished for a range of g-levels (equivalent ground peak acceleration) and soil conditions representative of a plant located on very soft soil to hard rock.

Many significant results were documented. The most important results were measurement of separate lumped core and core support floor resonant frequencies. The effective damping ratio of the lumped core mode was determined to be over 18%.

The data indicated a minimal amount of cross-axis response consistent with observations from the planar array tests. It appears, therefore, that three-dimensional methods are unnecessary and two- and even one-dimensional analytical codes can provide realistic results.

Emphasis was placed on recording representative fuel element impact loads and dowel pin forces at several radial core locations and elevations. Using a special measurement technique, flat, edge, and corner impact loads were determined. It is important to correlate all these data with the analysis since different fuel element strength allowables are specified for such loads. These data were employed in the verification of the multicolumn code (MCOCO).

The successful completion of the above tests to achieve the desired test objectives and produce valid data is very dependent on the instrumentation and its applications. Since the start of the first test program, there has been a continuous development effort to improve the methods and

accuracy of data measurement. The use of Kistler-type load washers embedded in the fuel element to measure impact loads has in particular proved to be an effective and reliable method. Likewise, the use of eddy current probes to measure small displacements and record accurately the velocity at element impact is a considerable improvement over old methods. In addition, considerable effort has been expended in developing data reduction software, which has resulted in computer programs providing meaningful and organized data that can be readily compared with analytical results.

The accuracy of the test data was assessed by a number of random error analyses. The total random error was obtained by either combining the contributing error sources or performing statistical calculations on a sample of data obtained from repeated tests. The largest error sources occurred in the test input, specimen geometry, and some instrument calibrations. Considerable data scatter was present in some core response measurements. This scatter could induce a relatively large error in the mean value of the measurement unless several repeated tests were run. Since the correlation method uses mean values, larger emphasis on repeated testing in the future is recommended.

Comparisons between 1/5-, 1/2-, and full-scale test data were performed where possible to establish the validity of the scaling laws and to check the effect of model property distortions. The results from collision tests, rocking tests, and two-dimensional array tests indicate that the element forces and contact time for impacting elements do not scale. This was caused by utilizing graphite as a structural material for the 1/5- and 1/2-scale elements, which results in an incorrect ρE ratio affecting the stress wave propagation through the element. This is a local phenomenon, and does not affect the overall motion of the element assemblies. Hence, the scaling relationships for displacement, velocity, and frequency, as shown by the test data, are correct within the test data error bounds.

1.4. CORRELATION OF THE ANALYTICAL CODES AND TEST RESULTS

The criteria for correlating the analytical results with the test data are specified in Section 6.1. The primary design parameters correlated were core resonant frequency, element deflections, velocities, impact forces, boundary support forces, and dowel shear forces.

An acceptable correlation error for each of these parameters was established. These errors were based on the random errors in the test data, code numerical error, and inaccuracies in the analytical modeling. This code verification was achieved if the correlation errors for all code design parameters were equal to or less than the acceptance errors.

In most cases, the code results satisfied the correlation criteria. However, where the criteria were not met, further modeling refinements are expected to bring the analytical values within the specified limits.

The most extensive correlation study to date has been with the CRUNCH-1D code. The initial comparisons have been made with the collision tests: one moving core element colliding with three stationary elements, and four moving elements colliding with a bumper support. For the inter-element collisions, both test and analysis show identical velocity trends after impact. The correlation errors were only 0.03 to 0.08, which demonstrated that the single and multiple element collisions were very well modeled. The correlation with the bumper test data was not as good. However, errors of 0.20 to 0.22 were obtained, which met the correlation criteria.

The CRUNCH-1D code did not correlate well with the reduced planar array tests. The 1/5-scale, 73-element planar array test was compared with the CRUNCH-1D analytical results. Both frequency response and load magnitude errors exceeded correlation criteria limits. The discrepancy in load calculations was apparently due to the hard boundary supports employed in the test, producing loads that were very sensitive to support adjustment tolerances.

The CRUNCH-1D correlation with the 1/5-scale, full-array test was performed with a model incorporating the effects of the column and core support floor structures. In the case where the core was laterally supported by soft boundary supports, the lumped core motion was accurately simulated by the CRUNCH-1D model. Boundary forces for several seismic time histories for a range of acceleration levels from 0.1 to 0.5 g show correlation errors equal to or less than 0.20, which satisfies the correlation criteria. The correlation error for the resonant frequency was 0.14 at 0.3 g and 0.10 at 0.5 g, both within the criteria. The CRUNCH-1D results did not correlate as well with the boundary forces when hard boundary supports were incorporated as in the planar array test model. This is of lesser consequence since hard boundary supports are not representative of the HTGR design.

Interelement forces, measured in the dowel force test, were relatively insensitive to boundary support stiffness, and correlated quite well. In most of the cases, considering several time histories and g-levels, the correlation was within the acceptance criteria, or the analytical values exceeded the test values.

Based on the above results, it was concluded that the CRUNCH-1D model is adequately simulating the three-dimensional HTGR core for the purpose of preliminary design evaluation and parameter studies.

The CRUNCH-2D code was correlated with the planar array tests including simultaneous two-axis excitation tests with the 1/2-scale planar array model. Results similar to that of CRUNCH-1D were obtained showing correlation of the resonant frequency within the criteria limit and poorer correlation of boundary support forces. The latter result was again due to the hard boundary supports in these test models.

Results from a full 600-element CRUNCH-2D model were correlated with the 1/5-scale, full-array dowel force test data. Comparison with core boundary support forces showed that maximum loads correlated well within

the criteria. However, the interelement forces did not meet the criteria. Additional correlation and other model refinements of biaxial effects are required for final verification of this code.

The COCO single-column model was developed for inclusion into MCOCO, which models an array of columns. Single-element models were first verified by comparison with full-scale fuel element rocking tests consisting of two elements rocking on a clamped base element. These correlations showed that the element rocking motion was adequately simulated by the analytical model, the rocking period satisfying the correlation criteria.

The COCO horizontal and vertical column resonances were compared with the results from the single-column test. The correlation showed that both satisfied the criteria on resonant frequency. The response magnitude, however, was in both cases overestimated, which suggests that additional column damping is needed for better analytical predictions.

The COCO model was also correlated with results from horizontal and vertical time history excitation input ranging from 0.25 g to 0.75 g. The code did not achieve acceptable correlation for element rocking angles, impact forces, and dowel forces, which again demonstrated that the hard boundary supports employed in the tests did not produce suitable data for code correlation. On the other hand, correlation of these parameters in the COCO code was not important since the single column model is not an adequate representation of the full HTGR core. However, the single-column frequency response correlation results were considered to have demonstrated the adequacy of modeling basic column characteristics in MCOCO.

Initial results of the 28-column MCOCO full-array model were compared with data from the 1/5-scale, full array and dowel force tests. A comparison of frequency response from a sine sweep up to 4.4 Hz has so far proved inconclusive. The sine sweep did not produce the core resonance, which occurred at 4.1 Hz in the test. It was found, however, that overall core behavior was predicted consistent with test observations, showing predominately bumped core oscillations.

A time history run of 1 sec duration showed acceptable correlation of fuel element rocking angles but inadequate core correlation of boundary support forces, element impact forces, and dowel forces.

Further frequency and time history response comparisons will be performed when the run costs of the analytical model can be drastically reduced with the use of an array processor.

1.5. RECOMMENDATIONS

Since 1974, the seismic methods verification task has followed the recommendations jointly arrived at by ERDA and GA. These recommendations consisted of computer code improvements and additional tests for code verification, which would bring the task to a successful completion. A program plan to accomplish this was issued in 1975 (Ref. 1.1-1), and many of these recommendations have since been implemented. However, during this period the analysis, testing, and code correlation performed have led to reassessment of early recommendations. As a result, a somewhat modified program plan is now recommended, the details of which are discussed below.

1.5.1. Additional Computer Program Improvement

No development of new analytical methods for core seismic analysis is recommended, and only modifications to the existing codes are necessary to obtain better correlation with some test data, achieve improved efficiency, and reduce run cost. Several decisions that greatly influenced further code development were reached. Use of analytical modeling as the impulse momentum principle was abandoned since neither higher accuracy nor cost savings resulted from this technique. The COCO code was not given design code status since it was concluded that the representation of the core as a single column was too simple. For that reason, COCO is merely regarded as a development step towards the multicolumn code MCOCO. It has also been decided not to attempt to develop a three-dimensional code since the cost of analyzing a full-core array consisting of more than 8000 elements is at the present time prohibitive.

1.5.1.1. CRUNCH-1D. Program CHUNCH-1D represents an inexpensive tool that can provide preliminary design loads and evaluate the effect of core parameter variations and environmental changes. There are basically two areas of CRUNCH-1D that need further improvement: modeling of the core support floor, and the fuel element column. These improvements are aimed at achieving better correlation with the 1/5-scale, full-array and dowel force tests, and further confirm the validity of CRUNCH-1D to analyze 3D core configurations.

1.5.1.2. CRUNCH-2D. Program CRUNCH-2D models the columns and core support floor in a manner similar to CRUNCH-1D. Hence, the model improvements discussed in Section 1.5.1.1 will equally benefit CRUNCH-2D.

1.5.1.3. COCO. No plans presently exist for additional correlation or model improvement for the COCO code. The COCO code has been correlated adequately with the single-column shake test to establish a unified, basic column model for use in MCOCO. The COCO code will not be used for design analysis.

1.5.1.4. MCOCO. Program MCOCO was correlated to a limited extent. Additional correlation studies with the 1/5-scale, full-array tests are necessary to verify the MCOCO model. At the same time, code modeling deficiencies are to be corrected to enhance the similarity between the analytical model and the test configuration. These consist of inclusion of a permanent side reflector block restraint, more detailed core gap definitions, revised interaction between the core support floor and the lateral support, and the inclusion of friction elements between adjacent vertical core element faces.

1.5.1.5. COCOROD. Correlation of this code is not necessary since it retains all the features of the COCO model with the addition of a control rod. As the mass of the control rod is very small in comparison with the fuel elements, it does not affect the column motion characteristics. Improved control rod mechanical properties are required at a later date to calculate final control rod design loads.

1.5.2. Reduced Computer Model Studies

A large number of computer runs are usually needed to produce final core seismic design loads. The cost of such an analysis with CRUNCH-2D and MCOCO can therefore be enormous since both codes are very expensive to run. Reduced models of these codes are therefore under development with the objective of reducing the number of degrees of freedom in the models while retaining the important characteristics of the larger degree-of-freedom systems. This will still ensure realistic design information but at reduced cost.

In CRUNCH-2D, the reduced model consolidates the seven fuel elements of a refueling region into one element. This reduces the number of elements in the full core from about 600 to 100. In MCOCO, the model reduction was accomplished by reducing the 14-element column to a 5-element column. The block heights in the column were based on the break points observed in the full column analysis. In addition, one column was located on a core support block, which reduced the total number of columns; however, the total mass and core gap were retained.

1.5.3. Additional Testing for Code Verification

The test program has provided a large and varied data base from which selected data have been utilized in the code-correlation analysis. These data represent the more important core design parameters, and have been obtained for typical reactor conditions. So far the correlation of analysis with test results has proven successful, and further testing to expand on this data base is not considered necessary.

This includes earlier plans to conduct further tests with the 1/5-scale, full-array model with simultaneous horizontal and vertical excitation input or a proposed alternative test consisting of a vertical array of 1/2-scale columns. These tests would have been modified to represent more exactly the model scaling laws by eliminating the distortions in the present model element designs (see Section 4.1). By better modeling,

these tests were meant to provide an improved data base for code correlation as well as verify core biaxiality behavior. However, comparisons of normalized test data from test assemblies of 1/5-, 1/2-, and full-scale elements indicated that the present model distortions only seriously affected the forces generated by impacting core elements, and had only a small effect on velocity and resonant frequency. (See Sections 4.3.4. and 4.4.4.). This proves that although forces were not obtained to scale in the test models, the prototype motion characteristics were adequately represented. Hence, the present data base was considered to provide sufficiently "true" core behavior for code validation. Also, since the 1/5-scale, full-array tests indicated a very small amount of structural cross coupling (less than 10%), it was not considered important to further assess the magnitude of the core biaxiality factors.

Further tests, however, are needed to establish improved material property data for input to the analytical models. These relate to fuel element impact load calculations for corner and edge collisions, and the effect of irradiation on the graphite properties.

1.5.3.1. Nonflat Collision Tests. During a seismic event, fuel element collisions along an edge or on a corner occur more frequently than flat collisions. Such loads, in particular the corner loads, can be close to their design allowables, as indicated from analysis. More accurate material property impact representation of nonflat impact configurations is therefore needed. The tests will be carried out on full-scale fuel elements in the same manner used for the flat impact tests. Contact times and impact velocities will be measured to provide data from which dynamic spring constants and coefficients of restitution can be obtained.

1.5.3.2. Irradiated Fuel Element Tests. It is likely that the collision properties are different for irradiated fuel elements, and this could affect the calculated core design loads. Collision tests on irradiated fuel elements are therefore proposed to obtain a set of adjusted properties. These tests will be performed with end-of-life Fort St. Vrain elements when such elements become available.

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2. CONFIGURATION AND SEISMIC INPUT

2.1. GENERAL

The reactor core and core support components of an HTGR are contained by a prestressed concrete reactor vessel (PCRV), which is a multicavity structure such as the one shown in Fig. 2.1-1. The reactor core is located in the central cavity, which is connected to steam generator cavities by horizontal ducts. The primary coolant, helium, enters the core cavity through the top ducts, flows through the reactor core, and exits through the bottom ducts to the steam generators. Similar ducts lead to the auxiliary heat exchangers, which remain closed except during emergency conditions. Although the PCRV arrangement for an HTGR-GT plant is different, the core and core support structures remain unchanged. The core seismic methods verification program, therefore, is equally applicable to both concepts.

2.2. CORE COMPONENTS

The HTGR core for a large reactor consists of over 8000 hexagonal graphite elements stacked in columns normally separated by small gaps, as shown in Fig. 2.2-1. The elements are aligned in columns by means of short dowels, and are supported on core support blocks, which in turn are supported by effectively pin-ended columns. Although gaps exist between the core support blocks, they are much smaller than those between fuel element columns. The active core is surrounded by both replaceable reflector elements, which have the same hexagonal cross section as the fuel elements, and permanent reflector elements, which are significantly larger and of varying shapes. The lateral core restraints consist of nonlinear spring packs designed to absorb the core motion resulting from an earthquake. The vertical core support system comprises the core support floor

Fig. 2.1-1. Typical HTGR-SC overall arrangement

HTGR REACTOR CORE AND SUPPORT ARRANGEMENT

Fig. 2.2-1. Partial view of core cavity

and the core support posts. The reactor core and its support system, with the exception of the fuel, the nonlinear spring packs, and the top plenum elements (Fig. 2.2-1), are constructed of graphite. The following sections describe the components in detail.

2.2.1. Reactor Core

The reactor core is comprised of a large number of prismatic graphite elements of hexagonal cross section. Three basic types of elements exist: fuel elements, control elements, and reflector elements. Each full height element is approximately 31 in. in length and 14 in. across the flats of the hexagonal cross section. The fuel element, shown in Fig. 2.2-2, has a large number of closely spaced vertical holes for the passage of coolant or the containment of fuel. The coolant holes pass through the block while the fuel holes are blind. The fuel itself is in the form of coated pellets bonded together by a graphite binder and formed into fuel rods or sticks. The fuel rods are inserted into the fuel holes and the holes are plugged with graphite. The control and reflector elements have the same cross sectional shape as the fuel element. However, in some instances their length is reduced to one-half or three-fourths of a normal element. In addition, the number and size of vertical holes for the control and reflector elements differ from the fuel element. Control elements are of two types: fuel and reflector. The fuel type contains fuel and coolant holes and the reflector type contains only coolant passages. All control elements have three larger through-holes of about 4 in. in diameter, two for the control rods and one for the reserve shutdown pellets. Reflector elements do not contain fuel. However, depending on their location in the core, reflector elements may have coolant passages. In addition to these graphite elements, plenum elements are located at the top of the core. Plenum elements are comprised of stainless steel canisters filled with shredded graphite.

The elements of the core are stacked on top of each other to form fuel columns, control columns, and reflector columns. A typical fuel region

consists of a central control column surrounded by six fuel columns. The periphery of the core primarily contains reflector columns. Figure 2.2-3 depicts the plan view of a large HTGR core. Fuel regions are distinguished by pronounced solid lines. Columns outside the solid line are reflector columns.

A typical fuel column consists of, from bottom to top: two reflector elements, one of which is half-height; eight fuel elements; two reflector elements, one of which is half-height; and one plenum element. The middle eight fuel elements constitute the active core. The top reflector elements have the same coolant hole pattern as the fuel elements, while the bottom ones have partly vertical, partly slanted coolant passages which channel the helium flow to the passage through the core support blocks. These passages are designed to achieve optimum mixing. Several typical fuel columns can be seen in Fig. 2.2-1. The control rod columns are of a similar composition, while the reflector columns at the boundary of the core contain only solid reflector elements and plenum elements.

Gaps exist between the individual columns. In a new core, the gaps are small, nominally 0.04 in., and essentially uniform throughout the core. As the graphite shrinks with irradiation, the gaps increase to reach a maximum of approximately 0.15 in.

The elements within a column are aligned by dowels. These dowels transfer horizontal shear forces, but offer essentially no resistance to vertical motion. The dowels maintain alignment of the coolant holes and control rod channels between adjacent elements. During an earthquake, the dowels will be subjected to shear forces. Figure 2.2-2 shows a fuel element with a three-dowel configuration. Other dowel configurations are possible and may be modeled with the techniques described herein. The lowermost control reflector element is a three-quarter-height element. Through this arrangement, the core is "staggered" in that the joints of the control column are offset relative to the other columns.

Fig. 2.2-2. Typical fuel element

Fig. 2.2-3. Typical core plan view

2.2.2. Permanent Side Reflector

The reactor core is surrounded by the permanent side reflector, which consists of columns of stacked graphite elements. The elements are shaped to make the transition from the irregular outer core boundary formed by the hexagonal reflector columns to a polygonal cylinder that is nominally concentric with the core cavity (see Fig. 2.2-3). Each side reflector element is approximately 36.5 in. wide and the radial thickness varies from 16 in. to 36 in. Vertically each column consists of six equal-height elements. The outer face of each element contains vertical grooves along its edge. These grooves form channels approximately 3 in. deep and are continuous between two adjacent columns for interfacing with the core lateral restraint spring packs (Section 2.2.4). This keying of the permanent side reflector provides rotational restraint for itself and the core. Additional dowels and keys prevent misalignment in the horizontal and vertical directions.

2.2.3. Core Support Floor and Posts

The core support floor consists of graphite blocks supported by graphite posts. Each seven-column fuel region is supported on a single graphite core support block having the same star shape in plan view. Permanent side reflector columns are supported on individual core support blocks. The support blocks are installed with small clearances, which close during operation to form the core support floor. Figure 2.2-4 shows the layout of a typical core support floor. Each core support block has six coolant passages, one under each fuel column, and a mixing chamber. The gas flow in the central control column is directed into the surrounding six passages through windows in the bottom reflector element. Figure 2.2-5 is a cross-sectional view of the core support floor.

Each core support block is supported on three core support posts, which are approximately 6 ft. in length and 7 in. in diameter. The ends of the core support post are spherical and fit into similarly shaped

PLAN VIEW

Fig. 2.2-4. Typical core support floor

LOWER CORE CAVITY

Fig. 2.2-5. Core support structure - partial view

recesses in the core support floor elements and the PCRV bottom head. The radii of curvature of the ends of the post and the seats differ to accommodate relative motion between the core and PCRV. During a seismic excitation, the posts transfer vertical loads, but essentially no horizontal loads.

2.2.4. Core Lateral Restraint

The core lateral restraint structure is composed of a series of discrete assemblies, called spring packs, located between the permanent side reflector and the PCRV liner. These spring packs are spaced such that there is one at each intersection of four adjacent permanent side reflector blocks or permanent side reflector and core support floor blocks. The spring packs transfer lateral core loads from the permanent side reflector into the liner and support the steel plates that form the side shield.

Each spring pack contains a group of helical coil springs arranged in parallel inside a cylindrical spring housing with a pair of stiffer disk springs in series at the outer end of this housing (Fig. 2.2-6).

A face plate attached to the inner ends of the coil springs interfaces with the permanent side reflector and transfers loads into the spring. Axial and lateral deflections of the coil springs are limited by physical limit stop features. Hence, slow relative movements due to thermal expansion and PCRV shrinkage and creep are accommodated by the coil springs without developing excessive static loads. Horizontal seismic excitation of the core is transmitted through the spring packs.

2.2.5. Top Plenum Layer and Control Rods

Graphite-filled steel plenum elements form the top layer of the core. The plenum elements within a fuel region, excluding the control column, are keyed together. The recesses formed in the top of the core by the

Fig. 2.2-6. Lateral restraint structure (spring pack)

shorter control columns serve as a seat for the orifice valves used to adjust the helium flow into various regions. The control rod guide tubes connect the orifice valves and the control rod drives. The guide tubes are articulated to permit relative motion between the core and the PCRV and at the same time provide clear channels for the control rods. The control rods are also articulated to permit insertion into the core. Each rod is composed of short cylindrical segments joined together with universal joints. The segments are made up of two concentric tubes with outside diameters of 3.5 and 2 in., respectively. The space between the tubes contains graphite and neutron absorbing material in the form of boron carbide.

2.3. OPERATING ENVIRONMENT

The environment within the core cavity during normal operation, which must be accounted for when analyzing a seismic event, is discussed below. The primary coolant and its flow through the reactor core are treated along with the specific temperature, pressure, and conditions of irradiation.

The primary coolant is helium of high purity. The only impurities of concern are the small amounts of oxidants present in the form of water, carbon monoxide, and carbon dioxide. The oxidants react with the graphite and affect its strength and other mechanical characteristics. Helium enters the upper plenum above the core through the top cross ducts, flows down the core coolant passages, through the core support blocks, and into the lower plenum. A small portion of the helium flows between the columns, through the control rod channels, or bypasses the core, i.e., flows between the permanent side reflector and the PCRV. From the lower plenum, the helium flows through the lower cross ducts into the steam generator cavity.

In addition to the vertical flow, there is crossflow in the core. Crossflow may take the form of radial inflow through the permanent side

reflector or flow through the horizontal gaps between adjacent elements in the same column. In an idealized configuration, these gaps are closed. However, practically speaking, small gaps due to manufacturing tolerances and nonuniform dimensional changes will exist. In addition, during a seismic event the motion of the core will tend to increase these gaps.

The helium pressure in the upper plenum and in the annulus between the permanent side reflector and the sidewall of the PCRV during normal full power operation is 725 psia. The pressure in the core varies between 725 and 715 psi, such that the pressure drop is 10 psi. There is an additional 1.5 psi drop through the core support floor, for a total pressure differential between the upper and lower plenum of 11.5 psi. Of the 10 psi drop through the core, a fraction takes place at the orifice valves, and the rest is lost in friction inside the coolant holes.

The radial pressure drop across the permanent side reflector varies from nothing at the top to 10 psi at the bottom. The variation is approximately linear. The radial pressure drop puts the permanent side reflector into hoop compression, which tends to close the gaps and thereby reduce the radial inflow.

During normal full-power operation, the average coolant temperature is 600°F at the core inlet and 1430°F at the core outlet. Local hot streaks may approach 1980°F. The graphite temperatures during normal operation vary over similar limits with the lower temperatures occurring near the top of the core.

The fast neutron flux affects the properties of graphite and can result in distorted elements. The maximum neutron dose is 6.5×10^{21} nvt. The maximum distortion occurs in the middle of the core and reduces axially and radially. The maximum core gap occurs at end-of-life, and is predicted to be approximately 3.97 in. in the refueling condition.

2.4. SEISMIC EXCITATION OF THE CORE

The input motion to the core is determined from an overall dynamic analysis of the Reactor Containment Building (RCB) and the PCRV, including the amplification effects of the structures as well as radiation damping resulting from soil-structure interaction. For the core analysis and test programs, the PCRV is assumed to behave rigidly. The horizontal excitation of the core is determined from the PCRV response at the middle of the core cavity, while the vertical excitation of the core is determined from the PCRV response at the bottom of the core cavity. Hence, the PCRV motion is treated as a prescribed input to the core. In addition, the large differences in mass and stiffness of the PCRV compared to the core itself preclude significant interaction effects.

To determine the response of the RCB/PCRV, and, hence, the input to the core, a standard HTGR plant configuration was analyzed for a wide variety of site conditions. Similar analyses of other HTGR configurations have shown little differences in PCRV seismic response when considering a wide range of site conditions. Hence, the results presented are applicable for describing the core input motion irrespective of size.

2.4.1. Site Conditions

Applicable site impact conditions for the plant dynamic model were based on a survey of a wide range of potential sites (Ref. 2.4-1). This survey covered nearly 100 nuclear power units within the United States, and site soil parameters for more than 50 sites were investigated. Site data were summarized for the following parameters, as available:

1. Geologic profile (layering and depth to rock).
2. Velocities of each near-surface formation, i.e., compression wave velocity and shear wave velocity.

3. Density.
4. Poisson's ratio.
5. Damping values.
6. Dynamic moduli (shear moduli).
7. Applicable safe shutdown earthquake (SSE) and operating basis earthquake (OBE) values.

The sites were divided into classes with similar geologic and soil conditions, which varied from exposed bed rock to very thick soils. The sites were analyzed to determine the theoretical soil amplification spectra, effective shear wave velocity, and equivalent elastic half-space soil moduli. This range of site parameters was expanded slightly to consider the following soil properties:

<u>Site Condition</u>	<u>Shear Wave Velocity (ft/sec)</u>	<u>Soil Shear Modulus (psi)</u>
Competent rock	8000	2.5×10^6
Soft rock	3500	3.5×10^5
Firm soil	1900	9.0×10^4
Intermediate soil	1100	2.5×10^4
Soft soil	400	3.6×10^3

2.4.2. Overall Plant Seismic Analysis

The overall seismic analysis of the RCB/PCRV, including the effects of soil-structure interaction, provided the input motion to the core for the test and analysis. A schematic drawing of a typical RCB/PCRV configuration is shown in Fig. 2.4-1 with the mass point locations of the dynamic model superimposed. This is a general three-dimensional model with six

Fig. 2.4-1. Schematic drawing of HTGR RCB/PCRV with mass point locations

degrees of freedom per mass point. Stiffness properties between mass points are determined from appropriate theory or detailed static finite element models. Simplified dynamic models of major components are included in the overall model to account for coupled dynamic response. These models reproduce the fixed base fundamental frequencies of the components, their total mass, and center of gravity. The response of the points denoted "midheight PCR" and "bottom PCR core cavity" determine the horizontal and vertical excitations, respectively, of the core. In general, response spectrum analysis is performed on the coupled soil-structure system. However, the analysis of the core requires time history input due to its nonlinear behavior.

The time history analysis of the RCB/PCR was performed by rigorously coupling the mathematical model of the structure to an elastic half-space representation of the soil. The frequency-independent compliance functions of a rigid base resting upon the surface of an elastic half-space given in Ref. 2.4-2 were utilized in the analysis. Variations in soil properties are taken into account by means of the aforementioned parametric study. The response of the core is determined for real and artificial earthquake time histories. Natural earthquakes utilized in the study included the N-S component of the 1940 El Centro and Taft events. Artificial time histories for the horizontal and vertical ground motions, which produced response spectra enveloping the design response spectra of Ref. 2.4-3, were also utilized. The damping characteristics of the components comprising the overall plant model were consistent with those specified in Ref. 2.4-4.

2.5. REFERENCES

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- 2.4-3. U.S. NRC Regulatory Guide 1.60, "Design Response Spectra for Nuclear Power Plants," 1973.
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3. ANALYTICAL MODELS

3.1. GENERAL

A large HTGR core consists of 8000 or more individual graphite blocks of various types. The computer code models described in this section assume that each of these graphite blocks can be represented as a rigid body that contains the geometric, mass, and inertia properties of the core block. The motion of any point on the block that contacts another block or structure is defined by its position in the block. Contact between adjacent blocks or a block to the structure is represented by massless point models that contain gap, stiffness, energy loss, and collision effects.

If modeled in its three-dimensional entirety, the system would contain six degrees of freedom per block, or up to 48,000 degrees of freedom. The computational effort for the analysis of such a system is overwhelming. Fortunately, the core has a regular symmetrical pattern that lends itself to lesser order analysis. The approach has been to utilize a series of one- and two-dimensional models to represent the three-dimensional characteristics of the core.

Several computer programs have been developed. CRUNCH-1D models a single strip of blocks across the core at one elevation for a single horizontal excitation. CRUNCH-2D expands this representation to an entire horizontal section of the core at a single elevation, and also considers two-axis horizontal excitations. Three computer programs have been developed to evaluate vertical motion and rocking effects by modeling one or more core columns. The blocks in each column rest on each other vertically and transmit block-to-block horizontal shear forces through dowels

and friction. The program COCO models a single column of the core subjected to horizontal and vertical excitations. This single column code cannot represent the core and its restraint system completely since it treats one column alone without considering block-to-block impact. The program MCOCO expands the single-column model into a series of columns assumed to lie in a vertical plane. The program can consider a full or partial strip of columns across the core including the permanent side reflector block columns, the spring packs, the core support floor, and the core support posts. COCOROD considers a single column with a control rod that can be inserted to different levels. The effect of the inserted control rod on the response of the column is evaluated with this code. In each of the seismic codes, the PCRV is considered as a rigid boundary. The input motion to the core is determined from a separate overall plant analysis (see Section 2). The horizontal motion is transmitted to the core through the spring packs, while the vertical motion is transmitted through the core support posts.

Collisions between two graphite blocks are modeled by a linear spring and damper system. In all of the programs, explicit integration techniques are used to compute the response of the core as a function of time. The motion of each block at the start of a time step is used to determine the loads and acceleration of the block at the end of the time step. Explicit integration methods were selected over implicit techniques due to the small time steps required to accurately integrate the collision forces.

The analytical models developed for each of the core analysis computer programs are discussed below.

3.2. HORIZONTAL STRIP MODEL (CRUNCH-1D)

CRUNCH-1D models a single horizontal strip of blocks, each with one horizontal degree of freedom. The code can be used to model a strip from

the HTGR core or a single two-block collision. Figure 3.2-1 presents the model used to analyze a horizontal strip of the core. The purposes of CRUNCH-1D are to:

1. Verify the collision model through correlation with the dynamics collision tests.
2. Provide an inexpensive model to determine interblock collision forces and spring pack forces.
3. Provide parameter studies to be used to optimize the core design and to establish the critical design parameters for CRUNCH-2D, MCOCO, and COCOROD analyses.

Design loads produced by CRUNCH-1D are preliminary and must be verified using CRUNCH-2D and MCOCO. This results from the simplicity of the model based on the modeling assumptions listed below.

1. All motion is in a single horizontal direction.
2. All collisions are flat-to-flat (i.e., no corner or edge collisions).
3. Friction forces are approximated using column damping and core support floor-to-ground damping.
4. Horizontal two-dimensional effects are not included.
5. Column effects are approximated using a nonlinear column model.
6. Coefficient of restitution and contact time are not a function of impact velocity.

Fig. 3.2-1. CRUNCH-1D horizontal strip model of the HTGR core

Seismic excitation is provided by defining the motion of the PCR.V. This motion is transferred to the core through the core and core support floor spring packs. Collisions are modeled by a linear spring in parallel with a viscous damper.

The fuel columns and reflector columns are represented by a linear spring in parallel with a viscous damper. The effect of column buckling is modeled by limiting the column spring force to the force required to cause the column to buckle. The column springs are connected to the core support floor.

The core support floor is modeled as a single mass constrained between two massless spring packs. A viscous damper connecting the core support floor to ground (ground is defined as a point on the PCR.V) is provided to model the energy loss due to friction and collisions between the blocks that make up the core support floor.

A rigid link prevents the reflector blocks from moving closer together than a preassigned distance. The purpose of the rigid link option is to model the solid ring (double arch) formed in the actual three-dimensional core when the reflector blocks in the ring move toward each other. A pre-load represents the pressure differential between the bypass area outside of the ring of reflector blocks and the core cavity.

Section 5.2 presents a discussion of how the CRUNCH-1D input parameters are selected. A detailed description of the code is presented in Ref. 3.2-1.

3.3. HORIZONTAL PLANAR MODEL (CRUNCH-2D)

A two-dimensional array of the HTGR core is represented by the CRUNCH-2D horizontal planar model. The model consists of a horizontal layer of hexagonal graphite core blocks surrounded by irregularly shaped permanent side reflector blocks and a series of nonlinear spring packs and dampers.

A horizontal planar core model of a large HTGR is shown in Fig. 3.3-1. CRUNCH-2D is a relatively general two-dimensional computer code capable of handling a wide range of core blocks and boundary arrangements coupled with one- or two-axis horizontal ground acceleration inputs. The program logic is similar to the one-dimensional CRUNCH-1D code, where forces are calculated using a spring-mass-damper model.

The basic purpose of CRUNCH-2D is to determine:

1. The horizontal distribution of boundary support forces (radial and tangential components).
2. The collision forces between adjacent core elements, between core elements and permanent side reflector blocks, and between adjacent permanent side reflector blocks.
3. The loads from simultaneous two-axis horizontal excitation.

The basic assumptions of CRUNCH-2D are:

1. Elements have translational horizontal motion only, no rotation.
2. Element forces are normal to the faces; no friction or other moment-producing loads are allowed.
3. Side shield elements have a rotational degree of freedom.
4. PCRV motion has no torsional component.

The mathematical model of the HTGR core used in CRUNCH-2D consists of three types of elements. The first type is a hexagonal core element that can be either a fuel element or a reflector block. Hexagonal core elements are numbered sequentially starting at the core center and proceeding

Fig. 3.3-1. HTGR core horizontal planar array model

spirally in a counterclockwise direction as shown in the figure. The second type of element is the irregularly shaped permanent side reflector block. Permanent side reflector blocks are numbered sequentially after the core elements. The third type of element is a hexagonal block used to simulate the rigid boundary in the planar array tests (Section 4.4). These blocks are numbered sequentially after the core elements. It should be kept in mind that either the second or the third type of boundary block is used, but never both. The spring pack model simulates the actual spring pack with a face plate attached. The face plate is assumed to have both radial and tangential motion. Figure 3.3-2 shows a geometrical representation of the spring pack model that includes various dampers, gap spacing, and radial and tangential springs.

In the CRUNCH-2D model, each fuel or reflector column is represented as a single mass attached to the core support floor by a column spring in parallel with a viscous damper. The core support floor is modeled as a single mass constrained by the same number of spring packs as those that surround the permanent side reflector blocks in the core model. A viscous damper connecting the core support floor to ground is provided to represent the energy and friction losses due to the collision between the core support floor blocks. A more detailed description of the column model and core support floor as well as the various dynamic properties and parameters of the CRUNCH-2D model are discussed in Section 5.3 and in Ref.

3.3-1. Correlation with experimental two-dimensional scale tests is discussed in detail in Section 6.3.

3.4. SINGLE COLUMN MODEL (COCO)

The previous two sections described one- and two-dimensional representations of a horizontal section of the core. In these models, the remaining elements in a column are simulated by column springs and dampers. To investigate the effects of a stack of graphite elements, the COCO program was developed.

Fig. 3.3-2. CRUNCH-2D spring pack model

COCO models a single column of the HTGR core constrained within a rigid boundary which is excited by specifying the horizontal and vertical motion of the boundary. The behavior of each element is modeled by a spring-mass-damper representation. The properties of the column described herein apply equally to MCOCO and COCOROD.

The basic purposes of COCO are to:

1. Establish the basic element and column model for use in the multicolumn program MCOCO through correlation with the 1/5-scale, single-column shake test.
2. Investigate the vertical response characteristics of a core column.

The basic assumptions of COCO are:

1. Each block has three in-plane degrees of freedom - horizontal and vertical translation and the corresponding rotation.
2. Column element forces act at fixed positions along the element boundaries with no change in load direction due to the displaced element position.
3. Shear forces arising from the dowel pin link and friction between elements occur at the top and bottom faces only.
4. The model can be excited by either acceleration or displacement boundary motion, in separate or combined horizontal and vertical translation. No rotational input motion is allowed.

The element flexibility and energy absorption capability are modeled as corner and center springs and dampers. The dead weight of the elements

is included in the formulation. In the column, relative motion between elements is constrained by dowels and friction forces acting at the top and bottom element interfaces. The dowels limit lateral motion, but permit vertical and rocking motions between elements. The dowels are treated as flexible members. A small clearance between the dowel and the mating hole normally exists. This gap must be closed for the dowel force to begin acting. A considerable friction force may be developed along the interelement interface. A Coulomb friction model is used in which the magnitude is linearly dependent on velocity and limited to the total vertical force multiplied by a friction coefficient. Figure 3.4-1 shows a schematic drawing of a COCO model, while Fig. 3.4-2 depicts the interface region between elements. A detailed description of the model is contained in Ref. 3.4-1.

3.5. MULTICOLUMN MODEL (MCOCO)

The program MCOCO expands the single column model of COCO into a series of columns assumed to lie in a vertical plane. This is essential to assessing the dynamic behavior of several columns interacting by interelement impact. The fuel columns are modeled in the same manner as in COCO (Section 3.4). To more closely represent the actual HTGR core configuration, several additional components were modeled. The core support floor, core support posts, permanent side reflectors, and the boundary spring packs were incorporated into the model as shown in Figs. 3.5-1 and 3.5-2. Plate elements may also be included to model core barrel plates that existed in the 1/5-scale test configuration. The columns are excited by specifying the horizontal and vertical motions of the boundary.

The basic purposes of MCOCO are:

1. To provide interelement collision forces, spring pack forces, dowel forces, and support post loads along with all other necessary loads and horizontal and vertical core response characteristics for use in the design of HTGR cores.

Fig. 3.4-1. COCO model of a column of blocks

Fig. 3.4-2. Element interface models in COCO

Fig. 3.5-1. MCOCO model of core support block and posts supporting three fuel columns

Fig. 3.5-2. MCOCO model of a reduced core array

2. Using reduced models, to provide parameter sensitivity studies for identification of the critical design conditions.
3. To calculate the basic column dynamics to be used as boundary motion in COCOROD for evaluation of the control rod design loads.

The basic assumptions for MCOCO are:

1. All motion occurs in the vertical plane with each element allowed three degrees of freedom, horizontal and vertical translation, and in-plane rotation.
2. Element forces act at fixed locations on the block and do not change direction with element movement. The element model is the same one used in single column COCO.
3. Shear forces occur at the top and bottom element faces only.
4. Core support blocks support either three fuel columns or one column of reflector blocks.
5. There are two core support posts modeled for each support block.
6. The model accepts only translational acceleration input from the boundary, horizontal or vertical (separate or combined), with no rotational component.

The model of the core support block, core support posts, and fuel and control rod columns is shown in Fig. 3.5-1. The fuel elements transmit lateral loads to the core support blocks through Coulomb friction dampers and dowel springs. Vertical forces are transmitted through contact springs and dampers. Under each core support block, the two support posts

provide restraint in both the vertical and lateral directions. Core support blocks may sustain impacts from forces transmitted through four corner spring-damper "collision mechanisms." Each support block has three degrees of freedom.

The fuel element width was not required to be uniform throughout the core although the elements in any one column must have the same width. The geometrical and physical properties of the core support blocks can be arbitrarily selected, except that the block widths should be compatible with the width of the three columns they support. The gaps between the fuel element columns and between the core support blocks are separately assigned.

The outer core support blocks support the reflector columns. The lateral restraint between the reflector column and the outer (PCRV) boundary was modeled by a series of nonlinear springs having a bilinear stiffness, simulating the HTGR lateral spring packs. Appropriate gaps were input between the reflector column and these springs. Plate elements incorporated between the reflector blocks and the spring packs represented the core barrel plates in the 1/5-scale, full-array test. These are discussed further in Section 5.5.

A full-array MCOCO model is shown in Fig. 3.5-3. The components of this model include hexagonal fuel elements (full, half, and three-quarter height), plenum elements (half-height), permanent reflector blocks (PRB), core barrel plates, core support elements, and spring packs. Spring packs are located at the upper and lower corners of the core barrel plates. The model accepts acceleration input in the form of a sinusoidal sweep, dwell, or time history. A more detailed description of the model is contained in Ref. 3.5-1.

Fig. 3.5-3. MCOCO model of the 1/5-scale, full-array test configurations

3.6. SINGLE COLUMN CONTROL ROD MODEL (COCOROD)

The large HTGR reactor core contains over 100 control rods operated in pairs by control rod drive mechanisms, which raise and lower the rods through two holes in the fuel element columns. The insertion of a control rod introduces nonlinear coupling between the stacked elements and the control rod canisters when the system is subjected to seismic motion. The program COCOROD models a single COCO column with one channel through which a control rod is inserted to varying depths (Fig. 3.6-1). The COCOROD model is excited by boundary motions in both the horizontal and vertical directions. The column properties are the same as in COCO except for the addition of the control rod.

The basic purposes of COCOROD are to:

1. Analyze the seismically induced loadings on the control rods, including impact and joint loads for use in control rod design.
2. Determine the effect of core seismic motion on control rod insertion dynamics.
3. Evaluate the influence of the control rods on the HTGR core dynamics.

The control rod is represented by a series of rigid mass canisters connected by spherical ball joints having a prescribed amount of friction. The flexibility of the connecting rods is included. The shear, bending, and axial stiffnesses of the supporting cable may be accounted for in the model.

The basic assumptions of COCOROD are as follows:

1. The control rod is assumed to hang on a flexible cable with its top end moving with a prescribed motion such as that of the top section of the PCRV.

Fig. 3.6-1. COLOROD model of fuel element column and control rod

2. Each column element and control rod element has three in-plane degrees of freedom and the single-column configuration of COCO is used.
3. Both the column elements and the control rod elements are rigid masses with point impact models made up of springs and dampers.
4. The control rods are inside the fuel elements, and the contact points between the control rods and column elements are dependent on insertion position. Load directions are fixed, however, for each insertion position.
5. Control rod elements are connected by ball joints, which provide tensile restraint for the control rods unlike the fuel element interfaces.
6. Originating from COCO, the model accepts either acceleration or displacement boundary motion in separate or combined horizontal and vertical translation. No rotational input motion is allowed.

Depending on the location of the individual control canisters relative to the adjacent elements, different types of impacts may occur, as shown in Fig. 3.6-1. This results from the variations in the stiffnesses of the canister body, corner, and stand-off fins as well as the element corners and channels. The HTGR core was designed such that the cumulative gap between columns across the core was limited in order that the relative rotation between adjacent elements cannot cause binding or crushing of a canister. Simultaneous impact of all three types on a single canister was thus prevented. Although contact points were assigned at more than one location on the surface of a canister, significant impact forces were usually produced by the impingement of stand-off fins against the channel wall. Collisions between the canister body and the channel wall, at the ends of a fuel element, seldom occurred. Further details of the COCOROD model are contained in Ref. 3.6-1.

3.7. REDUCED CORE MODELS

Since a large number of computer runs must be made to verify the seismic design of the reactor core, use of the present two-dimensional core models CRUNCH-2D and MCOCO will result in prohibitive costs. Reduced models of these codes are currently being developed. The models have fewer degrees of freedom but contain the physical features and dynamic behavior of the original codes.

3.7.1. Reduced CRUNCH-2D Model

The basis for the reduced CRUNCH-2D model is to consolidate the seven fuel elements making up a fuel region into one block as depicted in Fig. 3.7-1. This model would be run to establish the most severe loading condition on the elements, which in turn would be reanalyzed with the original code.

3.7.2. Reduced MCOCO Model

The typical full-array MCOCO model includes 24 or more fuel columns, each of which contains 6 to 14 elements. The total number of degrees of freedom (three for each block) can be 1000 or more. MCOCO is the most costly analytical tool in the core seismic analysis library, and any reduction in the model size would significantly reduce design costs.

Two basic techniques were employed in the derivation of the reduced MCOCO model. First, the number of elements in a column was reduced from 14 to 5. The height of the element in the reduced model was specified by the observed break points in the full column, as shown in Fig. 3.7-2. The second reduction technique for the model was the consolidation of three columns on a fuel element into a single column.

The parameters of the reduced models (for example, element mass, spring rates, damping ratios, across-core gap,) are currently being

SEVEN BLOCK
FUEL REGION

REDUCED
MODEL

Fig. 3.7-1. CRUNCH-2D model reduction

FULL
FOURTEEN-
ELEMENT
COLUMN

REDUCED
FIVE-
ELEMENT
COLUMN

Fig. 3.7-2. MCOCO reduced column model

adjusted so that this model exhibits a response similar to that of the original code. Response quantities include resonant frequency, lumped mode behavior, boundary support load, and fuel element collision and dowel pin loads. As in the case of the reduced CRUNCH-2D model, the reduced MCOCO model is planned for identification of the worst loading conditions, which will be subsequently reanalyzed using the full-core column code.

3.7.3. Array Processor for Reduced Computer Costs

An array processor unit is planned as an addition to the General Atomic Company Univac 1110 computational system. This device will reduce the computational costs of running the core seismic codes by more than a factor of 10. The efficiency of the array processor is derived from simultaneous execution of many computational processes, and use of the unit as a satellite to the Univac 1110 system.

3.8. REFERENCES

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4. TEST PROGRAM

This section summarizes the seismic test program performed in support of the analytical development described in Section 3. The scale-model tests were designed to provide basic data on individual core element behavior, and to give information on the interaction of groups of elements, including two- and three-dimensional core arrays.

4.1. GENERAL

4.1.1. Test Program Scope and Objectives

Table 4.1-1 summarizes the scope of the test program. Three categories of tests were performed as follows:

1. Collision dynamics and dynamic response tests of individual core elements or small groups of elements of 1/5, 1/2, and full scale. These tests had two basic objectives:
 - a. Preparation for the more extensive tests of categories 2 and 3 by verification of testing techniques, instrumentation, and data reduction methods.
 - b. Establishment of the basic dynamic properties needed for analytical development, such as coefficient of restitution, dynamic stiffness, damping, etc.
2. Hydromechanical shaker tests on 1/5- and 1/2-scale partial sections of the core. These tests were performed to study the

TABLE 4.1-1
HTGR CORE SEISMIC TEST PROGRAM FOR ANALYTICAL CODE VERIFICATION

No.	Task	Objective
1	Pendulum collision test (1/5, 1/2, and full scale)	Coefficient of restitution - study of model scaling laws
2	Multiblock collision test (1/5, 1/2, and full scale, 2 to 5 elements)	Study of collision behavior - parameter selection for collision models
3	Basic rocking test (1/5 and full scale, 2 to 4 elements)	Study of rocking behavior - parameter selection for analytical collision/rocking models
4	Two-dimensional section test (1/5 and 1/2 scale, 73 elements)	Core gap study - code correlation, CRUNCH-1D and -2D
5	Two-dimensional two-axis test (1/2 scale, 73 elements)	Study of simultaneous horizontal axes excitation - code correlation, CRUNCH-1D and -2D
6	Single column test (1/5 scale, 14 elements)	Core column dynamic properties - study of simultaneous horizontal and vertical excitation - code correlation, COCO
7	Three-dimensional test, uniaxial (1/5 scale, full array)	Core dynamic characteristics - study of excitation axes, lateral support spring rate, and seismic input - code correlation, CRUNCH-1D and -2D, MCOCO
8	Dowel force test (1/5 scale, full array)	Obtain dowel pin forces - code correlation, CRUNCH-1D and -2D, MCOCO

effects of varying basic parameters, such as in-core gaps, and to provide data for analytical correlation.

3. Hydromechanical shaker tests on a 1/5-scale, full-array model of the core and core support system representing an HTGR reference plant design. The test results were used to study the seismic response of the core in terms of loads, deflections, and velocities and for final analytical correlation.

4.1.2. Test Specifications

The design and execution of each test were preceded by written test specifications. These contained objectives, work scope, model descriptions, and requirements for the test facility, the instrumentation, and the test procedures, as well as quality assurance and schedule requirements. The test specifications were subjected to formal review before being issued according to General Atomic standard procedures.

The approved specifications were used as the basis for a test subcontractor bid proposal in case the test was performed by an outside contractor. This has been the policy in the past. The responsibility of the test subcontractor, however, was limited to test facility, test rig, instrumentation and hardware design, testing, and data recording. The data reduction and data analysis tasks as well as the test reports were done by GA.

4.1.3. Modeling and Scaling Laws

A set of scaling laws, prepared prior to the design of the 1/5-scale, full-array test, was subsequently used for all test models (Ref. 4.1-1).

A number of independent parameters that are important for predicting the mechanical response of the core and core supports were defined. These

parameters and their dimensions are listed in Table 4.1-2. The parameters were reduced to the following nondimensional relationship:

$$\Pi = \phi \left(e, \mu, \frac{x}{t_g^2}, \frac{x^3 \rho}{t_k^2}, \frac{x^2 \rho}{t_p^2} \right) \quad (4.1-1)$$

The design restrictions below were then applied to the model:

1. A model scaling factor of λ was employed ($\lambda = 1/5$).
2. Acceleration input to the test model (m) equaled full-scale (p) HTGR acceleration magnitudes ($\ddot{X}_m = \ddot{X}_p$).
3. Graphite was chosen as the material for the core elements ($\rho_m = \rho_p$).

The scaling laws summarized in Table 4.1-3 were obtained by examining the similitude requirements in Eq. 4.1-1.

The coefficient of restitution is an important parameter since large numbers of interblock collisions occur and changes in e could affect the core motion characteristics significantly. The scaling laws require that the coefficient of restitution of the model elements, e_m , must equal that of the prototype elements, e_p . Since graphite is employed, this is easily achieved if the exact geometric similitude in element modeling exists with respect to the prototype; however, the 208 fuel and coolant holes were impractical and uneconomical to model in a 1/5-scale element. Therefore, seven-hole and one-hole models were designed and modified until the required coefficient of restitution was obtained and the correct mass was achieved using tubular steel inserts. As a result of this process, however, the element stiffness characteristics were not exactly scaled.

TABLE 4.1-2
LIST OF VARIABLES

Parameter	Basic Variable	Dimensions
Model length, displacement of PCRV, reflector, fuel element, and column gaps	x	L
Time	t	T
Support spring rate and element stiffness	k	MT^{-2}
Element density	ρ	ML^{-3}
Gravitational constant	g	LT^{-2}
Pressure drop	p	$ML^{-1}T^{-2}$
Coefficient of restitution	e	--
Coefficient of friction	μ	--

TABLE 4.1-3
SCALING LAWS FOR TEST MODEL

1. Length	$X_m = \lambda X_p$
2. Velocity	$\dot{X}_m = \sqrt{\lambda} \dot{X}_p$
3. Acceleration	$\ddot{X}_m = \ddot{X}_p$
4. Time	$t_m = \sqrt{\lambda} t_p$
5. Force	$F_m = \lambda^3 F_p$
6. Stiffness	$K_m = \lambda^2 K_p$
7. Modulus	$E_m = \lambda E_p$
8. Coefficient of restitution	$e_m = e_p$
9. Coefficient of friction	$\mu_m = \mu_p$

λ = scale factor
 m = model
 p = prototype HTGR

The scaling laws require equal coefficients of friction, μ , in model and prototype. This was impossible to achieve since environmental factors such as temperature and helium atmosphere could not be incorporated in the modeling. The net result is a lower coefficient of friction in the model core compared to the prototype, which results in a conservatively lower damped structure.

The requirement on x/t^2g couples the time scale to the length scale and gravitational field. Since the latter two variables are fixed, the time scale for the model becomes:

$$t_m = \frac{t_p}{\sqrt{5}} .$$

This means the events will transpire faster in the model.

The requirement on $x^3\rho/t^2k$ relates the stiffness (across-the-flat stiffness of a core element) to the material property, length, and time scales. Since graphite is employed in the model, density does not change and the stiffness scale becomes:

$$k_m = 25 k_p .$$

It is apparent that even if the model element were a faithful reproduction in graphite, the result would be a stiffness that is higher than the scaling laws stipulate since there has been no attempt to scale the elastic modulus E . However, by introducing the one- and the seven-hole patterns in the 1/5-scale blocks, the across-the-flat stiffness was lowered, although not enough. The result is a contact time for 1/5-scale impacting elements that is too small. The impact forces in the model blocks, therefore, are larger than the scaling laws predict. The side

support forces, however, are not affected by the element stiffness since they depend on the spring pack coil stiffness, which can be modeled accurately.

The requirement on $x^2\rho/t^2p$ relates the core column pressure drop to the density, length, and time. Since the core design was to represent the reactor in a cold and shutdown state at end of life, the pressure drop was ignored in the test design. However, for operating reactor conditions, the pressure drop adds a possible significant stiffening and restoring effect to the core column, which may influence the core resonant frequency and element forces. A further discussion of the scaling analysis for the present 1/5-scale, full-array model is obtained from Refs. 4.1-1 and 4.1-2.

4.1.3.1. "Adequate" Model Design. It is apparent from the preceding discussion that the 1/5-scale core model design is inadequate for predicting prototype forces by scaling. Such predictions were, however, not the objective of the tests. Test results are only used for code correlation purposes and prototype loads are to be obtained by analysis. Therefore, some distortion in the model is acceptable. Although a "true" model design is nearly impossible to achieve if all design conditions are to be satisfied (for a length scale not equal to unity), accurate predictions of a limited number of characteristics of the prototype, including in-core and boundary support forces, can be made from a less than perfect, or "adequate," model. The design of such a model is briefly outlined below, and may be incorporated in future testing with two- and three-dimensional core arrays. Previous work done in this area is reported in Ref. 4.1-3.

A new set of scaling laws was obtained from the following non-dimensional relationship, which considered Young's modulus (E) of the core element.

$$\Pi = \phi \left(e, \mu, \frac{\rho g x}{E}, \frac{p}{E}, \frac{g t^2}{x}, \frac{1}{E x}, \frac{w^2 x}{g} \right) \quad (4.1-2)$$

The summary in Table 4.1-4 is based on the following design restrictions:

1. A model scaling factor of λ was employed ($\lambda = 1/5$).
2. Graphite was chosen as the material for the core elements ($\rho_m = \rho_p, E_m = E_p$).

From the similitude requirement on $\rho g x/E$, it follows that an artificial gravity field of 5 g is required for the 1/5-scale model. Consequently, a downward force must be applied to the model elements to make up the 4 g difference. A possible design is a nearly massless arrangement of low modulus springs and wires to hold down the elements. In two-dimensional planar array tests, the spring/wire concept is not needed, and such tests based on the new set of scaling laws become much simplified. In either case, the boundary input acceleration must be five times that of the prototype.

Since the similitude requirement is still ignored for the internals of the model blocks, forces and stresses within the block are not representative of the prototype, and the prediction of force is valid only at the block surface. Hence, block stresses must be obtained from analysis or a different set of tests.

TABLE 4.1-4
NEW SET OF SCALING LAWS

1. Length	$X_m = \lambda X_p$
2. Velocity	$\dot{X}_m = \dot{X}_p$
3. Acceleration	$\ddot{X}_m = \frac{1}{\lambda} \ddot{X}_p$
4. Time	$t_m = \lambda t_p$
5. Force	$F_m = \lambda^2 F_p$
6. Stiffness	$K_m = \lambda K_p$
7. Modulus	$E_m = E_p$
8. Coefficient of resitution	$e_m = e_p$
9. Coefficient of friction	$\mu_m = \mu_p$

λ = scale factor
m = model
p = prototype HTGR

If graphite is not employed for the model, but $g_m = g_p$ is assumed, the requirement $\rho g x / E$ shows that:

$$\frac{\rho_m}{E_m} = 5 \frac{\rho}{E} .$$

Thus, a core model design is possible using a suitable denser material or a combination of graphite and inserted or dispersed heavy metal such as uranium oxide or lead. However, as with the spring/wire concept, shape distortions inside the model elements only permit surface forces to be predicted.

Studies of these design concepts have been undertaken in the event that further seismic testing with scale models is conducted.

4.1.4. Model Fuel Element Design

The standard 1/5-scale and 1/2-scale model fuel elements employed in the tests are shown in Figs. 4.1-1 and 4.1-2, respectively. These elements, made from commercial grade graphite H-327, are scaled versions of the prototype HTGR element (fuel included). However, exact similitude was not obtained since the prototype fuel and gas cooling holes were not represented.

The 1/5-scale standard element is nominally 6.24 in. high and 2.81 in. across the hexagonal flats and solid except for one large center hole 1.781 in. in diameter. A metal sleeve is fitted in the hole to increase the total element weight to 2.08 lb. The three dowel pins in the top surface are made of steel with a diameter of 0.124 in. and a length of 1.03 in. The three dowel pin sockets in the bottom surface contain metal sleeves, giving a total dowel/socket gap value of 0.0075 in. nominal.

Fig. 4.1-1. One-fifth-scale element, full height

Fig. 4.1-2. One-half-scale element, full height

The 1/2-scale element is nominally 14.61 in. high and 7.085 in. across hexagonal flats. The element has a seven-hole pattern with one hole in the middle of the block 2.0 in. in diameter. The six outer holes are enlarged for 2/3 of the element length such that metal bars can be inserted to achieve the correct scaled weight of 32.4 lb. These elements did not contain dowels since the elements were only assembled in a horizontal array. Instead, three spherical seats were embedded in the bottom of the element, each linking up with a standoff for vertical element support.

These elements were tested to verify the correct coefficient of restitution during element-to-element impact. The results of these tests are given in Section 4.2.

4.1.5. Instrumentation Design and Calibration

This section presents a general description of the transducers employed in the test program and some special design applications for measuring the core element impact force, dowel pin force, and element relative displacement, including uplift and rocking angle. Some methods and typical results of instrument calibration and verification are also described.

4.1.5.1. Instrumentation. The test instrumentation is categorized in the following groups: test rig instrumentation, boundary support instrumentation, and in-core (element) transducers.

In most tests, a strain gage accelerometer and/or a linear velocity displacement transducer (LVDT) were used to measure test rig acceleration/displacement and provide feedback for the hydraulic shaker servomechanism. Figure 4.1-3 is a block diagram of the control system for the 1/2-scale two-dimensional test. The displacement feedback functioned best in the lower frequency range (below 10 Hz), and the accelerometer was typically employed in high frequency studies above this value.

4-15

Boundary support instrumentation included LVDTs and Kistler load washers. Some tests required element to boundary relative displacement and velocity measurements, for which the LVDT was adequately suited. The LVDT was also employed to record the free vibration decay response of a core array following instantaneous arrest of the test rig for calculations of structural damping. Direct core support load measurements were most conveniently made with the Kistler load washers, which needed no calibration. This system, which consisted of several washers in a load cell sandwich design, is described in detail in Ref. 4.1-4.

Instrumentation of the graphite fuel element has been the subject of continuous study and development since the start of the first test program. Originally, standard instrumentation included accelerometers, strain gages for measuring element impact force, capacitance displacement gages (DEES) for measuring element relative displacement and velocity, and contactors for obtaining the collision time. These transducers were located in a group of three horizontal elements, as shown in Fig. 4.1-4, and moved as a unit to different positions in order to obtain the distribution of response throughout a core array. In later tests (dowel force tests) this scheme was expanded to include instrumentation distributed in a group of columns containing a set of transducers at several core column elevations (Fig. 4.1-5). This provided for a more efficient and cost-effective method of obtaining the distribution of the core response. By this time, newer and more accurate transducers were also employed; e.g., eddy current gages for measuring element relative displacement, including element uplift and rocking angle, and Kistler load washers for obtaining element impact forces as well as dowel pin forces. The applications of these transducers are discussed below.

It was quickly realized that the usefulness of the in-core accelerometer was limited. Attempts to obtain velocity and displacement information by signal integration were unsuccessful since the accelerations merely reflected the stress wave properties due to impact rather

Fig. 4.1-4. Three-element instrumentation package for the 1/5 scale two-dimensional and full array tests

Fig. 4.1-5. Five-column instrumentation scheme for the dowel force test

than overall block motion. Neither could the acceleration data be utilized for obtaining element forces since the element masses associated with the element collisions were unknown due to core lumping. Lumping patterns could be determined from the contact gage data in a limited way, but they were difficult to interpret. The contactors were only used extensively in the collision dynamics tests for direct measurement of contact time.

The DEES gages determined maximum separation of the fuel elements, and by utilizing a sufficiently small rate of digitization, the displacement trace was differentiated to give relative element velocities. This transducer gave reliable results, but needed calibration checks at regular intervals because of instrument sensitivity to temperature changes. The transducer was eventually replaced by the eddy current probe, which did not have this problem. The probe produced a magnetic field that generated eddy currents on conductive surfaces close by. The eddy currents caused a loss of power, which can be measured as a function of the distance to the conductive surface. In this way, the probe produced effective gap measurements up to 0.160 in. This is sufficient to calculate maximum element collision velocities and measure fuel element uplift or rocking angles up to 10 degrees. To obtain the rocking angle, simultaneous gap measurements from three probes were required, as shown in Fig. 4.1-6. The angle, rocking axis orientation, and uplift were calculated using the computer program ANGLES described in Section 4.1.8.

One method of obtaining element impact forces was from a strain gage located circumferentially in an element hole close to the impacting block surface. In the 1/5-scale, full-array test this method included one gage close to the top end of the element and one gage close to the bottom end. Since the element was subjected to two types of loading (the impact load resulting from free body collisions and the compression load resulting from a pile up of elements on the support boundary), different strain gage calibrations were required for the two loading conditions. The calibration curves are shown in Fig. 4.1-7. This method of obtaining forces has

Fig. 4.1-6. Fuel element eddy current probe for measuring rocking angles

Fig. 4.1-7. Fifth scale fuel element force calibrations

some major weaknesses. Since an impact between two elements rarely occurs flat-on, but is misaligned to some extent causing predominant edge or corner hits, the calibration curves were not always valid and large errors could be induced. This is demonstrated by the scatter in the calibration data, as shown in the figure. Furthermore, strains caused by hits on off-axis hexagonal element faces could affect the estimate of the frontal force or be misinterpreted. For this reason, in the 1/2-scale, two-dimensional tests, two sets of three strain gages located at the top and bottom of the element in separate holes were assembled to resolve the simultaneously occurring collision forces on three frontal faces. From the drop tests, illustrated in Fig. 4.1-8, force/strain factors were calculated for each impact orientation. These were then assembled in a matrix and utilized to calculate the three independent forces. Theoretically, the concept presented a logical method for obtaining fuel block loads, but it fell short of expectancy because of the problem with flat-on impacts discussed earlier.

The final, and by far the most accurate, solution for determining element impact loads consisted of the use of precalibrated load washers mounted on the side of a block behind a graphite-coated preload plate. This technique was employed in the dowel force test; 1/2-scale, two-dimensional, two-axis test; and single column test; and was incorporated to measure boundary support forces as well. The design of the 1/5-scale load cell block shown in Fig. 4.1-9 features both a five-load-cell and a two-load-cell design. In each case, part of the element was machined away and the load washers were mounted and preloaded by an aluminum plate covered with a 1/8-in.-thick graphite slab. The purpose of the graphite was to retain the impacting surface characteristics. Since the load cell system was much stiffer than the graphite element structure, the collision contact time was not altered by the instruments on the block.

The biggest advantage of the load cells was that they required no calibration. Load verification tests were performed, however, with impact

Fig. 4.1-8. Calibration of strain gages for determination of fuel element forces

FIVE-LOAD-CELL BLOCK

TWO-LOAD-CELL BLOCK

Fig. 4.1-9. Load cell instrumentation for fuel element collision forces

loads delivered from a pendulum mounted with (1) a single load washer and (2) a plate assembly with two load washers. The results of several tests using both impact devices showed good correlation between the input and the total output load consisting of the sum of the individual load washer readings. Overall, as shown in Table 4.1-5, the data gave a 6% error for the two-load-cell block and a 2% error for the five-load-cell block based on one standard deviation. These systems, in particular the five-load-cell design, were also capable of defining the impact orientation based on individual load washer readings. Similar error values were obtained for the 1/2-scale load cells, for both the block and support boundary designs.

The 1/5-scale, full-array test was repeated in order to obtain measurements of dowel forces. Two instrumentation schemes for this purpose were developed, one with strain gages and the other with a Kistler load cell. The strain gage design consisted of three steel dowel pins embedded in the element, as shown in Fig. 4.1-10. The dowel diameter, protrusion length, and stiffness were scaled from the prototype HTGR fuel element. The cantilever portion of the dowel had two strain gages attached at the base, one in the direction of excitation and the other 90 degrees to it. By calibrating these gages, the individual dowel shear loads were obtained as well as the total dowel load which was obtained by the use of electronic summers in the signal conditioning instrumentation.

Strain gage calibration was performed statically as well as dynamically, although the dowel cantilever natural frequency (1100 Hz) was high compared to the frequency range associated with the impact period (10 to 200 Hz). Dynamic calibration was performed with a pendulum arrangement, as described earlier. By adjusting the pendulum mass and using different impact media, the load magnitude and duration were varied. The results, Fig. 4.1-11, show that the dynamic calibration factor is 25% lower than the static factor.

TABLE 4.1-5
ELEMENT LOAD CELL DYNAMIC VERIFICATION TESTS
(DOWEL FORCE TEST)

Load Cell Type	Impact Configuration	Input Load (lb)	Output Load (lb)
Two-load cell block	1 flat	335	326
	2 flat	318	294
	3 flat	302	258
	4 flat	312	278
	5 point	144	124
	6 point	144	142
	7 point	144	142
Five-load cell block	1 flat	145	150
	2 flat	144	153
	3 point	151	157
	4 point	152	133

Fig. 4.1-10. Fuel element dowel strain gage instrumentation

Fig. 4.1-11. Dowel strain gage calibration

The alternative method for measuring the dowel load employed a two-component stress-sensitive load cell arranged in the fuel element as shown in Fig. 4.1-12. This load cell contains two shear-sensitive quartz wafer rings placed on top of each other and aligned with their sensitive axis at 90 degrees. The load cell was clamped down with a tube anchored to a preload plate, which also contained the standard dowel socket pattern. The load measured was the total dowel shear load for the three dowels. This concept had the advantage of providing direct load measurements, but was not suited for the 1/5-scale fuel block design due to its relatively large size and weight. Including the load cell, the nominal fuel block weight increased by 0.7 lb to 2.75 lb, and the element was noticeably top heavy. None of these problems, however, appeared in the heavier permanent reflector block design where dowel forces were also measured by this method. Dynamic verification of the two-component load cell was performed in a similar manner as for the block impact load cell, supplying a known impact load with a pendulum. Comparisons between the input and output loads are shown in Fig. 4.1-13, including the load registered orthogonal to the impact direction. The figure shows that the manufacturer's calibration constant for the load cell was not achieved in this particular application.

4.1.5.2. Signal Conditioning Instruments. Special signal conditioning instruments were designed to obtain improved digital response data. These included a peakholder designed to hold the absolute value of the peak transducer signal between multiplexer passes. This was necessary since some transducers such as the fuel block impact and dowel force instrumentation produced high frequency response that was not effectively picked up with the standard damping period of 0.005 sec. A second method for accurate determination of the peak value was to allocate more than one multiplexer channel to a transducer. In this way, the transducer was sampled several times during the 0.005-sec period. Four to 12 channels were commonly used for this purpose.

Fig. 4.1-12. Fuel element dowel load cell

Fig. 4.1-13. Dowel load cell dynamic verification

Another instrument used to manipulate the data was a summing circuit where several signals could be algebraically combined before being digitized and recorded on tape. Summed signals were also peak held in some cases. Specifically, the summer was employed for recording the total fuel block impact load from five load washers or the total dowel force and torque from three instrumented dowel pins. In the case of the dowel forces, the equations implemented in the summer circuit were:

$$\Sigma F_x = R(S_{1x} + S_{2x} + S_{3x}) \quad ,$$

$$\Sigma F_y = R(S_{1y} + S_{2y} + S_{3y}) \quad ,$$

where S_{1x} and S_{2y} are signals from the x- and y-axis strain gages on dowel numbers 1 and 2, respectively, and R is the calibration constant for the gages.

4.1.6. Data Acquisition System

A block diagram of a typical data acquisition system employed for these tests is shown in Fig. 4.1-14. The signal from each load cell, strain gage, etc., was in the range of 0 to 10 V and followed two separate paths. One was to an analog signal recorder (oscilloscope), which plotted voltage versus time. The other was through a multiplexer to a Varian 620/L-100 computer for conversion to a digital equivalent. The multiplexer served to monitor all incoming instrument signals at intervals of 0.005 sec, which constituted a pass. The computer converted the data in each pass to an equivalent integer value represented as "counts." The conversion factor was always constant at 409.6 counts per volt. Since response may vary from zero to ± 10 V, the range of these integer values was zero to ± 4096 counts. Response greater than 10 V was still output at 10 V which means the instrument is saturated. The calibration log sheets issued by the test contractor allowed conversion of the data in counts to engineering units.

Fig. 4.1-14. Typical data acquisition system

4.1.7. Excitation Input

The excitation input to the test rig structures consisted of several types of waveforms:

1. Sinusoidal sweep at constant g-level in the range of expected core frequency response.
2. Sinusoidal dwells at constant g-level.
3. Time-history input representing actual and synthesized earthquakes.

The sinusoidal sweeps were used to study the nonlinear resonance characteristics of the core models, both horizontal and vertical. The sweeps were run at 0.5 decade/minute sweeping both up and down.

The sinusoidal dwells were run for a minimum of 10 cycles at selected frequencies. The dwell was usually preceded by a sweep, in particular for dwells near resonance in order to maintain maximum amplitude level. At the conclusion of a dwell, a near-instantaneous shutdown (inside 20 msec) of the excitation was performed. This was done in order to obtain the free vibration decay rate of the core motion from which an estimate of the structural damping could be made.

The horizontal time history input represents the PCRV response at an elevation corresponding to the reactor core center of gravity with time appropriately scaled. The derivation of this input from ground excitation is described in Section 2.4. Both the natural earthquakes (El Centro and Taft) and the synthesized earthquakes represent several site soil conditions and structural damping factors. Furthermore, the synthesized earthquakes were made to satisfy the current NRC design spectrum curves (Regulatory Guide 1.60).

Due to NRC criteria changes made in December 1973, some tests employed time history input satisfying the design spectra prior to this date and some after this date. The following tests employed input satisfying the requirements prior to December 1973:

1. 1/5-scale, full-array test.
2. 1/5- and 1/2-scale, two-dimensional test.
3. 1/2-scale, two-dimensional, two-axis test.

The time history inputs for these test are shown in Figs. 4.1-15 through 4.1-23, normalized to 1/5 scale and 0.25 g equivalent ground motion. They represent site conditions as specified in Table 4.1-6.

The following tests employed time history input satisfying the requirements after December 1973:

1. 1/5-scale, full-array, dowel force test.
2. 1/5-scale, single-column test.

The time histories employed in these tests are shown in Figs. 4.1-24 through 4.1-30, normalized to 1/5 scale and 1.0 g equivalent ground motion. They represent site conditions as specified in Table 4.1-7.

4.1.8. Data Reduction

This section documents the tape handling procedures and routines for reduction of GA core seismic test data. All routines described were cataloged at the completion of the 1/5-scale dowel force test final reports; in some cases they required minor modifications for use with data from other tests.

All computer programs described are stored on punched cards as well as on magnetic tape. Further detailed descriptions and computer program listings are found in Ref. 4.1-5.

Fig. 4.1-15. Synthesized earthquake, shock 1, prior to December 1973

Fig. 4.1-16. Synthesized earthquake, shock 2, prior to December 1973

Fig. 4.1-17. Synthesized earthquake, shock 3, prior to December 1973

Fig. 4.1-18. El Centro, shock 4, prior to December 1973

Fig. 4.1-19. Taft, shock 5, prior to December 1973

Fig. 4.1-20. Synthesized earthquake, shock 6, prior to December 1973

Fig. 4.1-21. Synthesized earthquake, shock 7, prior to December 1973

Fig. 4.1-22. Synthesized earthquake, shock 8, prior to December 1973

Fig. 4.1-23. El Centro, shock 9, prior to December 1973

TABLE 4.1-6
TIME HISTORY SEISMIC INPUT CONDITIONS PRIOR TO DECEMBER 1973

Shock Number	Type	Soil Condition (modulus psi)	Structural Damping (% critical)
1	Synthesized	Rock 3.0×10^6	5
2	Synthesized	Firm 0.9×10^6	5
3	Synthesized	Soft 65,000	5
4	El Centro	Rock 3.0×10^6	5
5	Taft	Soft 65,000	5
6	Synthesized	Soft 65,000	5
7	Synthesized	Soft 65,000	2
8	Synthesized	Super soft 10,000	5
9	El Centro	Soft 65,000	5

Fig. 4.1-24. Synthesized earthquake, shock 1, after December 1973

Fig. 4.1-25. Synthesized earthquake, shock 2, after December 1973

Fig. 4.1-26. Synthesized earthquake, shock 3, after December 1973

Fig. 4.1-27. Synthesized earthquake, shock 4, after December 1973

Fig. 4.1-28. Synthesized earthquake, shock 5, after December 1973

Fig. 4.1-29. El Centro, shock 6, after December 1973

Fig. 4.1-30. Synthesized earthquake, shock 3 vertical, after December 1973

TABLE 4.1-7
TIME HISTORY SEISMIC INPUT CONDITIONS AFTER DECEMBER 1973

Shock Number	Type	Soil Condition (modulus psi)	Structural Damping (% critical)
1	Synthesized	Rock 10×10^6	5
2	Synthesized	Firm 9×10^4	5
3	Synthesized	Soft 2.5×10^4	5
4	Synthesized	Soft 2.5×10^4	2
5	Synthesized	Very soft 3.6×10^3	5
6	El Centro	Soft 2.5×10^4	5

4.1.8.1. Test Laboratory Data Tapes. Nine-track magnetic tapes containing the raw test data in digital counts were received from the test laboratory. These tapes are historically referred to as Tape 9.

The data were recorded by a Varian 620/L-100 computer and assembled into logical records containing 1944 16-bit words. The first record, however, contained two 10 x 6 arrays of title information identifying the test, date, g-level, and frequency, while the second record contained an instrument identification table. Several succeeding records and several records at the end of the test data contain instrument tape records and dc insert calibration data. The remaining logical records contain an array of 81 channels of data by 24 multiplexer passes for a total of 1944 words each. Each record was spaced by a record gap, and end-of-file marks were used to separate data from successive tests.

4.1.8.2. General Atomic Data Tapes. The nine-track data tapes transmitted by the test laboratory were converted to General Atomic seven-track magnetic tapes (Tape 10) using routines DATAT and NEWTEN, described in Section 4.1.8.3, by incorporation of calibration factors also submitted by the test laboratory. The No. 10 tapes were compatible with all data reduction routines, and contained records of 7776 32-bit words arranged in arrays of 81 channels by 96 multiplexer passes. Four logical records of 24 multiplexer passes each on the No. 9 tapes were condensed into one physical record on the No. 10 tapes containing 96 multiplexer passes in order to reduce the total number of record gaps and allow for more test data per tape. This 4:1 conversion of record numbers was performed within the data reduction routines, except where specified in the program input instructions. Hence, the user simply inputs the logical record numbers specified in the test log sheets (for the No. 9 tapes) in order to process blocks of data (on the No. 10 tapes) associated with a particular test.

4.1.8.3. Data Reduction Programs. Computer programs and subroutines were developed to reduce the test data from all tests where the data were stored on magnetic tape in a digital format. A summary description of these routines is given in Table 4.1-8.

TABLE 4.1-8
COMPUTER PROGRAM SUMMARY DESCRIPTION

Program	Description
1. DATAT	Converts digital data on nine-track magnetic tape to engineering units on seven-track tape incorporating a set of nominal calibration factors
2. NEWTEN	Modifies specific channels of engineering data by incorporating new calibration data in the form $Y = mx + b$
3. PEAKS	Defines peak instrument response within a specified time interval
4. SPEED (Subr)	Outputs velocity data by differentiating displacement
5. PLOTT (Subr)	Plots data on the UNIVAC line printer
6. ANGLES (Subr)	Calculates rocking angle, rocking axis orientation, and vertical separation from displacements measured by three eddy current probes
7. DATAP	Provides numerical printout and page plots of data
8. DATADF	Provides numerical printout and page plots of net dowel forces
9. DATAR	Provides printout of rocking angle, orientation of the rocking axis, and vertical separation between two core blocks
10. DFPHASE	Calculates the phase angle of the response with respect to the test rig displacement
11. HANDY	Provides maximum and/or minimum response in an interval of time or frequency, 4020 plots
12. HANDYR	Provides maximum and/or minimum rocking angles in an interval of time or frequency, 4020 plots
13. VIEW4	Provides data from up to three instruments sampled at up to four times per multiplexer pass, 4020 plots
14. VIEW1	Provides data from up to eight instruments sampled only once per multiplexer pass
15. VIEWD	Prints and 4020 plots up to two channels of data for 47 sec of a sine sweep, at 0.5 decades per minute
16. VIEWR	Provides printout and 4020 plots of time history, rocking angle, and orientation angle, for two instrumented core blocks
17. PEAKAB	A search routine based on two parameters for specifying the required relative magnitude of peaks and troughs in the response
18. PEAKF	A search routine similar to PEAKAB but using a constant parameter to specify the required absolute magnitude of peaks and troughs in the response

4.1.9. Quality Assurance Requirements

Each test in the seismic program was performed in accordance with General Atomic quality assurance (QA) procedures. The QA requirements were spelled out in the test specifications for the particular test.

The main QA document for these projects was the Quality Assurance Manual (QAM), which states the policies, assigns the responsibilities, and describes the procedures at GA. This manual applies also to activities conducted under programs contracted with the U.S. Department of Energy. This QAM and any supplementary quality assurance program documents implement the requirements of 10CFR50, Appendix B. In accordance with the definitions of QAM, all seismic tests under this project were classified as QAL II, DV&S - nondeliverable.

4.1.10. Documentation and Records

The primary document for each test program is the GA test report written by the cognizant test engineer. It contains the test description, data presentation, and discussion of test results. These reports are referenced in the test abstracts presented in later sections.

Other documentation is kept in GA Record Storage (Sorrento Valley) for an indefinite time after completion of the test program. These include test and materials specifications, contractual documents, and a number of test laboratory documents. Where appropriate, test rig design reports and drawings were issued. The test laboratory retained all original drawings, but copies of these were transferred to the GA archives under foreign print numbers. A list of drawings is usually included in the GA test report. The test laboratory also issued procedures for test rig assembly, instrumentation and system calibrations, and testing. During the test period, monthly program reports were received, and at the end of the program test laboratory instrumentation development (if appropriate) and final test reports were issued.

The actual test data exist in three basic forms as follows.

1. All data are contained on digital data tapes stored in the GA computer archives. These are accompanied by data packages in Record Storage containing information for locating the data on the tapes and factors for converting the raw data to engineering units. The contents of the data package are:
 - a. Test log sheets.
 - b. Digital log sheets.
 - c. Notice of deviation.
 - d. Instrumentation table.
 - e. System calibration summary.
 - f. DC insert calibrations.
 - g. Header records, pre- and post-test records, and data examination records.
2. Converted and reduced data are kept in Record Storage in the form of computer printouts utilizing the software described in Section 4.1.8. All the data reduction program listings are also found in Record Storage.
3. The final forms of data, consisting of tables and hand and computer plots, are contained in appendices to the test reports.

4.1.11. Test Data Error Analysis

An analysis was performed for each test to evaluate the random errors contained in all relevant test parameters. This section defines all

relevant error sources and contains descriptions of the methods employed in the error evaluation. Further details can be obtained from the dowel force test report (Ref. 4.1-4). A summary of the total random errors in the main test parameters is given in Section 6.1 (Table 6.1-3).

In general, the test data contain both random and systematic errors. If data from repeated tests are available in a reasonable sample, statistical analysis of the measurements can be employed to estimate the total random error involved. If repeated tests are not available, the random errors in the test system components must be obtained separately and compounded to obtain the total (random) error in the data measurements.

Systematic errors that tend to have the same algebraic sign are not amenable to statistical treatment. In most instances, however, they are easily obtained from the raw data plots. The data reduction codes can assess this error and automatically adjust the data point, thus removing the systematic errors.

4.1.11.1. Error Sources. The instrument circuit diagram shown in Fig. 4.1-31 illustrates the common sources of error in the tests and serves as a component error model in the error analysis to follow.

Transducer Circuit Error

These errors are associated with the instrument circuit downstream of the calibration point as shown in Fig. 4.1-31 and originate from the summer, peak holder, and computer components. Typical error values in these components as specified by the manufacturer are shown in Table 4.1-9.

Calibration Error

Instrument calibration was conducted using all the circuitry from the transducer to the computer. Thus, random and systematic errors in the transducer and amplifier circuits are accounted for in the calibration

Fig. 4.1-31. Test system component error model

TABLE 4.1-9
TRANSDUCER CIRCUIT RANDOM ERROR

Source	Instrument	Error ^(a) (%)
Computer	All	0.03
Peak holder	Force transducers	0.50
Summing circuit	Dowel strain gages	0.50

(a) All errors are corrected to parent population and represent one standard deviation.

data. This was referred to as an "end to end" calibration technique. Calibration error components include amplifier error (manufacturers' quote), dowel strain gage bonding material hysteresis error, charge amplifier low frequency fall-off, deviation in impact orientation, eddy current probe measurement on an inclined surface, load cell nonuniform preload, and load cell eccentric load effect. Typical instrument calibration error values are given in Table 4.1-10.

Extraneous Errors

Figure 4.1-31 indicates extraneous errors that are often present but are somewhat ambiguous in nature. For example, a dc shift was sometimes seen on the data plots, which possibly originated in the bridge amplifier and could be due to temperature changes in other components. Also, 60-cycle noise often entered at one or more of the electrical circuits, and a 4.5-Hz beat frequency of unknown origin has been observed. These errors were generally handled test by test, compensating for the systematic error component. The typical random noise level from the test data was about 1% to 2%.

Core Element Property Errors

Changes in element properties that can affect the core response are deviations in graphite density (block weight), Young's modulus (block stiffness), and coefficient of friction. The random error in the response as a result of expected deviations in these quantities was not derived experimentally. The error assessment was therefore made on a theoretical basis. From core parameter sensitivity studies (Ref. 4.1-3), the effects of element density and friction changes are small in comparison with a change in Young's modulus. The mean element modulus for H-451 graphite in the radial direction was experimentally determined as $E = 1.07 \times 10^6$ lb/in.² with a standard deviation of 0.06×10^6 lb/in.². The modulus only affects the core element and core support forces since displacement and velocity are virtually independent of stiffness K . Thus, assuming $F \propto \sqrt{K}$, the error in the response became 2.7%. Combined with estimated effects

TABLE 4.1-10
TYPICAL INSTRUMENT CALIBRATION ERRORS
(1/5-SCALE, FULL-ARRAY AND DOWEL FORCE TESTS)

Instrument	Calibration Error ^(a) (%)
LVDT	0.5
Eddy current probe	7.7
Dowel pin strain gages	8.5
Dowel pin two-component load cell	10.6
Fuel element strain gage	55.0
Fuel element two-block load cells	6.0
Fuel element five-block load cells	2.0
Spring pack support strain gages	0.5 ^(b)

(a) All errors are corrected to parent population and represent one standard deviation.

(b) Maximum calibration error in dynamic compression.

from changes in density and friction, the total error estimate due to property variations was 2.8%

Geometry and Initial Condition Errors

There is a variation in instrument response magnitude as a result of slight changes in core geometry due to instrument relocation and core gap adjustments. These are caused by manufacturing tolerances. The error relates to such sources as core block dimensional tolerances, location and size tolerances of the dowel pin and dowel pin socket, and boundary support size and adjustment tolerances. Most sensitive to variations in these tolerance values were support and in-core block loads. The assessment of these random errors, accomplished by several controlled parameter variation tests, is summarized in Table 4.1-11.

The core initial condition is actually a geometry parameter. An error in the response measurement may result if the fuel element gap configuration within the core is not the same initially. However, insignificant influence on the maximum response is anticipated because the high damping in the core structures will quickly eliminate any starting transients. The error in maximum response due to initial condition changes was therefore ignored.

Test Rig Control Error

Since the core response is a function of the test rig input motion, it is necessary to determine the accuracy of the actual rig motion relative to the nominal input specified. The error in the actual motion originates in tape processing and rig control circuitry and is also influenced by the test rig LVDT transducer by which the rig motion was measured. The error in the rig control was calculated separately for sinusoidal and time history test inputs since each involved a different control scheme. In the 1/5-scale, full-array tests for time history excitation, typical error values up to 2% were obtained based on several tests at a particular g level. The error in the sinusoidal excitation was calculated to be 5% maximum.

TABLE 4.1-11
TEST CONFIGURATION GEOMETRY ERRORS
(1/5-SCALE, FULL-ARRAY AND DOWEL FORCE TESTS)

Core Response	Geometric Error ^(a) (%)
Core and element deflection	1.0
Dowel force	5.0
Fuel element impact force	4.0
Support boundary force	5.0

(a) All errors are corrected to parent population and represent one standard deviation.

The 1/5- and 1/2-scale, two-dimensional tests, however, experienced much larger errors in the response since, in these tests, the core elements were virtually unconstrained in all six degrees of freedom. A small random deviation in the input, therefore, would cause a large variation in core element motion. Typically, in these tests an error corresponding to one standard deviation of 16% was observed in the boundary support load and 14% in the in-core element load. The errors in core velocity and displacement response were considerably smaller as expected.

4.1.11.2. Error Analysis Methods. The random error in measured data from repeated tests was obtained as the fractional standard deviation with respect to the mean (Ref. 4.1-6).

$$\hat{S}_u = \frac{\left[\frac{1}{N} \sum_{n=1}^N (u_n - \bar{u})^2 \right]^{1/2}}{\bar{u}_m} \quad (4.1-3)$$

where N = number of data points,

u_n = the n th data point,

$\bar{u}$ = mean value of a group of data or a mean curve fit
to a distribution of data,

$\bar{u}_m$ = mean value of all data points in the data range,

$$\left(\bar{u}_m = \frac{1}{N} \sum_{n=1}^N u_n \right) .$$

For the parent population, which represents an infinite number of data points, S is equal to σ , which means that the probability is 0.683 that an error is smaller than one standard deviation. However, in most cases the number of data points or repeated tests is small. According to Ref. 4.1-6, as long as the variations in the data are random, having removed the systematic error, the theory holds for even a very small sample of

data. The best estimate of the standard deviation of the infinite parent distribution is therefore obtained by multiplying by the factor

$$\sqrt{\frac{N}{N-1}} \quad . \quad (4.1-4)$$

This will increase the dispersion of the data and, hence, the calculated error.

The error in boundary support load measurements was obtained from repeated tests since the sensors employed to obtain this information remained in the same position throughout the testing. The in-core sensors on the other hand were moved to several positions in order to obtain the response at several locations in the core. Hence, these sensors did not produce repeated data.

For the in-core data, therefore, the random component errors arising from the independent sources defined in Section 4.1.11.1 were compounded to obtain the total error in the measurements. Mathematically, the approach was to obtain the random error or fractional standard deviation in the dependent variable u (the measured quantity) as a function of the random errors in the independent component variables $G_1, G_2, \dots G_j$ (i.e., component gain factors as shown in Fig. 4.1-31). Using a Taylor series expansion, the deviation for discrete values of the independent variables was first obtained:

$$\delta u_n = (u_n - \bar{u}) \approx \frac{\partial u}{\partial G_1} \delta G_{1n} + \frac{\partial u}{\partial G_2} \delta G_{2n} + \dots \frac{\partial u}{\partial G_j} \delta G_{jn} \quad (4.1-5)$$

where $u = f(G_1, G_2, \dots G_j)$,

$\delta G_{jn} = G_{jn} - \bar{G}_j$,

$\bar{u}$ = the mean of u_n ,

$\bar{G}_j$ = the mean of G_{jn} ,

j = j th independent variable,

n = n th data point.

The standard deviation in u is obtained by summing the square of the deviations in Eq. 4.1-5. The assumption of random or independent deviations eliminates the cross product terms with the result:

$$S_u = \left[\sum_{j=1}^J \left(\frac{\partial u}{\partial G_j} \right)^2 S_{G_j}^2 \right]^{1/2}, \quad (4.1-6)$$

where the S_{G_j} 's are the standard deviations of the independent variables, which are either known or can be estimated from test data (e.g., calibration tests). The fractional standard deviation of the random error is then obtained by the division of the mean value of u :

$$\hat{S}_u = \frac{S_u}{\bar{u}}. \quad (4.1-7)$$

The remaining task is to define an expression from which all random error sources identified can be incorporated. This is done with the aid of the component error model, Fig. 4.1-31. This model has the following characteristics:

1. $u(g, \omega)$ is the true response of a core element as a function of the g -level and frequency $\left\{ \frac{g}{\omega} \right\}$ of the input waveform. Due to deviations in core element properties and core geometry, the actual core response u_T deviates from its true value. The random errors were represented in the model by component gain factors G ,

$$G = \bar{G}(1 \pm e),$$

where $\bar{G}$ = nominal value of the gain,

e = random error or fractional deviation in G .

u_T is then expressed as

$$u_T = G_E G_G u(g, \omega) ,$$

where G_E = element property gain (element modulus),

G_G = core geometry gain.

Each nominal gain value in this case is unity. A similar gain factor was used for each component variable identified in Fig. 4.1-31.

2. The instrument signal representing the element response is v_A . This signal is usually amplified, and may contain drift, which is a systematic error. v_A is obtained in units of volts and is related to u_T by the calibration equation,

$$v_A \Big|_{D=0} = G_A (m u_T + b) , \quad (4.1-8)$$

which represents an RMS linear curve fit to experimental data,

where D = amplifier drift ($D = 0$ during instrument calibration under controlled conditions),

G_A = the gain factor representing the random error over the range of transducer calibration,

m = slope of calibration curve (volts/lb, in., etc.),

b = ordinate intercept (volts).

Rearranging and including instrument drift,

$$v_A = \frac{G_A}{m} (u_T - B) + D , \quad (4.1-9)$$

where $M = 1/m$,
 $B = -(b/m)$.

3. v_D is the digital response signal recorded by the computer, and it is expressed in "counts." In most cases, this signal is passed through additional circuit instrumentation such as summers, peak holders, and an analog/digital converter. The signal may contain random noise N_R and other extraneous systematic signals N_S , which are assumed to enter at the computer. v_D can then be expressed in terms of v_A as follows:

$$v_D = G_C (G_P G_S v_A + N) ,$$

where G_C = A/D converter gain (counts/volt),
 G_P = peak holder gain,
 G_S = summer gain,
 $N = N_S \pm N_R$.

However, since systematic errors from drift and extraneous signals can easily be removed from the output data, the corrected digital signal output becomes

$$v_D^C = v_D - \overline{G_S G_P G_C} D - \overline{G_C} N_S . \quad (4.1-10)$$

By manipulation of Eqs. 4.1-8, 4.1-9, and 4.1-10, the recorded digital signal v_D can be expressed in terms of the core response as follows:

$$v_D^C = \frac{G_{CPSAEG}}{M} \left[u(g, \omega) - \frac{B}{G_{GE}} \right] + G_C N_R , \quad (4.1-11)$$

where $G_{CPSAEG} = G_C G_P G_S G_A G_E G_G$.

Equation 4.1-11, which is in "counts," is converted to engineering units by first multiplying by the nominal value of $1/\bar{G}_c$ and processing by calibration constants M and B. Hence,

$$v_D^C = \frac{G_{CPSAEG}}{\bar{G}_c} u(g, \omega) + \frac{G_c}{\bar{G}_c} N_R, \quad (4.1-12)$$

where N_R now is represented in engineering units ($\bar{N}_R = 0$).

To obtain the standard deviation from expression 4.1-5, the partial derivatives of v_D^C with respect to the independent variables are obtained, i.e., $\partial v_D^C / \partial G_c$, $\partial v_D^C / \partial G_p$, ..., $\partial v_D^C / \partial N_R$, $\partial v_D^C / \partial \omega$. Substituting into Eqs. 4.1-6 and 4.1-7 and assuming $G_{PSAEG} = 1$ since all gain factors are approximately unity, gives

$$\begin{aligned} \hat{S}_u = & \left\{ \bar{u}^2(g, \omega) \left[\hat{S}_{G_c}^2 + \hat{S}_{G_p}^2 + \hat{S}_{G_s}^2 + \hat{S}_{G_A}^2 + \hat{S}_{G_E}^2 + \hat{S}_{G_G}^2 \right] + \hat{S}_{N_R}^2 \right. \\ & \left. + \left[\frac{\bar{g}}{\bar{u}(g, \omega)} \right]^2 \left[\frac{\partial \bar{u}(g, \omega)}{\partial g} \right]^2 \hat{S}_g^2 + \left[\frac{\bar{\omega}}{\bar{u}(g, \omega)} \right]^2 \left[\frac{\partial \bar{u}(g, \omega)}{\partial \omega} \right]^2 \hat{S}_\omega^2 \right\}^{1/2} \end{aligned} \quad (4.1-13)$$

where

$$\hat{S}_{G_c} = \frac{S_{G_c}}{\bar{G}_c}, \quad \hat{S}_{G_p} = \frac{S_{G_p}}{\bar{G}_p}, \quad \dots, \text{etc., and}$$

$$\hat{S}_{N_R} = \frac{S_{N_R}}{\bar{u}(g, \omega)} \quad (\text{random noise-to-signal ratio of the measured data, expressed as one standard deviation}).$$

In Eq. 4.1-13, S_G was computed with the analog-to-digital conversion gain constant $\overline{G}_C$ equal to 409.6 counts/volt. Although $u(g, \omega)$ was not known since only one measurement existed, its best estimate was used, which was the measured value.

The last two terms in Eq. 4.1-13 represent the effect of the random errors in the input excitation with respect to g -level and frequency. The terms $\partial u(g, \omega) / \partial g$ and $\partial u(g, \omega) / \partial \omega$ are determined from the measured variations in $u(g, \omega)$ with respect to g -level and frequency. For time history data, it is assumed that $\partial u(g, \omega) / \partial \omega = 0$.

Equation 4.1-13 is applicable to all test data recorded using the circuitry shown in Fig. 4.1-31. Generally, component standard deviations can be added to or subtracted out of the equation depending on what instrumentation is present in the circuitry.

4.2. COLLISION DYNAMICS TESTS

This test program was initiated to investigate the collision dynamics phenomena of HTGR graphite fuel elements of 1/5-, 1/2-, and full-scale, and to establish the coefficient of restitution (e) and contact time (ct) for those elements as a function of impact velocity.

The tests on the 1/5- and 1/2-scale elements were primarily conducted to verify their design with respect to the prototype H-327 fuel elements assuming governing scaling laws. These elements were used in all core seismic test models. This section presents a summary of the test documentation contained in Ref. 4.2-1.

4.2.1. Test Objectives

The specific objectives of this test program were as follows:

1. Verify the value of coefficient of restitution (e) for the 1/5- and 1/2-scale elements previously designed, and determine the functional relationship of e to the element impact velocity.
2. Provide additional 1/5- and 1/2-scale test data in terms of contact time for two-element collisions and postimpact velocity distribution for multiple element collisions and boundary collisions.
3. Obtain similar data for full-scale prototype fuel elements made of H-451 graphite.
4. Evaluate the application of the scaling laws to collision dynamics phenomena.

4.2.2. Descriptions

4.2.2.1. Graphite Elements. The 1/5- and 1/2-scale elements are scale models of the prototype HTGR fuel element made from H-327 graphite. The scaling laws and designs are discussed in detail in Sections 4.1.3 and 4.1.4. Both H-327 and H-451 full-scale elements were tested. The H-451 material was incorporated since this was the graphite of fuel elements in future HTGRs. The full-scale fuel elements tested did not contain uranium fuel. To compensate for the weight of this fuel, steel bars were inserted into some of the fuel holes.

4.2.2.2. Test Equipment. Early tests were performed in a pendulum test rig. These involved 1/5- and full-scale elements of H-327 graphite. The pendulum test rig is shown schematically in Fig. 4.2-1. The framework supporting the graphite elements was made of small-diameter, thin-wall aluminum tubing; consequently, its weight and rotary inertia were small compared with that of the graphite elements. Bearings were used at the pivot points. Tests confirmed that friction and windage losses were negligible. Later tests were performed on a track where the elements mounted on near-frictionless roller bearings would roll on steel rails.

Fig. 4.2-1. One-fifth-scale pendulum collision test fixture

The full-scale test track used to test H-451 elements is shown in Fig. 4.2-2. Figure 4.2-3 shows the method of attaching the graphite elements to the track. Similar test equipment was used for the 1/5- and 1/2-scale H-327 element tests except that the roller bearings, the brackets, and the track were reduced in size, and the rods tying the brackets together ran outside the elements rather than through coolant holes as for the full-scale setup.

Acceleration of all elements to the desired preimpact velocity was performed manually.

Tests on the track consisted of interelement collisions and collision of elements against a rigid boundary support situated at the end of the track as illustrated in Fig. 4.2-4. The 1/5-, 1/2-, and full-scale boundary stiffnesses were as follows:

<u>Scale</u>	<u>Stiffness (lb/in.)</u>
1/5	468,000
1/2	1,560,000
Full	6,000,000

4.2.2.3. Instrumentation. For the pendulum tests, one rotary potentiometer was used on each of the two pendulum arms to measure angular displacement. These signals were recorded on oscillograph paper, providing traces proportional to angular displacement. Impact and rebound velocities were obtained using the relation

$$V = R\omega ,$$

where V is linear velocity, R is the mean radius to the center of each element, and ω is the angular velocity in radians per second obtained by differentiating each displacement versus time trace.

Fig. 4.2-2. Overall view of full-scale test setup for multielement collision with boundary

Fig. 4.2-3. Typical attachment fixture arrangement

Fig. 4.2-4. One-half-scale test rig with boundary support

The 1/5- and 1/2-scale track tests employed spark generators and paper tape to produce records of displacement versus time from which velocity was obtained by differentiation. Two spark electrodes were fixed to each element and connected to the spark generator by thin trailing wires. These recorded separate, distinct records of forward (+) and backward (-) displacement. In the full-scale tests, the velocity data were obtained from a displacement indicator consisting of a linear gear with the inter-tooth spaces filled with potting compound. The tooth pitch was 0.196 in. A wiper arm attached to the element provided a make-break circuit depending upon whether it contacted a gear tooth or the nonconductive potting compound. The displacement data represented by the make-break information were recorded on oscillograph paper, which provided timing references. Velocity was then obtained by differentiation of the oscillograph trace.

Contact time was obtained in the pendulum and track tests by strips of metal foil glued to the elements acting as a make-break circuit. The current traces were obtained on visicorder paper or displayed on an oscilloscope and photographed for record purposes.

For impact tests against a boundary support involving 1/5- and 1/2-scale elements, strain gages mounted on the boundary structure were employed to measure force and contact time. The boundary test rig was statically calibrated in a Riehle testing machine to obtain load magnitude from the strain gage signals. Full-scale boundary loads were obtained from a Kistler load cell mounted between the support structure and the concrete slab designed as a reaction mass.

Other instruments, including strain gages and accelerometers mounted on the element, provided alternative means of measuring contact time and measurement of impact acceleration.

4.2.2.4. Test Scope. The pendulum tests consisted of drawing both elements back an equal angular distance, simultaneously releasing them, and recording the transducer signals indicating impact and rebound velocity. Numerous tests of this kind were performed with 1/5- and full-scale

elements in the impact velocity range of 5 to 30 in./sec and 10 to 50 in./sec, respectively. A number of tests were discarded on the basis that flat-on impact did not take place or preservation of momentum did not occur.

The track tests for the 1/5-, 1/2-, and full-scale elements consisted of manually accelerating one or more elements to approximately the desired velocity and releasing them to continue at essentially constant velocity until impact with either one or more stationary or moving elements. Similar tests were also performed with two moving elements impacting each other and one or more elements impacting against a boundary support. The test plan for the various track tests is shown in Tables 4.2-1 through 4.2-7.

4.2.3. Data Reduction

The following expression was used to compute the coefficient of restitution e from preimpact and postimpact velocity data:

$$e = \frac{(V_{\ell} - V_r)_f}{(V_{\ell} - V_r)_i},$$

where the ℓ and r subscripts refer to the left and right hand elements, respectively, and f and i refer to final and initial.

A median line was drawn on each of the plots of results as an aid in observing trends. The data median and standard deviations were computed for use in the error analysis. This is further discussed in Section 4.1.11.

4.2.4. Results and Conclusions

4.2.4.1. Coefficient of Restitution. Figure 4.2-5 shows full-scale data for H-237 obtained from pendulum tests. These data represent the basis

TABLE 4.2-1
ONE-FIFTH-SCALE INTERELEMENT TESTS

Sequence Number ^(a)	Pre-Impact Element Configuration ^(b)	Impact Velocity (in./sec)
1	() ()	9.4 to 49.25
2	() () ()	16.3 to 59.3
3	() () () ()	25.1 to 55.6
4	() () () () ()	16.8
5	() () () ()	26.4 to 57.2

(a) Each sequence consisted of from 6 to 15 trials.

(b) Each set of parentheses represents one element. The left-hand element or group of elements was in motion and the right-hand group was stationary prior to impact.

TABLE 4.2-2
ONE-FIFTH-SCALE BOUNDARY TESTS

Sequence Number ^(a)	Number of Grouped Elements Impacting Bumper	Impact Velocity (in./sec)
1	()	9 to 43.5
2	() ()	10.2 to 34.5
3	() () ()	15 to 36.5
4	() () () ()	12 to 42.5
5	() () () () ()	15.6 to 39.5

(a) Each sequence consisted of from 14 to 51 trials.

TABLE 4.2-3
ONE-HALF-SCALE INTERELEMENT TESTS

Sequence Number (a)	Pre-Impact Element Configuration (b)	Impact Velocity (in./sec)
1	() ()	8.5 to 46.9
2	() () ()	10.7 to 39.4
3	() () () ()	12.5 to 39.7
4	() () () ()	8.2 to 47.3
5	() () () () ()	13.5 to 47.8

(a) For sequence 1, the elements were in motion toward each other with approximately equal velocity. For sequences 2 through 5 the left-hand element or group of elements was in motion prior to impact and the right-hand group was stationary. Each sequence consisted of approximately 20 trials.

(b) Each set of parentheses represents one element.

TABLE 4.2-4
ONE-HALF-SCALE BOUNDARY TESTS

Sequence Number (a)	Number of Grouped Elements Impacting Bumper	Impact Velocity (in./sec)
1	()	7.9 to 42.9
2	() ()	33.1 to 42

(a) Each sequence consisted of approximately 15 trials.

TABLE 4.2-5
FULL-SCALE INTERELEMENT TESTS

Sequence Number(a)	Pre-Impact Element Configuration(b)		Impact Velocity (in./sec)
1	()	()	9 to 50.25
2	()	() ()	13.3 to 58.8
3	()	() () ()	12.9 to 58
4	()	() () () ()	12.6 to 53.9
5	()	() () () () ()	9.8 to 52.5
6	() ()	()	11.8 to 49.4
7	() ()	() ()	10.3 to 45.2
8	() ()	() () ()	9.3 to 50.7
9	() ()	() () () ()	11.2 to 52
10	() () ()	()	12 to 47.4
11	() () ()	() ()	10.9 to 47
12	() () ()	() () ()	11.5 to 53
13	() () () ()	()	9.8 to 45.2
14	() () () ()	() ()	9.7 to 50.3
15	() () () () ()	()	9.5 to 48
16	()	()	11.2 to 47.9

(a) For sequences 1 through 15 the left-hand element or group of elements was in motion prior to impact and the right-hand group was stationary. For sequence 16 the elements were in motion toward each other with approximately equal velocity. Each sequence consisted of 5 to 8 trials.

(b) Each set of parentheses represents one element.

TABLE 4.2-6
FULL-SCALE BOUNDARY TESTS

Sequence Number ^(a)	Number of Grouped Elements Impacting Bumper	Impact Velocity (in./sec)
1	()	9.1 to 50.3
2	() ()	10.9 to 48.2
3	() () ()	9 to 50.3
4	() () () ()	10.4 to 50.7
5	() () () () ()	13 to 52.5
6	() () () () () ()	9.4 to 50.7

(a) Each sequence consisted of 5 trials.

TABLE 4.2-7
ONE-FIFTH-SCALE PENDULUM TESTS

Sequence Number ^(a)	Pre-Impact Element Configuration	Impact Velocity (in./sec)
1	() ()	10.7
2	() ()	16.5
3	() ()	21.5
4	() ()	26.8

(a) Sequence 1 consisted of one trial. Sequences 2, 3, and 4 each consisted of three trials.

Fig. 4.2-5. Full-scale coefficient of restitution versus impact velocity (pendulum tests)

for the design of the 1/5- and 1/2-scale elements. It is observed that e increases with impact velocity.

The 1/5-scale test data are shown in Fig. 4.2-6. The linear least squares line characterizes the data points well, with the exception of a few widely scattered points.

The 1/2-scale data shown in Fig. 4.2-7 have a similar trend but a slightly higher mean value compared to 1/5-scale data.

All e values from 1/5-, 1/2-, and full-scale tests on H-327 graphite are shown in Fig. 4.2-8 for comparison. Reasonable agreement is obtained between the different scale tests which show that the 1/5- and 1/2-scale elements are designed for adequate coefficient of restitution values.

The full-scale data for H-451 graphite obtained from linear track tests are shown in Fig. 4.2-9. The median values of e are much higher than that of the H-327 graphite full-scale pendulum tests. The reason for this lies in both the difference between H-327 and H-451 graphite material properties and the methods of testing. It is felt that the pendulum tests method caused lower than actual values of e . Specifically, vibrations in the test rig caused by the impact contributed to additional energy losses, which reduced the coefficient of restitution. Thus, the difference in e due to changes in material properties alone is probably not that large.

4.2.4.2. Contact Time. The full-scale element impact contact time data (Fig. 4.2-10), obtained from pendulum tests on H-327 graphite, show a decreasing trend with increasing values of impact velocity. This is represented by the median curve in Fig. 4.2-10. The 1/5-scale contact times (Fig. 4.2-11), obtained from both pendulum tests and linear track tests, were widely scattered and the trend is not obvious. The scatter is due to the difficulty in achieving flat-on impacts. The 1/2-scale data in Fig. 4.2-12, obtained from linear track tests, show far less scatter and the trend is more visible.

Fig. 4.2-6. One-fifth-scale coefficient of restitution versus impact velocity

Fig. 4.2-7. One-half-scale coefficient of restitution versus impact velocity

Fig. 4.2-8. Composite coefficient of restitution versus impact velocity

Fig. 4.2-9. Full-scale coefficient of restitution versus impact velocity (linear track test)

Fig. 4.2-10. Full-scale contact time versus impact velocity (pendulum test)

Fig. 4.2-11. One-fifth-scale contact time versus impact velocity

Fig. 4.2-12. One-half-scale contact time versus impact velocity

In Fig. 4.2-13, which compares 1/5-, 1/2-, and full-scale contact time data, the 1/2-scale and full-scale contact time data are normalized to 1/5 scale according to the relations

$$t_m = \lambda t_p \quad ,$$

$$v_m = v_p \quad ,$$

(from the scaling analysis outlined in Section 4.1.3).

The curves show that the 1/5- and 1/2-scale elements, in general, have smaller contact times than the full-scale elements (normalized to 1/5 scale). Therefore, element designs are too stiff according to the scaling laws described.

The contact time values for H-451 full-scale elements are shown in Fig. 4.2-14 as obtained from the linear track tests. From the analysis of the test data, there was a large difference between the minimum contact time of the four contact gages and the average contact time. The lower curve with minimum contact time is probably a more realistic measurement of flat-on impact contact time and is recommended for analytical use. The contact time for H-451 graphite is found to be lower than the contact time for H-327 graphite, which is to be expected since H-451 has a higher elastic modulus.

4.2.4.3. Multiple Element Collisions. Samples of test results from multiple element collisions are shown in Figs. 4.2-15 through 4.2-17 for the 1/5-, 1/2-, and full-scale elements, respectively. The results are presented as plots of the final velocity of a given element versus the initial velocity of the impacting element. The final velocity, given in percentage of initial velocity, is corrected to 100% conservation of initial momentum. These figures represent one element colliding with two stationary elements, and all exhibit the same trend. The impactor element, element No. 1, loses momentum as a function of increasing impact

Fig. 4.2-13. Composite contact time versus impact velocity (normalized to 1/5 scale)

Fig. 4.2-14. Full-scale contact time versus impact velocity (linear track test)

Fig. 4.2-15. One-fifth-scale postimpact velocity distribution versus impact velocity

Fig. 4.2-16. One-half scale postimpact velocity distribution versus impact velocity

Fig. 4.2-17. Full-scale postimpact velocity distribution versus impact velocity

velocity, and the extreme element in the series (farthest from the impactor) gains momentum. The momentum change of the intermediate elements in each series remains nearly constant with impact velocity.

Similar trends are seen in collisions of one moving element with up to four stationary elements.

4.2.4.4. Boundary Collisions. Figure 4.2-18 presents boundary loads as a function of element impact velocity for full-scale elements. A linear trend toward increasing load with increasing impact velocity is evident for both one- and two-element configurations. Similar results were obtained for 1/5- and 1/2-scale elements.

For single and multiple element collisions with the boundaries, test results are also presented in terms of final-to-initial momentum ratios versus impact velocity. For two-element collisions with the boundaries, Figs. 4.2-19 through 4.2-21, trends in momentum change are similar to those discussed in Section 4.2.4.3 for interelement collisions; i.e., the element nearest the initial impact site (element No. 1) loses momentum with increasing impact velocity, and the element farthest from the site increases its momentum with increasing impact velocity.

4.2.5. Error Analysis

The error analysis was based on a broad statistical base from as many as 51 repetitive tests giving the random error in the test data represented by the fractional standard deviation $\hat{S}$ (1 σ). The expression is derived in Section 4.1.11. Table 4.2-8 presents the total random error in each test series for coefficient of friction, contact time, and the post-impact momentum distribution parameter.

Random errors in these tests were attributed to element contact surface irregularity, dynamic test rig response at impact, rotary potentiometers and recorders used in the pendulum tests, spark generator frequency variation in the 1/5- and 1/2-scale track tests, and the recorder used in

Fig. 4.2-18. Full-scale boundary force versus impact velocity

Fig. 4.2-19. Postimpact momentum ratio versus impact velocity; two 1/5-scale elements impacting the boundary

Fig. 4.2-20. Postimpact momentum ratio versus impact velocity; two 1/2-scale elements impacting the boundary

Fig. 4.2-21. Postimpact momentum ratio versus impact velocity; two full-scale elements impacting the boundary

TABLE 4.2-8
TOTAL RANDOM ERROR SUMMARY

	Coefficient of Restitution $\hat{S}$ (%)	Contact Time $\hat{S}$ (%)	Post-Impact Momentum Distribution	
			Interelement (a) $\hat{S}$ (%)	Boundary (a) $\hat{S}$ (%)
1/5 scale	20.0	20.0	12.0	18.0
1/2 scale	10.0	10.0	15.0	12.0
Full scale	8.0	18.0	11.0	5.0

(a) The $\hat{S}$ values listed represent the arithmetic averages of $\hat{S}$ computed for each element involved in each of several inter-element and boundary collisions.

the full-scale tests. A major source of error was the less than perfect flat-on impacts which caused erroneous contact time measurement. From four contact strips, one near each corner of the impacting face used for full-scale tests, variations in contact time up to 10.5 msec (13.3 msec versus 2.8 msec) at 11 ips impact velocity were recorded. These variations diminished to 2.55 msec (3.8 versus 1.25 msec) at 48 ips impact velocity. To illustrate the difference, both the average of the four readings from each of the four contact strips and the minimum were used in preparing Fig. 4.2-14.

4.3. BASIC ROCKING TESTS

The rocking tests were designed to investigate the free rocking motion of a stack of 1/5- and full-scale model graphite fuel elements when subjected to various initial (angular) separations. This section presents a summary of the test documentation. Further detailed information is contained in Ref. 4.3-1.

4.3.1. Objectives

The objectives of the tests were:

1. To provide information about rocking decay motion, dowel shear forces, and rock-down loads to be used to establish analytical model input parameters such as collision spring rates and damping coefficients.
2. Establish the dynamic scaling relationships between 1/5-scale and full-scale elements within the scope of the test.

4.3.2. Description

The test fixture for 1/5-scale elements, Fig. 4.3-1, consisted of a base slab to which an element was rigidly clamped in an upright position. The rig was capable of supporting up to three 1/5-scale blocks (excluding

Fig. 4.3-1. One-fifth-scale test rig and fuel block assembly

the clamped block) stacked one on top of the other at an angle relative to the block below. A device was incorporated to simultaneously release the blocks from the initial tilted configuration. From this initial condition, the blocks were forced to rock about one of the element edges coinciding with the x, y, or z axis, as defined in Fig. 4.3-2.

The test fixture for the full-scale blocks was designed to the same principles as the 1/5-scale test fixture except it permitted only two elements rocking on the base element. The test fixture is shown in Fig. 4.3-3.

4.3.2.1. Graphite Elements. Each 1/5-scale element is a scale model of a prototype HTGR fuel element. The scaling laws and the design are discussed in detail in Sections 4.1.3 and 4.1.4. In the 1/5-scale block, steel dowels rather than graphite dowels were used to facilitate the attachment of instrumentation for measuring dowel shear forces. The steel dowels had a diameter of 0.31 in. and a bending stiffness of 3800 lb/in.

The full-scale elements were accurate reproductions of the HTGR fuel elements. However, the weight of the fuel was simulated by steel rods inserted in the fuel holes. Aluminum dowels were incorporated in two of the elements for instrumentation purposes (Fig. 4.3-4). Each dowel had a diameter of 1.5 in. and a design stiffness of 95,000 lb/in. This represents the mean value of several tests on H-451 dowel/socket systems.

The metal dowels employed both in the 1/5- and full-scale test specimens produced some distortions in the model design. It was determined from verification tests that the dowel stiffness was an average 13% lower than the design value. The metal-to-graphite interface might also affect the values of coefficient of restitution and coefficient of friction. These distortions could have some influence on the dowel force response, but this was not investigated.

4.3.2.2. Instrumentation. Instrumentation for both tests was almost identical and included transducers, signal conditioning, and data recording

Fig. 4.3-2. Identification of rocking axes and dowel pin strain gage orientations

Fig. 4.3-3. Full-scale test rig and fuel block assembly

Fig. 4.3-4. Dowel pin design for rocking tests

equipment. Element transducers consisted of semiconductor strain gages mounted on the dowel pins for measuring dowel shear forces, Kistler load washers for measuring rock-down loads, and Dymal eddy current probes for measuring element angular displacement. The full-scale element employed LVDTs instead of eddy current probes because of the larger displacements measured. Tables 4.3-1 and 4.3-2 give the layout of the transducers in 1/5- and full-scale blocks, respectively.

The load cell data acquisition system is illustrated in Fig. 4.3-5. Each transducer converts a given dynamic reaction to a dc voltage. Calibration of the instrument establishes the response, from zero up to ± 10 volts, in engineering units. The instrument signal could either be output on an oscilloscope recorder or converted to a digital equivalent by a Varian 620 computer. The computer writes the digital equivalent, which is represented as counts, onto a magnetic tape.

4.3.2.3. Test Scope. Tables 4.3-3 and 4.3-4 give the description of all 1/5- and full-scale tests performed. The tables identify the test according to block configuration, initial release position, and rocking axis. As an example, block configuration B/C/D means block D is the clamped base block, C is located on top of D, and B on top of C. The angles represent the relative angular tilt between stacked blocks (B/C/D at angles $8^\circ/20^\circ$ means B tilts 8° with respect to C and C tilts 20° with respect to D). The rocking axes, designated as x, y, and z, are defined in Fig. 4.3-2.

4.3.3. Data Reduction

Several data reduction codes unique to the rocking test were used to process the fundamental data stored on the magnetic tape.

BRDUMP provided a dump of the raw digitized data after translation to engineering units. These data could be represented as time history plots via the SC4020 Datagraphics System.

TABLE 4.3-1
ONE-FIFTH-SCALE ELEMENT TEST INSTRUMENTATION

Block	Top	Bottom
A	Dummy element	--
B	Dowel strain gages	Four load washers
C	Two eddy current probes	--
D	Dowel strain gages	Two eddy current probes

TABLE 4.3-2
FULL-SCALE ELEMENT TEST INSTRUMENTATION

Block	Top	Bottom
A	Six load washers, dowel strain gages	1 LVDT
B	--	1 LVDT
C	--	1 LVDT
D	--	1 LVDT

Fig. 4.3-5. Data acquisition system

TABLE 4.3-3
ONE-FIFTH-SCALE ROCKING TEST PLAN

Test No.	Configuration	Rocking Axis	Test No.	Configuration	Rocking Axis
1	A/B 5°	x	27	B/C/D 0°/10°	y
2	A/B 20°	x	28	B/C/D 20°/0°	y
3	A/C 5°	x	29	A/B/D 20°/0°	y
4	A/C 20°	x	30	A/B/D 0°/10°	x
5	A/D 5°	x	31R	A/B/D 20°/8°	x
6	A/D 20°	x	32	A/B/D 20°/8°	x
7	B/C 5°	x	33	A/B/D 20°/0°	y
8R	A/D 20°	y	34	A/B/D 0°/10°	y
9R	A/D 20°	y	35	A/B/D 20°/8°	y
10	A/D 20°	z	36	A/B/C/D 20°/0°/0°	y
11	C/D 5°	x	37	A/B/C/D 0°/0°/2°	y
12	C/D 5°	x	38	A/B/C/D 0°/0°/8°	y
13	B/C/D 20°/0°	x	39	A/B/C/D 5°/5°/2°	y
15	B/C/D 8°/20°	x	40	A/B/C/D 20°/8°/5°	y
16	B/C/D 8°/20°	x	41	A/C/B/D 20°/0°/0°	x
17	A/C/D 20°/0°	x	42	A/C/B/D 0°/0°/2°	x
18	A/C/D 0°/10°	x	44	A/C/B/D 5°/5°/2°	x
19	A/C/D 0°/10°	x	45	A/C/B/D 20°/8°/5°	x
20	A/B/C/D 20°/0°/0°	x	46	A/C/B/D 20°/0°/0°	y
23	B/A/C/D 20°/0°/0°	x	47	A/C/B/D 0°/0°/2°	y
24	B/A/C/D 0°/0°/8°	x	48	A/C/B/D 0°/0°/8°	y
25	B/A/C/D 20°/8°/5°	x	49	A/B/C/D 5°/5°/2°	y
26	B/C/D 20°/0°	y	50R	A/B/C/D 20°/8°/5°	y

TABLE 4.3-4
FULL-SCALE ROCKING TEST PLAN

Test No.	Configuration	Rocking Axes
1R	B/A 5°	x
2R	B/A 15°	x
3	B/A 5°	y
4R	B/A 10°	y
5	B/A 15°	y
6	D/C 5°	x
7	D/C 15°	x
8	D/C/A 15°/0°	x
9	D/C/A 0°/10°	x
10	C/B/A 15°/0°	x
11	C/B/A 0°/10°	x
12R	C/B/A 10°/6°	x
13	C/B/A 10°/0°	x
14	C/B/A 10°/0°	x
16	C/B/A 10°/0°	x
17	C/B/A 6°/10°	x
18	C/A/B 0°/10°	x
19	C/A/B 6-1/2°/10°	x
20	C/A/B 17-1/2°/10°	y
21	C/A/B 0°/10°	y
22	C/A/B 6-1/2°/10°	y

PROBE, which is a subroutine to BRDUMP, was written to determine angular separation between rocking elements. The calculated angles were based on measurements from 1/5-scale eddy current probes.

FSCOMP is a modification to BRDUMP, which gave the instantaneous sum (inside a time interval of 0.005 sec) of several transducers. Hence, the rock-down load was obtained as the direct sum of the magnitudes of each individual load washer. The total dowel shear force was represented as the vector sum of the forces on all three dowels:

$$\text{Dowel Force} = \sum_{i=1}^3 \sqrt{x_i^2 + y_i^2} \quad ,$$

where x' and y' represent forces from dowel strain gages as oriented in Fig. 4.3-2.

4.3.4. Results and Conclusions

Unfortunately, the usefulness of the 1/5-scale test data was limited due to an instrument malfunction or data transmission problem that went undetected for the duration of the testing. The instrument in question was a Kistler load washer that never gave a load reading above the general noise level. Hence, the total rock-down loads obtained may not be correct. Furthermore, from the strain gage data, it was concluded that in some cases the elements were not rocking simply about the rocking axis, but showed considerable wobbling motion. This phenomenon might have been caused by slight "binding" of a dowel due to small clearances between the dowel pin and socket. This effect was not noticeable in the full-scale element rocking since these elements were much heavier.

4.3.4.1. Two-Block Configurations. Figures 4.3-6 through 4.3-9 show 1/5- and full-scale results from one element rocking on top of another element about the x-axis tilted initially at an angle of 5°. The rocking angle

Fig. 4.3-6. Rocking motion - 1/5-scale, two-block configuration, 5° initial angle, x-axis

Fig. 4.3-7. Rocking motion - full-scale, two-block configuration, 5° initial angle, x-axis

Fig. 4.3-8. Rock-down force - full-scale, two-block configuration, 5° initial angle, x-axis

Fig. 4.3-9. Dowel force - full-scale, two-block configuration, 5° initial angle, x-axis

decay time histories, Figs. 4.3-6 and 4.3-7, are very similar for the 1/5- and full-scale tests. (The spikes in the full-scale traces are caused by noise in the data acquisition system.) The rocking frequency is shown to increase as the angular displacement becomes smaller. By measuring the log decrements, the 1/5-scale tests exhibit a larger damped motion. Typical rock-down load and dowel forces are shown in Figs. 4.3-8 and 4.3-9. In both 1/5- and full-scale tests, the maxima consistently occurred at zero rocking angle, and in most cases the overall maxima occurred on the first rock-down after release.

Figure 4.3-10 shows the distribution of maximum rock-down load at the six corners of the element (full scale) and load sharing between the three dowels for rocking about the x-axis resulting from a 5° initial angle. Increasing the initial angle to 15° causes a less than linear proportional increase in forces as shown in Fig. 4.3-11. Rocking about a different axis, the z-axis, Fig. 4.3-12 shows nearly identical maximum rock-down and dowel load magnitudes. A maximum total dowel shear load of 1200 lb was recorded for only a 5° rocking angle.

4.3.4.2. Multiblock Configurations. The rocking behavior of two full-scale elements stacked on top of a clamped element is shown in Figs. 4.3-13 and 4.3-14. When the top element is initially tilted and released, it rocks down and practically transfers all its angular momentum to the middle element on initial impact. The two elements then rock together in a manner described for two-block rocking. Almost identical behavior is exhibited when both of the two top elements are initially displaced. The same behavior was observed with 1/5-scale elements.

4.3.4.3. Comparisons Between 1/5-Scale and Full-Scale Tests. It was difficult to compare 1/5- and full-scale test results directly since the initial conditions (release angle) did not always correspond. However, by plotting angular displacement as a function of rocking frequency, a comparison independent of initial conditions and time was achieved. Such a plot

TEST NUMBER: 1R
 ELEMENT CONFIGURATION: B/A
 INITIAL ROCKING ANGLE: 5°
 ROCKING AXIS: X

Fig. 4.3-10. Distribution of rock-down load and dowel forces - full-scale, two-block configuration, 5° initial angle, x-axis

TEST NUMBER: 2R
 ELEMENT CONFIGURATION: B/A
 INITIAL ROCKING ANGLE: 15°
 ROCKING AXIS: X

Fig. 4.3-11. Distribution of rock-down load and dowel forces - full-scale, two-block configuration, 15° initial angle, x-axis

TEST NUMBER: 5
 ELEMENT CONFIGURATION: B/A
 INITIAL ROCKING ANGLE: 15°
 ROCKING AXIS: Z

TOTAL ROCK-DOWN FORCE = 2500 lb
 TOTAL DOWEL SHEAR FORCE = 1790 lb

Fig. 4.3-12. Distribution of rock-down load and dowel forces - full-scale, two-block configuration, 15° initial angle, z-axis

Fig. 4.3-13. Rocking motion (block C) - full-scale, three-block configuration, 15°/0° initial angle, x-axis

Fig. 4.3-14. Rocking motion (block B) - full-scale, three-block configuration, 15°/0° initial angle, x-axis

representing two-block rocking is shown in Fig. 4.3-15, where the full-scale data are normalized to 1/5 scale. The figure shows reasonable agreement for rocking motion, in particular at smaller angular displacements. This shows that the distortions in the 1/5-scale element modeling caused by incorrect modeling of the ρ/E ratio, as discussed in Section 4.1, do not have a significant effect on element rocking motion.

The effect on rock-down loads and dowel shear forces is considerably more pronounced. This is demonstrated in Table 4.3-5 although exact initial conditions are not compared as commented earlier. The table shows that the 1/5-scale rock-down loads are largely overestimated, which is expected since the element is too stiff. The comparison of dowel forces is better since care was taken to model the dowel stiffnesses more accurately.

4.3.5. Errors in the Test Data

A statistical estimate of the random errors in the 1/5- and full-scale test data was made from repeated tests. This method is further described in Section 4.1.11. Repeated testing as shown from the test plan was carried out both for two-block and three-block configurations. Some tests were repeated with the elements in the same relative positions and some with interchanged element configurations. The latter tests truly form the basis for evaluating the total error since variations in element properties and geometry configurations are accounted for.

Total errors estimated from both types of tests are shown in Table 4.3-6, all represented as one standard deviation. The table shows that the errors in the rocking angle and frequency data are relatively small for two-block tests of 1/5- and full-scale conducted at small initial angles (5°). The errors in the rock-down loads and dowel forces are larger. A marked increase in the error values occurs for three-block data, which show that those tests were very difficult to control. From the table, it is also evident that the error due to deviations in element properties and geometry has a large effect on the response.

Fig. 4.3-15. Comparison between 1/5-scale and full-scale rocking motion

TABLE 4.3-5
COMPARISON BETWEEN 1/5-AND FULL-SCALE MAXIMUM ROCK-DOWN LOADS
AND DOWEL SHEAR FORCES

Block Configuration	Net Rock-Down Load (lb)		Net Dowel Shear Force (lb)	
	1/5 ^(a)	Full ^(b)	1/5	Full ^(b)
Two-block, 5°	90 ± 0.5	20	5.1 + 1.5 - 0.6	9.4
Two-block, 15° to 20°	116	17.6	6.5 ± 0.3	11.7
Three-block, 15° to 20°	40	25 ± 0.8	4.5 + 2.2 - 1.5	6.8 ± 1.8

(a) On the low side since one load cell did not function.

(b) Normalized to 1/5 scale.

TABLE 4.3-6
TOTAL ERRORS^(a) IN THE 1/5-AND FULL-SCALE TEST DATA

Parameter	1/5 Scale (%)		Full Scale (%)	
	Two-Block	Three-Block	Two-Block	Three-Block
Frequency	0.5	(4.0)	0.5	15.3 (1.8)
Rocking angle	7.2 [37]	--	3.3	26.0 (0.8)
Rock-down load	11.4	(6.4)	--	7.3 (1.9)
Dowel shear force	15.3	24 (8.3)	--	25.0 (4.1)

(a) All errors are expressed as ±1σ values.

() Repeated test with the blocks in the same relative positions.

[] Large initial release angle (20°).

4.4. TWO-DIMENSIONAL HORIZONTAL ARRAY TESTS

These tests involved 1/5- and 1/2-scale core models consisting of 73 elements in a horizontal array. A summary of the test documentation is presented in this section. Further description of the testing and details of results are given in Ref. 4.4-1.

4.4.1. Objectives

The tests had the following objectives:

1. To provide data for code correlation in two different scales in order to show the universality of the codes with respect to block size.
2. To compare identical tests in 1/5 and 1/2 scale to aid in evaluating the scaling laws assumed for the model design.
3. To ascertain the behavior of the core model in terms of resonant frequency, boundary force, and interelement velocities with changes in gap between the fuel elements.

4.4.2. Description

4.4.2.1. Test Scope. Shaker tests were conducted on planar arrays of 73 hexagonal graphite blocks representing HTGR fuel elements as shown schematically in Fig. 4.4-1. Uniaxial input excitation was applied separately to two orthogonal axes: across-the-flats of a fuel element and across-the-corners of a fuel element.

The input to the test rig in both axes was of three different types:

1. Sinusoidal sweep at 0.5 decade/minute from approximately 1.5 Hz up to 15 Hz and back down to 1.5 Hz, at constant acceleration of 0.75 g.

Fig. 4.4-1. Schematic of 73-element, two-dimensional section

2. Sinusoidal dwell at a selected frequency for a minimum of 10 cycles at a steady state. The acceleration was 0.75 g. The selected frequency was one of interest (usually near resonance) determined during the sine sweep. A dwell was concluded by an instantaneous shutdown of the excitation, which provided damping information as the block motion died out.
3. Time history motion represented by both the El Centro (referred to as shock 9) and an artificial earthquake (shock 3). The maximum peak acceleration of the time histories was 0.5 g equivalent ground motion, which corresponded to approximately 1.0 g fixture acceleration depending on the amplification characteristics of the structure for the particular soil conditions being considered. Shocks 3 and 9 were both generated for soft soil conditions (65,000 lb/in.²) and 5% structural damping. These are further described in Section 4.1.7 and shown in Figs. 4.1-17 and 4.1-23, respectively.

The core models were tested over a wide range of core gaps. For the 1/5-scale tests, core gaps were 0.05, 0.10, 0.15, 0.20, 0.25, 0.30, 0.35, and 0.40 in. and for 1/2-scale tests, 0.125, 0.25, 0.375, 0.50, 0.625, 0.75, and 1.0 in.

A summary of all the 1/5-scale and 1/2-scale tests performed is given in Tables 4.4-1 and 4.4-2, respectively.

4.4.2.2. Test Rig Assemblies. Figs. 4.4-2 and 4.4-3 show test rig and core arrangements for both 1/5- and 1/2-scale tests. Both test rigs were designed as rigid containment structures for the horizontal array of fuel blocks. The purpose of the rigidity was to assure that all response was purely a function of the block stiffness and not of the test rig stiffness. The test rigs are hexagonal in shape to match the outline of the core model, and they are provided with individually adjustable boundary supports.

TABLE 4.4-1
TEST SCOPE - 1/5-SCALE, TWO-DIMENSIONAL TESTS

Test No.	Tape No.	Test Type	Ground Acceleration ^(a) (g)	Frequency Range (Hz)	Inst. Block Loc. ^(b)	Total Core Gap (in.)
Across-Flats						
1	102	Sine sweep	0.75	2.2-15-2.2	1	0.05
		Sine sweep	0.75	2.2-15-2.2	1	0.10
	106	Sine dwell	1.0	14.0	1	0.10
		Time history	0.5	--	1	0.10
		Sine sweep	0.375	2.2-15-2.2	2	0.10
	107	Sine dwell	0.75	7.5	2	0.10
		Time history	0.5	--	2	0.10
2	108	Sine sweep	0.75	2.2-15-2.2	2	0.20
		Sine dwell	0.75	8.0	2	0.20
		Time history	0.5	--	2	0.20
		Sine sweep	0.75	2.2-15-2.2	1	0.20
	111	Sine dwell	0.75	8.0	1	0.20
		Time history	0.5	--	1	0.20
	113	Sine sweep	0.75	2.2-15-2.2	1	0.15
3	114	Sine sweep	0.75	2.2-15-2.2	1	0.25
		Sine sweep	0.75	2.2-15-2.2	1	0.30
	116	Sine dwell	0.75	7.0	1	0.30
		Time history	0.5	--	1	0.30
		Sine sweep	0.75	2.2-15-2.2	2	0.30
	117	Sine dwell	0.75	7.0	2	0.30
		Time history	0.5	--	2	0.30

TABLE 4.4-1 (Continued)

Test No.	Tape No.	Test Type	Ground Acceleration (a) (g)	Frequency Range (Hz)	Inst. Block Loc. (b)	Total Core Gap (in.)
Across-Flats						
4		Sine sweep	0.75	2.2-15-2.2	2	0.40
		Sine dwell	0.75	6.0	2	0.40
		Time history	0.5	--	2	0.40
		Sine sweep	0.75	2.2-15-2.2	1	0.40
	124	Sine dwell	0.75	6.0	1	0.40
		Time history	0.5	--	1	0.40
	125	Sine sweep	0.75	2.2-15-2.2	1	0.35
Across-Corners						
5		Sine sweep	0.75	2.2-15-2.2	3	0.10
	140	Sine dwell	1.0	13.0	3	0.10
		Time history	0.5	--	3	0.10
		Sine sweep	0.75	2.2-15-2.2	4	0.10
	127	Sine dwell	0.75	9.0	4	0.10
		Time history	0.5	--	4	0.10
6		Sine sweep	0.75	2.2-15-2.2	4	0.20
	128	Sine dwell	0.75	9.0	4	0.20
		Time history	0.5	--	4	0.20
		Sine sweep	0.75	2.2-15-2.2	3	0.20
	129	Sine dwell	0.75	4.0	3	0.20
		Time history	0.5	--	3	0.20
7		Sine sweep	0.75	2.2-15-2.2	3	0.30
	130	Sine dwell	0.75	7.0	3	0.30
		Time history	0.5	--	3	0.30
		Sine sweep	0.75	2.2-15-2.2	4	0.30
	131	Sine dwell	0.75	3.5	4	0.30
		Time history	0.5	--	4	0.30

TABLE 4.4-1 (Continued)

Test No.	Tape No.	Test Type	Ground Acceleration ^(a) (g)	Frequency Range (Hz)	Inst. Block Loc. ^(b)	Total Core Gap (in.)
Across-Corners						
8	132	Sine sweep	0.75	2.2-15-2.2	4	0.40
		Sine dwell	0.75	6.0	4	0.40
		Time history	0.5	--	4	0.40
	133	Sine sweep	0.75	2.2-15-2.2	3	0.40
		Sine dwell	0.75	3.0	3	0.40
		Time history	0.5	--	3	0.40

(a) Sine sweep and sine dwell acceleration refer to fixture level.

(b) See Fig. 4.4-5.

TABLE 4.4-2
TEST SCOPE - 1/2-SCALE, TWO-DIMENSIONAL TESTS

Test No.	Test Type	Ground ^(a) Acceleration (g)	Frequency Range (Hz)	Instrumented Element Location (b)	Total Core Gap (in.)
Across-Flats					
8	Sine sweep	0.75	1.5-15-1.5	1	0.125
7	Sine sweep	0.75	1.5-15-1.5	1	0.25
7	Sine dwell	0.75	TBD	1	0.25
7	Time history	0.75	--	1	0.25
9	Sine sweep	0.75	1.5-15-1.5	2	0.25
9	Sine dwell	0.75	TBD	2	0.25
9	Time history	0.75	--	2	0.25
10	Sine sweep	0.75	1.5-15-1.5	2	0.50
10	Sine dwell	0.75	TBD	2	0.50
10	Time history	0.75	--	2	0.50
5	Sine sweep	0.75	1.5-15-1.5	1	0.50
5	Sine dwell	0.75	TBD	1	0.50
5	Time history	0.75	--	1	0.50
6	Sine sweep	0.75	1.5-15-1.5	1	0.375
4	Sine sweep	0.75	1.5-15-1.5	4	0.625
3	Sine sweep	0.75	1.5-15-1.5	1	0.75
3	Sine dwell	0.75	TBD	1	0.75
3	Time history	0.75	--	1	0.75
11	Sine sweep	0.75	1.5-15-1.5	2	0.75
11	Sine dwell	0.75	TBD	2	0.75
11	Time history	0.75	--	2	0.75
2	Sine sweep	0.75	1.5-15-1.5	1	0.875
1	Sine sweep	0.75	1.5-15-1.5	1	1.00
1	Sine dwell	0.75	TBD	1	1.00
1	Time history	0.75	--	1	1.00

TABLE 4.4-2 (Continued)

Test No.	Test Type	Ground ^(a) Acceleration (g)	Frequency Range (Hz)	Instrumented Element Location (b)	Total Core Gap (in.)
12	Sine sweep	0.75	1.5-15-1.5	2	1.00
12	Sine dwell	0.75	TBD	2	1.00
12	Time history	0.75	--	2	1.00
Across-Corners					
13	Sine sweep	0.75	1.5-15-1.5	3	1.00
13	Sine dwell	0.75	TBD	3	1.00
13	Time history	0.75	--	3	1.00
20	Sine sweep	0.75	1.5-15-1.5	4	1.00
20	Sine dwell	0.75	TBD	4	1.00
20	Time history	0.75	--	4	1.00
19	Sine sweep	0.75	1.5-15-1.5	4	0.75
19	Sine dwell	0.75	TBD	4	0.75
19	Time history	0.75	--	4	0.75
14	Sine sweep	0.75	1.5-15-1.5	3	0.75
14	Sine dwell	0.75	TBD	3	0.75
14	Time history	0.75	--	3	0.75
15	Sine sweep	0.75	1.5-15-1.5	3	0.50
15	Sine dwell	0.75	TBD	3	0.50
15	Time history	0.75	--	3	0.50
18	Sine sweep	0.75	1.5-15-1.5	4	0.50
18	Sine dwell	0.75	TBD	4	0.50
18	Time history	0.75	--	4	0.50
17	Sine sweep	0.75	1.5-15-1.5	4	0.25
17	Sine dwell	0.75	TBD	4	0.25
17	Time history	0.75	--	4	0.25
16	Sine sweep	0.75	1.5-15-1.5	3	0.25
16	Sine dwell	0.75	TBD	3	0.25
16	Time history	0.75	--	3	0.25

(a) Sine sweep and sine dwell acceleration refer to fixture level.

(b) See Fig. 4.4-5.

Fig. 4.4-2. One-fifth-scale, two-dimensional test rig and core

Fig. 4.4-3. One-half-scale, two-dimensional test rig and core

The 73-block core models were scaled HTGR fuel elements with respect to geometry and coefficient of restitution. Three of the blocks were instrumented and moved from location to location to provide data on the distribution of response within the core.

Each block of the core model was supported by three standoffs, which provided a low friction support that was designed to have a negligible effect on the core response. The three standoffs fixed each core block in a plane, and the four-bar-linkage nature of the block motion guaranteed parallelism between the block and the test rig floor. The blocks were, however, not constrained against rotation about the vertical axis. The effect of this type of support was to isolate the planar array model from column effects, resulting in element pitching which is present in the full-array core.

4.4.2.3. Instrumentation. The test instrumentation consisted of in-core and boundary instrumentation as shown in the layout in Fig. 4.4-4. The in-core instrumentation, Fig. 4.4-5, was located within a trio of blocks which could be relocated and consisted of strain gages to measure force on the block face, DEES capacitive-type displacement gages to measure inter-block velocity, and piezoelectric accelerometers for block acceleration. The boundary instruments consisted of five load cells, located as shown in Fig. 4.4-4, to measure boundary impact force and one displacement transducer attached to a peripheral block. Since the core tended to move as a lump, this displacement transducer gave readings of the overall motion of the core relative to the boundary.

Data acquisition instrumentation consisted of signal conditioning and amplification of the basic transducer signal and digitization and recording of the data onto magnetic tape. The digitization and recording stages were accomplished by a Varian 620/L-100 data acquisition computer incorporating a multiplexer unit. The computer was able to handle 80 channels of instrumentation. A digitization rate of 0.005 sec was employed. Records of analog data were also obtained on a Visicorder for spot checks during testing. A typical schematic of a data acquisition circuit is shown in Fig. 4.4-6.

- LEGEND**
- BOUNDARY FORCE
 - BOUNDARY VELOCITY
 - ▲ IN-CORE FORCE
 - | IN-CORE VELOCITY
 - 1 IN-CORE INSTRUMENT POSITION

Fig. 4.4-4. Layout of test instrumentation

Fig. 4.4-5. One-fifth-scale test in-core instrumentation layout

Fig. 4.4-6. Typical load cell block diagram

4.4.3. Data Reduction

The processing of the raw digital test data into final test results was performed in the same manner as for the 1/5-scale, full-array test. This included checks for saturated instruments, conversion of digital counts to engineering units, presentation of frequency response, and peak and peak average values in printed output and graphs. A description of data reduction software employed in these tests is given in Section 4.1.8.

4.4.4. Results and Conclusions

The overall dynamic behavior of the 1/5- and 1/2-scale planar core sections is similar to that of the full-array model in that the core elements tend to move as a lumped mass over a large range of the input excitation. The amount of lumping, as illustrated in Fig. 4.4-7, varies both with position of the core relative to the boundary and the frequency of excitation. During a cycle of sinusoidal excitation, maximum lumping occurs shortly after the core boundary impact force has peaked. Close to 100% lumping results at this time.

Typical resonance curves for the 1/5- and 1/2-scale test arrays are shown in Figs. 4.4-8 and 4.4-9. The curves are very similar and are characteristic of the behavior of a nonlinear single-degree-of-freedom system. At a certain frequency, which is a function of the cumulative core gap, a sudden dropoff in the response occurs. This dropoff occurs at the core resonant frequency as determined from plots of the phase shift between the core response and the input. A 90° phase angle occurs at resonance.

The resonant frequency varies inversely with core gap as shown in Figs. 4.4-10 and 4.4-11. During sweep-up, the resonance occurs at a higher frequency than during sweep-down. This characterizes a spring-hardening system. The difference in frequency values represents the region of instability. These plots also give the frequency of maximum

Fig. 4.4-7. Core lumping

Fig. 4.4-8. Frequency response curve (peak average force), 0.2 in. gap, across-flats, sweep-up

Fig. 4.4-9. Frequency response curve (peak force), 0.5 in. gap, across-flats, sweep-up

Fig. 4.4-10. Core frequency response as a function of gap, across-flats, 1/5-scale, two dimensional test

Fig. 4.4-11. Core frequency response as a function of gap, across-flats, 1/2-scale, two-dimensional test

force, which shows that the maximum forces do not necessarily occur at the lumped mode resonance, but most often at some lower frequency.

The above characteristics were described for excitation in the across-the-flats direction of a core element. Nearly identical results were obtained for excitation in the across-the-corners direction of a core element.

Maximum relative velocities and forces resulting from the GA design earthquake (shock 3) are given in Figs. 4.4-12 through 4.4-16 for both 1/5- and 1/2-scale tests. These values represent the overall maxima independent of time. The magnitude of the velocities and forces is larger at locations closer to the boundary. The response also generally increases as the core gap is made larger, which is demonstrated in Figs. 4.4-17 through 4.4-20.

A comparison between 1/5- and 1/2-scale test data was made to establish the effect of the model distortions as discussed in Section 4.1.3 on the core response. Since graphite was used in both models, the 1/5- and 1/2-scale element stiffness (ρ/E) characteristics were distorted with respect to the full-scale HTGR element, and also with respect to each other. The core resonant frequencies, in-core velocities, and forces were compared over the range of core gaps tested by normalizing the 1/2-scale response to 1/5 scale. Figure 4.4-21 shows the comparison between resonant frequencies, which agree within 15%. The in-core velocities agree very closely as shown in Fig. 4.4-22, but agreement between impact forces is poor (Fig. 4.4-23). These comparisons, therefore, show that ignoring the scaling of the ρ/E quantity tends to affect the force magnitudes but not the frequency and velocity response to any large extent.

4.4.5. Errors in the Test Data

A random error analysis, described in Section 4.4.11, was performed in order to obtain the expected accuracy of the presented data. The total random errors were obtained by two methods. The first method identified

Fig. 4.4-12. Maximum relative velocity distribution, GA design earthquake, 0.2 in. gap, across-flats

1/5 SCALE 2D TEST

LOAD CELL
ASSEMBLY

GA DESIGN EARTHQUAKE 3
ACROSS-FLATS
0.5 g GROUND ACCELERATION

Fig. 4.4-13. Maximum force distribution, GA design earthquake, 0.2 in. gap, across-flats

1/5 SCALE 2D TEST

LOAD CELL
ASSEMBLY

● IN-CORE AND
BOUNDARY FORCE (LB)

GA DESIGN EARTHQUAKE 3
ACROSS-CORNERS
0.5 g GROUND ACCELERATION
GAP = 0.2 IN.

Fig. 4.4-14. Maximum force distribution, GA design earthquake, 0.2 in. gap, across-corners

Fig. 4.4-15. Maximum force and relative velocity distribution for GA design earthquake, 0.5 in. gap, across-flats

Fig. 4.4-16. Maximum force and relative velocity distribution for GA design earthquake, 0.5 in. gap, across-corners

Fig. 4.4-17. Maximum relative velocity distribution, GA design earthquake, across-flats

Fig. 4.4-18. Maximum force distribution, GA design earthquake, across-flats

Fig. 4.4-19. Maximum relative velocity distribution for GA design earthquake, across-flats

Fig. 4.4-20. Maximum boundary forces for GA design earthquake as a function of gap

Fig. 4.4-21. One-fifth- and 1/2-scale comparisons - core frequency response

Fig. 4.4-22. One-fifth- and 1/2-scale comparisons - maximum element velocity response from GA design earthquake

Fig. 4.4-23. One-fifth- and 1/2-scale comparisons - maximum boundary force response from GA design earthquake

all relevant error sources such as error in input, core configuration, instrumentation, etc., and calculated the compounded effect on the response. The second method analyzed repeated test data statistically and calculated the standard deviation in the spread of data. The results from both methods are summarized in Tables 4.4-3 and 4.4-4 for the 1/5- and 1/2- scale tests, respectively. The errors are represented as one standard deviation. It was observed that the forces were the least accurate data recorded. In particular, large errors appear in the in-core impact forces which were based on strain gage measurements. This was due to the problem of allowing representative calibration factors for impacts other than flat-on. It was found that the single largest error contributor was the deviation in the test input.

4.5. HALF-SCALE, TWO-DIMENSIONAL, TWO-AXIS TEST

The two-axis tests were an extension of the 1/2-scale, two-dimensional tests described in Section 4.4, and were performed on the same 73-element, horizontal array. This section presents a summary of the testing and test results. Further details are described in Ref. 4.5-1.

4.5.1. Objectives

The specific objectives of this test were as follows:

1. To obtain data for correlation with the CRUNCH-2D computer code described in Section 3.3.
2. To ascertain the response of the core model to simultaneous two-axis excitation in terms of resonant frequency, boundary force, and interelement forces and velocities.
3. To check the reliability of the interelement force measurements employing new in-core instrumentation consisting of Kistler load cells.

TABLE 4.4-3
TOTAL ERRORS IN THE 1/5-SCALE TEST DATA

Test Data	Instrument	Random Error (%) ^(a)						Total
		Rig Control	Rig Config.	El. Properties	Data Acquisition	Inst. Cal.	Extraneous	
Resonant frequency	DC $\propto$ frequency	2.1	2.6	0	0.3	--	0.7	3.4 (1.7) ^(b)
Boundary support force	Load cells	16.0	1.2	2.8	0.8	1.7	0.7	16 (5.6)
Element deflection	Dees gage	7.0	1.6	0	1.6	2.0	0.7	7.7 (3.6)
Element velocity	Dees gage	9.0	1.6	0	1.6	2.6	0.7	9.70
Element impact force	Strain gage	14.0	0.7	2.8	2.4	16.5	0.7	22 (5.1)

(a) All errors represent 1 σ values.

(b) Numbers in brackets were obtained from repeated test data.

TABLE 4.4-4
TOTAL ERRORS IN THE 1/2-SCALE TEST DATA

Test Data	Instrument	Random Error (%) (a)						Total (RSS)
		Rig Control	Rig Config.	Element Prop.	Data Acquisition	Inst. Calibr.	Extraneous	
Resonant frequency	DC frequency	5.0	1.6	0	0.3	--	0.7	5.3 (2.7)(b)
Boundary support	Load cells	12.0	2.2	2.8	1.8	5.0	0.7	14 (12.9)
force								
Element deflection	Eddy current probe	6.0	0.6	0	0.6	1.7	0.7	6.3 (6.7)
Element velocity	Eddy current probe	8.0	0.6	0	0.6	2.4	0.7	8.4
Element impact	Strain gage	--	--	2.8	2.9	350	0.7	350
force								

(a) All errors represent 1σ values.

(b) Numbers in brackets were obtained from repeated test data.

4.5.2. Description

4.5.2.1. Test Scope. The tests were conducted on a planar array of 73 1/2-scale fuel elements, as shown in Fig. 4.5-1. The arrangement of the two-axis input along the x and y axes is defined in the figure. The x and y axes were located along $\pm 45^\circ$ directions from the across-flats direction, which corresponded to the single-axis input direction. The rig input motion along these two axes was of three different types:

1. Sinusoidal sweeps at 0.5 decade/minute in the frequency range 1.5 to 15 Hz. The input was applied to both axes with a phase angle ϕ between the x and y inputs:

$$x = A \sin \omega$$

$$y = A \sin (\omega + \phi)$$

The fixture acceleration input levels A were 0.53 g, and the phase angle was a constant value between 0° and 90° . This resulted in a combined test rig response that was elliptical, with the major axis aligned with the original uniaxial excitation direction (across-flats direction). For the case of 0° phase angle, the elliptical motion reduced to a straight line, and the rig motion coincided with that of the uniaxial tests. The following phase angles and corresponding correlation coefficients were employed in the tests:

<u>Phase Angle</u> <u>(deg)</u>	<u>Correlation Coefficient</u>
0.0	1.0
41.4	0.75
60.0	0.50
75.5	0.25
90.0	0.0

Fig. 4.5-1. Layout of shakers and shaker tables

2. Sinusoidal dwell at a selected frequency of interest and 0.53 g level, for a minimum of 10 cycles. The input was applied to both axes with a phase angle ϕ varied from 0° to 90° .
3. Time history motion represented by the El Centro earthquake (shock 9) and an artificial earthquake (shock 3). The maximum peak acceleration of the time histories was 0.355 g equivalent ground motion, inputs at the x and y axes. This corresponds to 0.5 g acceleration in previous uniaxial tests. Both shocks 3 and 9 were generated for soft soil (65,000 lb/in.) and 5% structural damping, and were identical in waveform to the uniaxial input shown in Figs. 4.1-17 and 4.1-23 of Section 4.1.7. The x- and y-axis inputs were applied at various time lags corresponding to the following correlation coefficients:

<u>Time Lag Shock 3 (sec)</u>	<u>Time Lag Shock 9 (sec)</u>	<u>Correlation Coefficient</u>
0.0	0.0	1.0
0.131	0.288	0.75
0.206	0.721	0.50
0.601	1.334	0.25
0.754	1.986	0.0

A constant total cross core gap of 0.5 in. was selected based on uniaxial test results. A summary of all tests performed is given in Table 4.5-1.

4.5.2.2. Test Rig Assembly. The test rig used in the two-axis tests, which was the same rig used for the uniaxial test, is described in Section 4.4.2.2. However, the shaker system, table, and bearings were modified to allow for biaxial motion (Fig. 4.5-2).

4.5.2.3. Control System. Amplitude and phase control for the two shakers are illustrated in Fig. 4.5-3. For sine sweep excitation, a phase angle

TABLE 4.5-1
TEST SCOPE

Test No.	Test Scope (Rig Input)	Ground Acceleration ^(f) (g)	Frequency Range (Hz)	Correlation Coeff./Phase Angle (ϕ)	Instrumented Block Position ^(a)
1	SINS ^(b)	0.53	1.5 - 15 - 1.5	0.75/41.4°	1
	DWELL ^(c)	0.53	5.2	0-90°	1
	TH ^(d)	0.355	--	0.75/-- ^(e)	1
2	SINS	0.53	1.5 - 15 - 1.5	0.50/60°	1
	TH	0.355	--	0.50/--	1
3	SINS	0.53	1.5 - 15 - 1.5	0.25/75.5°	1
	TH	0.355	--	0.25/--	1
	TH	0.175	--	0.25/--	1
	TH	0.355	--	0.25/--	1a
4	SINS	0.53	1.5 - 15 - 1.5	0/90°	1
	TH	0.355	--	0/--	1
	TH	0.175	--	0/--	1
	TH	0.355	--	0/90°	1a
5	SINS	0.53	1.5 - 15 - 1.5	0.75/41.4°	2
	DWELL	0.53	5.0	0/90°	2
	TH	0.355	--	0.75/--	2
6	SINS	0.53	1.5 - 15 - 1.5	0.50/60°	2
	TH	0.355	--	0.50/--	2
7	SINS	0.53	1.5 - 15 - 1.5	0.25/75.5°	2
	TH	0.355	--	0.25/--	2
	TH	0.175	--	0.25/--	2
8	SINS	0.53	1.5 - 15 - 1.5	0/90°	2
	TH	0.355	--	0/--	2
	TH	0.175	--	0/--	2
9	SINS	0.53	1.5 - 15 - 1.5	0.75/41.4°	3
	TH	0.355	--	0.75/--	3
10	SINS	0.53	1.5 - 15 - 1.5	0.50/60°	3
	TH	0.355	--	0.50/--	3

TABLE 4.5-1 (continued)

Test No.	Test Scope (Rig Input)	Ground Acceleration ^(f) (g)	Frequency Range (Hz)	Correlation Coeff./Phase Angle (ϕ)	Instrumented Block Position ^(a)
11	SINS	0.53	1.5 - 15 - 1.5	0.25/75.5°	3
	TH	0.355	--	0.25/--	3
	TH	0.355	--	0.25/--	3a
12	SINS	0.53	1.5 - 15 - 1.5	0/90°	3
	TH	0.355	--	0/--	3
	TH	0.355	--	0/--	3a
13	SINS	0.53	1.5 - 15 - 1.5	0.75/41.4°	4
	TH	0.355	--	0.75/--	4
14	SINS	0.53	1.5 - 15 - 1.5	0.50/60°	4
	TH	0.355	--	0.50/--	4
15	SINS	0.53	1.5 - 15 - 1.5	0.25/75.5°	4
	TH	0.355	--	0.25/--	4
	TH	0.355	--	0.25/--	4a
16	SINS	0.53	1.5 - 15 - 1.5	0/90°	4
	TH	0.355	--	0/--	4
	TH	0.355	--	0/--	4a
101	SINS	0.53	1.5 - 15 - 1.5	1/0°	2
102	SINS	0.53	1.5 - 15 - 1.5	1/0°	1
103	TH	0.355	--	1/--	1
104	TH	0.355	--	1/--	2

(a) Instrumented block positions as specified in Fig. 4.5-4.

(b) Sine sweep.

(c) Sine dwell.

(d) Time history earthquakes (shocks 3 and 9).

(e) Phase angle does not apply to time history input; instead, time lags are used (Section 4.5.2.1).

(f) Sine sweep and dwell accelerations refer to fixture level.

Fig. 4.5-2. One-half-scale test rig

Fig. 4.5-3. Sinusoidal and time history vibration control system (one channel), second method

meter monitored the phase between two filtered control signals from test rig accelerometers. The phase between the inputs was then manually adjusted to within $\pm 5\%$ of the specified value. For time history excitation, the two inputs, shocks 3 and 9, were electrically transmitted to the test system on a prerecorded analog tape. Two separate channels on the tape contained the two shocks, time-displaced in accordance with the specified requirements.

4.5.2.4. Test Instrumentation. The test instrumentation consisted of in-core and boundary support transducers as shown in the layout in Fig. 4.5-4. These transducers are identical to the ones employed in the uniaxial tests except for two new in-core load measuring devices (ILMD). These replaced the element strain gage system, which proved inadequate in the uniaxial tests.

The ILMD (Fig. 4.5-5) consisted of five crystal load washers mounted on the face of an in-core element. A trough equal to the width of the face and the entire block length was cut to a depth of approximately 1 in. This cutout accommodated a magnesium plate covered with a graphite sheet. The plate was blotted to the block with the five load washers between. The load cells were situated at the four corners of the face and at the center, making it possible to measure the distribution of load on the face. The signals from the five load washers were also electronically summed and represented the total impact load on the element. The ILMDs were incorporated into the three-block instrumentation unit (Fig. 4.5-6), which was periodically relocated to get a distribution of in-core loads and velocities.

The data acquisition system for the two-axis tests, which was the same as in the uniaxial system, used a Varian 620 computer to digitize and record the data on magnetic tape. An ILMD instrumentation circuit diagram is shown in Fig. 4.5-7.

Fig. 4.5-4. Core instrumentation positions

DIMENSIONS IN INCHES

Fig. 4.5-5. In-core load measuring device

Fig. 4.5-6. In-core instrument position 1a

Fig. 4.5-7. ILMD load cell instrumentation

4.5.3. Data Reduction

The processing of the raw digital test data into final test results was performed in the same manner as for the 1/5-scale, full-array test. This included checks for saturated instruments, conversion of digital counts for engineering units, presentation of frequency response, phase response, and peak and peak average values in printed output and graphs. A summary description of data reduction software employed for these purposes is given in Section 4.1.8.

4.5.4. Results and Conclusions

Typical core resonance curves for a two-axis sine sweep having a relative phase lag of 90° are shown in Figs. 4.5-8 through 4.5-10. These are very similar to resonance curves generated for 0° phase excitation, which is equivalent to a single-axis excitation described in Section 4.4 except that the resonant frequency is slightly lower. Figure 4.5-11 shows the resonant frequency plotted as a function of phase angle. The resonant frequency represented by both sweep-up and sweep-down is shown to decrease with increasing phase angles up to 90° . The reason for this is probably that out-of-phase excitation has a smaller maximum amplitude compared to 0° phase excitation, as demonstrated in Fig. 4.5-12. Since the core represents a spring-hardening system, the resonant frequency will therefore decrease.

The core velocities, boundary forces, and in-core forces are strongly phase dependent. Maximum forces and relative velocities near resonance (MNR) are shown in Figs. 4.5-13 and 4.5-14 for 0° phase angle and in Figs. 4.5-15 and 4.5-16 for 90° phase angle. Overall maxima, independent of core location, are shown to occur for a 0° phase angle.

A further illustration of how the core response changes with phase angle is given in Figs. 4.5-17 and 4.5-18. These figures represent sine dwells at 5.0 Hz where the phase angle is slowly varied. The in-core force, ILMD 057, decreases steadily with the phase angle between 0° and

Fig. 4.5-8. Frequency response curve (peak average core velocity, DX003), $\phi = 90^\circ$

Fig. 4.5-9. Frequency response curve (peak average force, LC002), $\phi = 90^\circ$

Fig. 4.5-10. Frequency response curve (peak average force, IL057-1), $\phi = 90^\circ$

Fig. 4.5-11. Resonant frequency as a function of phase angle

Fig. 4.5-12. Two-axis excitation modes for different phase angles

1/2 SCALE 2D TEST RESULTS
 *MNR VELOCITY DISTRIBUTION
 (IPS)

DURING SINE SWEEP-UP

0.53 g
 0° PHASE ANGLE

TEST 101/102

THE BOUNDARY RESPONSE
 REPRESENTS THE MEAN
 OF 2 VALUES

*AVERAGE OF 3 LARGEST VALUES WITHIN 1 Hz OF RESONANCE

Fig. 4.5-13. Distribution of velocity (peak average) at resonance, $\phi = 0^\circ$

1/2 SCALE 2D TEST RESULTS
 *MNR FORCE DISTRIBUTION
 (LB)

DURING SINE SWEEP-UP

0.53 g
 0° PHASE ANGLE

TEST 101/102

THE BOUNDARY RESPONSE
 REPRESENTS THE MEAN
 OF 2 VALUES

Fig. 4.5-14. Distribution of force (peak average) at resonance, $\phi = 0^\circ$

1/2 SCALE 2D TEST RESULTS
 *MNR VELOCITY DISTRIBUTION
 (IPS)

DURING SINE SWEEP-UP

0.53 g

90° PHASE ANGLE

TEST 10, 22, 32, 42

THE BOUNDARY RESPONSE
 REPRESENTS THE MEAN
 OF 4 VALUES

Fig. 4.5-15. Distribution of velocity (peak average) at resonance, $\phi = 90^\circ$

1/2 SCALE 2D TEST RESULTS
 *MNR FORCE DISTRIBUTION
 (LB)

DURING SINE SWEEP-UP

0.53 g

90° PHASE ANGLE

TESTS 10, 22, 32 & 42

THE BOUNDARY RESPONSE
 REPRESENTS THE MEAN
 OF 4 VALUES

*AVERAGE OF 3 LARGEST VALUES WITHIN 1 Hz OF RESONANCE

Fig. 4.5-16. Distribution of force (peak average) at resonance, $\phi = 90^\circ$

Fig. 4.5-17. In-core force, ILMD-1 (peak average), versus phase angle

Fig. 4.5-18. In-core force, ILMD-2 (peak average), versus phase angle

90° since the sensor is lined up in the rectilinear xy-direction. Force ILMD 061, on the other hand, reaches a maximum for a phase angle of about 70°, corresponding roughly with the angle the sensor makes with the xy-direction.

For time history excitation (shock 3), relative velocities and forces obtained for a phase shift corresponding to a correlation factor of 0.25 (Figs. 4.5-19 and 4.5-20) are compared with forces corresponding to a correlation factor of 1.0 (in-phase excitation) (Figs. 4.5-21 and 4.5-22). From these and other results representing correlation coefficients of 0.0, 0.50, and 0.75, it was again generally observed that the overall maxima occurred for in-phase excitation.

4.5.5. Errors in the Test Data

The random error analysis for the two-axis test was performed in the same manner as the uniaxial test. Since the test apparatus and instrumentation were basically the same, most component errors were calculated to the same magnitude. An exception was the error induced due to inaccuracies in the test rig control, since in this case two-axis motion was input. The rig control error component became larger by the RSS of the errors from separate axes. In addition, the component errors for the new ILMD were estimated.

Total errors in each test parameter representing one standard deviation are given in Table 4.5-2. These are the RSS of all component errors. Where possible, total error estimates are given based on repeated tests. It is seen that these values are very close to those obtained by compounding the component errors. The largest errors occurred in the boundary support forces and the in-core forces. These were estimated as 20.2% and 18.3%, respectively, based on one standard deviation. The errors in the in-core forces, therefore, were considerably reduced by using ILMDs instead of strain gages.

1/2 SCALE 2D TEST RESULTS
 *MAX VELOCITY DISTRIBUTION
 (IPS)

TIME HISTORY

SHOCK 3, $g = 0.71$

CORRELATION = 0.25

TESTS 7, 9, 20, 30, 31, 40 & 41

THE BOUNDARY RESPONSE
 REPRESENTS THE MEAN
 OF 7 VALUES

Fig. 4.5-19. Distribution of maximum velocity, shock 3, correlation = 0.25

1/2 SCALE 2D TEST RESULTS

*MAX FORCE DISTRIBUTION
(LB)

TIME HISTORY

SHOCK 3, $g = 0.71$
CORRELATION = 0.25

TESTS 7, 9, 20, 30, 31, 40 & 41

THE BOUNDARY RESPONSE
REPRESENTS THE MEAN
OF 7 VALUES

Fig. 4.5-20. Distribution of maximum force, shock 3, correlation = 0.25

1/2 SCALE 2D TEST RESULTS

*MAX VELOCITY DISTRIBUTION
(IPS)

TIME HISTORY

SHOCK 3, $g = 0.71$
CORRELATION = 1.0

TEST 103/104

THE BOUNDARY RESPONSE
REPRESENTS THE MEAN
OF 2 VALUES

*AVERAGE OF 3 LARGEST VALUES WITHIN 1 Hz OF RESONANCE

Fig. 4.5-21. Distribution of maximum velocity, shock 3, correlation = 1.0

1/2 SCALE 2D TEST RESULTS

*MAX FORCE DISTRIBUTION
(LB)

TIME HISTORY

SHOCK 3, $g = 0.71$
CORRELATION = 1.0

TEST 103/104

THE BOUNDARY RESPONSE
REPRESENTS THE MEAN
OF 2 VALUES.

*AVERAGE OF 3 LARGEST VALUES WITHIN 1 Hz OF RESONANCE

Fig. 4.5-22. Distribution of maximum force, shock 3, correlation = 1.0

TABLE 4.5-2
TOTAL RANDOM ERRORS IN THE 1/2-SCALE, TWO-DIMENSIONAL, TWO-AXIS TEST DATA

Test Parameter	Instrument	Random Error (%) ^(a)						
		Rig (b) Control	Rig Configuration	Element Properties	Data Aquisition	Instrument Calibration	Extraneous	Total ^(c)
Resonant frequency	DC $\propto$ frequency	0.5	4.8	0	0.3	--	0.7	4.9 (5.9) ^(d)
Boundary support force	Load cells	17.0	5.0	2.8	1.8	5.0	0.7	18.4 (20.2)
Element deflection	Eddy current probe	8.5	2.5	0	0.6	1.7	0.7	9.1
Element velocity	Eddy current probe	11.3	3.5	0	0.6	2.4	0.7	12.1
	LVDT	11.3	3.5	0	0.6	0	0.7	11.9 (12.0)
Element impact force	ILMD	17.0	5.0	2.8	1.9	2.9	0.7	18.3

(a) All errors represent 1σ values

(b) Represent effect of input error from both X' and Y' axes.

(c) Total obtained by RSS compounding of individual errors.

(d) Numbers in brackets are obtained from repeated test data.

4.6. 1/5-SCALE, SINGLE-COLUMN TESTS

This section documents a summary of the 1/5-scale, single-column shake test program. The types of tests conducted were static pull and column pluck tests and sine sweep and time history earthquake tests. The complete report, containing a full description of the test rig and model, test rig dynamic excitation, instrumentation, and results, is given in Ref. 4.6-1.

4.6.1. Objectives

The objectives of these tests were to ascertain the behavior and to measure the response of a loosely constrained, single-core column of 1/5-scale fuel elements to uniaxial and simultaneous horizontal and vertical seismic input. The results of the test were used for analytical code correlation.

4.6.2. Description

4.6.2.1. Column Model and Supports. The test model was made up of a full height core column of graphite blocks in 1/5-scale (Fig. 4.6-1). From bottom to top, this column consisted of one full size element, one half element, eight full elements, one half element, one full element, and one half element. The basic element simulating the core support floor block was a standard size fuel element with its weight adjusted to one-seventh that of the 1/5-scale floor block (2.30 lb) since a single column was only supported instead of a refueling region. The three-dowel pin design of scaled stiffness (4000 lb/in.) as described in Ref. 4.6-2 was used to connect each block in the column.

The column was vertically supported at its base by four spring supports with a stiffness of 1656 lb/in., corresponding to the stiffness of a typical core support post scaled to 1/5-scale.

Fig. 4.6-1. One-fifth-scale test column

The column was supported laterally by rigid support pads that could be adjusted independently at each element level, providing the capability for testing at different nominal boundary gaps and column end conditions.

4.6.2.2. Test Rig. The column test rig, shown in Figs. 4.6-2 and 4.6-3, was constructed from steel and designed to provide a "rigid" boundary over the entire length of the column and to be free of flexural oscillations during the dynamic phase of the testing. It also provided attachment points for boundary displacement and force transducers.

For the static pull and pluck tests, the lateral support pads were removed from one side of the rig. During the dynamic phase of testing, the whole rig was lowered into the shaker table to minimize overturning motion.

4.6.2.3. Test Facility. A biaxial shaker table providing simultaneous horizontal and vertical motion was used for the seismic tests. The table was outfitted with four Shore and Western hydromechanical shakers, two horizontal and two vertical with a total capacity of 29,000 lb and 36,000 lb, respectively. Maximum shaker displacement capability was 12.0 in. horizontal and 9.0 in. vertical. The upper frequency limit for sinusoidal excitation was specified as 70 Hz.

4.6.3. Test Program

Three separate series of tests were performed in the program.

4.6.3.1. Static and Pluck Testing. Two types of tests were performed prior to placing the test rig on the shaker table. First, the column was deflected in small increments under the action of known forces as illustrated in Fig. 4.6-4. Measurements of column deflections were then taken relative to the support boundary at several positions.

Fig. 4.6-2. Single-column test fixture configuration (top view)

Fig. 4.6-3. Single-column test fixture configuration (viewed from under the shaker table)

Fig. 4.6-4. Test setup for the static pull and column pluck tests

In the pluck tests, the column was released from a deflected position. After release, the free vibration deflections of the column were measured as well as the support forces if the column impacted against the side boundary.

4.6.3.2. Column Dynamic Testing. Horizontal and vertical uniaxial and simultaneous two-axis shaker tests were performed using the biaxial shaker facility. Sine sweep testing was conducted to a frequency of 30 Hz in the horizontal direction and 50 Hz in the vertical direction. Several values of phase shift between the input waveforms were used during the two-axis sinusoidal testing, corresponding to a set of maximum and minimum cross correlation factors. The horizontal and vertical time history input consisted of the GA design earthquake shock 3, corresponding to soft soil conditions (25,000 psi modulus) and 5% structural damping. These are further described in Section 4.1.7. During the two-axis time history testing of the column, various time lags were implemented between the horizontal and vertical rig input components based on calculated maximum and minimum cross correlation factors.

Preliminary tests were conducted to investigate shaker table and test rig performance, a plus or minus deflection bias in the column, and the possible effect of instrument wires on the motion. Column vibration in the direction across the flats of an element as well as across the corners was investigated. Column response was also obtained for motion without boundary impact, and free transient vibration decay was recorded in an attempt to predict column damping.

The test parameters that were varied included input g-level and nominal gap size between the support boundary and the core column. A summary of all the tests performed is given in Tables 4.6-1 through 4.6-6.

4.6.4. Instrumentation

4.6.4.1. Transducers. The test instrumentation was divided into the categories of rig, boundary, and column transducers. Additional instrumentation hardware is discussed in Section 4.6.4.2.

TABLE 4.6-1
STATIC DEFLECTION TESTS

Test Sequence	Load Elevation By Block No.	Load Direction
1	4/5	-X
2	Both 6/7 And 3/4	-X +X
3	Both 6/7 And 3/4	+X -X
4	4/5	+X

Rotate the fuel element column 90 degrees clockwise.

5	4/5	+X
6	4/5	-X

TABLE 4.6-2
COLUMN PLUCK TESTS

Test Sequence	Initial Displacement (in.)	Right Side (-X) Boundary Gap	Pull Point Block Number
1	0.10	1.0	7
2	0.25	1.0	7
3	0.50	1.0	7
4	1.00	1.0	7
Adjust Right Side Boundary (-X).			
5	0.50	0.1	7
6	1.00	0.1	7
Oscillograph recording for the remaining test in this table.			
7	0.75	0.1	7
8	Adjust number seven block boundary 0.005 in. toward the negative X boundary (all other parameters same as test 6).		
9	Adjust number seven block boundary 0.010 in. toward the positive X boundary (all other parameters the same as test 6).		
10 ^(a)	1.00	0.05	7
11	1.00	0.0	7

(a) With number seven block boundary realigned prior to test.

TABLE 4.6-3
UNIAXIAL SINE SWEEP TESTS

Test No.	Axis	G-Level (g)	Boundary Gap (in.)	Top Block ^(a) Gap (in.)	Bottom Block ^(a) Gap (in.)	Comments
1	Horizontal	0.5	0.0 Locked	0.0 Locked	0.0 Locked	Horizontal sweep in the frequency range 1.5 to 50 to 1.5 Hz Column rotated 180°
2	Horizontal	0.25	0.10	0.10	0.10	
3	Horizontal	0.25	0.10	0.10	0.10	
4	Vertical	0.25	0.10	0.0	0.0	Vertical sweep in the frequency range 1.5 to 50 to 1.5 Hz
5	Vertical	0.25	0.10	0.0	0.0	
6	Horizontal	0.25	0.10	0.10	0.10	
7	Horizontal	Exploratory	1.00	0.0	0.0 Locked	g-level increased to maximum level without column touching boundaries. Perform quick shutdown at resonance frequency Column rotated 90°
8	Horizontal	Same as 7	1.0	0.0	0.0 Locked	
9	Horizontal	Same as 7	1.0	0.0	0.0 Locked	
10	Horizontal	Same as 7	1.0	0.0	0.0 Locked	
11	Horizontal	Exploratory	1.0	0.0	0.0 Locked	
12	Horizontal	0.25	0.10	0.0	0.0 Locked	
13	Horizontal	0.50	0.10	0.0	0.0 Locked	
14	Horizontal	0.50	0.40	0.0	0.0 Locked	
15	Horizontal	0.50	0.40	0.40	0.20	
16	Vertical	0.25	0.10	0.0	0.0 Locked	
17	Vertical	0.50	0.10	0.0	0.0 Unlocked	

(a) Free to slide vertically except where locked (maximum gap = 0.005 in.).

TABLE 4.6-4
SINGLE-AXIS TIME HISTORY TESTS

Test No.	G-Level (g)	Boundary Gap (in.)	Top Block Gap (a) (in.)	Bottom Block Gap (a) (in.)	Comments
Horizontal Axis					
18	0.50	0.10	0.0	0.0	Base Block Locked
19	0.50	0.25	0.0	0.0	Base Block Locked
20	0.50	0.25	0.0	0.125	
Vertical Axis					
21	0.50	0.25	0.0	0.0	Base Block Locked
22	0.50	0.25	0.0	0.0	Base Block Unlocked

(a) Free to slide vertically except where locked (maximum gap = 0.005 in.)

TABLE 4.6-5
TWO-AXIS SINE SWEEP TESTS (a)

Test No.	G-Level		Boundary Gap (in.)	Top Block Gap (in.)	Bottom Block Gap (in.)	Phase Angle Degrees
	Horiz.	Vert.				
23	0.50	0.25	0.2	0.0	0.0 Locked	0.0
24	0.50	0.25	0.2	0.0	0.0 Unlocked	0.0
25	0.50	0.25	0.2	0.0	0.0 Locked	22.5
26	0.50	0.25	0.2	0.0	0.0 Locked	45.0
27	0.50	0.25	0.2	0.0	0.0 Locked	90.0
28	0.50	0.50	0.2	0.0	0.0 Locked	(b)
29	0.50	0.25	0.2	0.2	0.1 Unlocked	(b)

(a) Sine sweeps to be 1.5-50-1.5 Hz at 0.5 decade/minute.

(b) Value chosen depending on previous tests in this sequence.

TABLE 4.6-6
TWO-AXIS TIME HISTORY TESTS

Test No.	G-Level		Boundary Gap (in.)	Top Block Gap (in.)	Bottom Block Gap (in.)	Time Lag (Sec)	Comments
	Vert.	Horiz.					
30	0.25	0.50	0.10	0.0	0.0	0.0	Base block locked
31	0.25	0.50	0.10	0.0	0.0	0.18	Base block locked
32	0.25	0.50	0.10	0.0	0.0	1.17	Base block locked
33	0.25	0.50	0.10	0.0	0.0	0.0	Base block locked
34	0.25	0.50	0.25	0.0	0.0	0.0	
35	0.25	0.50	0.25	0.0	0.125	0.0	
36	0.25	0.50	0.25	0.25	0.125	0.0	
37	0.50	0.75	0.25	0.25	0.125	0.0	
38	0.50	0.50	0.25	0.25	0.125	0.0	

The rig instrumentation consisted of a control accelerometer, displacement transducer (LVDT), and three additional accelerometers mounted on the test rig to check for motion of the rig relative to the shaker table.

Boundary instrumentation included load cells and LVDTs at several locations for measurement of the column boundary impact forces and lateral displacements, respectively. Load cells were also employed to measure column vertical support forces, and eddy current probes were used to measure the vertical displacement between the top and bottom block of the column relative to the test rig.

The column instrumentation included eddy current probes to measure relative vertical displacement between the blocks for determination of rocking angle and uplift. Load cells were incorporated in the instrumented element design for measuring dowel forces and block rock-down forces.

All transducer assembly designs aside from the column vertical supports were the same as, or modified from, those successfully used in the basic rocking test, planar array test, and 1/5-scale dowel force test. These are further discussed and schematically shown in Section 4.1.5.

Schematic diagrams showing the column instrument configurations are given in Figs. 4.6-5 and 4.6-6.

4.6.4.2. Data Acquisition. The data acquisition and signal conditioning system, which was similar to that designed for the dowel force test, is described in Sections 4.1.5 and 4.1.6.

The signal from each transducer varied in the range of 0 to 10 volts, and was digitally sampled for computer tape storage by a multiplexer circuit having a period of 5 msec. Predetermined calibration factors for the instruments were subsequently used to convert the data from digital counts

Fig. 4.6-5. Pluck test instrument configuration

Fig. 4.6-6. Sine sweep and time history test instrument configuration

to engineering units. Additional electronic circuits were used to process the data from several of the 80 channels in the system. These were:

1. A high frequency filter used with all LVDTs.
2. Peak holding circuits to hold transducer signals having response time less than one multiplexer period.
3. Summing circuits used to measure the instantaneous sum of the forces.

4.6.5. Data Reduction

An array of computer programs was used to process the digitized data into special formats of engineering units as described in Section 4.1.8 with the exception of subroutine ANGLZ and program VIEW. However, these are basically the same programs used to reduce the 1/5-scale dowel force test data, with minor modifications.

Computer program VIEWL contains subroutine ANGLZ, which provides printout and 4020 plots of time history data.

4.6.6. Results and Conclusions

Since the test program produced over 143 million data points, not all of the data were reduced for the final report. The reduced data were collected in the appendices of Ref. 4.6-1 and were used for correlation with analysis and to check for shorted or open transducer circuits. The following abstract contains a summary of the reduced data and represents typical test results.

4.6.6.1. Static Deflection Tests. Static deflections were imposed on the column by the application of horizontal loads or moments according to

Table 4.6-1. Column deflections for an applied horizontal load and an in-plane moment, Tests 2 and 4, are shown in Figs. 4.6-7 and 4.6-8, respectively.

4.6.6.2. Column Pluck Tests. The column was deflected in the center and released from positions of initial displacements ranging from 0.10 to 1.00 in. according to Table 4.6-2. The time history motion of the free vibration decay was recorded in terms of deflection and relative rocking angles between elements. A typical column time history displacement, after release, representing 0.10 in. initial deflection, Test 1, is shown in Fig. 4.6-9. The damping estimated from this decay curve was 15%. Since the column was in a "clamped" configuration at the top and bottom ends, the vibration mode was that of the fundamental beam mode. The frequency associated with the vibration was 3.5 Hz. Both damping and frequency of vibration decrease with increasing displacement magnitudes as shown in Fig. 4.6-10. The frequency response indicates that the free column structure exhibits a spring-softening system.

4.6.6.3. Uniaxial Sine Sweep Test Results. The data from uniaxial sine sweep tests 12, 13, 16, and 17 were reduced in order to study the frequency response of the column for the restraint condition specified in Table 4.6-3.

Figures 4.6-11 and 4.6-12 show column horizontal resonance curves represented by the dowel shear force. The column has resonance characteristics similar to the full core resonance described in Section 4.7. The curves show the typical characteristics of a nonlinear and spring-hardening system. Thus, the vibration of a column with side restraints shows very different characteristics compared with those of a free column, as discussed in Section 4.6.6.2. The resonant frequency shifted from 6.4 Hz to 8.8 Hz for a change in input g-level from 0.25 g to 0.5 g.

Fig. 4.6-7. Column deflections due to an applied moment

Fig. 4.6-8. Column deflections due to an applied force

Fig. 4.6-9. Column free vibration time history

Fig. 4.6-10. One-fifth scale column shake test resonant frequency and damping versus pluck test vibration amplitude

Fig. 4.6-11. Core column horizontal resonance curve - sweep-up, 0.25 g

Fig. 4.6-12. Core column horizontal resonance curve - sweep-up, 0.5 g

The vertical column resonance at 0.5 g represented by the support post force is shown in Figs. 4.6-13 and 4.6-14. These figures represent the sweep-up and the sweep-down, respectively. The resonant frequency at approximately 29 Hz was identified as a support post resonance. This was verified by analysis considering the column as a lumped mass attached to a linear spring of stiffness equal to the post stiffness. The sweep-down results (Fig. 4.6-14) show the resonance at a slightly higher frequency, which determines the column to be a spring softening system in vertical excitation.

Additional resonance peaks are indicated in the figures at 25, 27, and 34 Hz. These have been determined to be shaker table structural resonances typically caused by a loosening effect of a manoball joint and vertical shaker and core column flexibility. These effects were observed during the pretest shaker table and test rig verification tests.

4.6.6.4. Simultaneous Two-Axis, Sine Sweep Tests. Resonance plots similar to those obtained for uniaxial excitation were obtained for simultaneous horizontal and vertical column resonances at exactly the same frequency values for identical excitation levels and column gaps. These curves were also useful in the further interpretation of the shaker table structural resonances.

4.6.6.5. Uniaxial Time History Tests. Uniaxial horizontal and vertical time history tests were performed according to Table 4.6-4 using the test rig input waveforms shown in Figs. 4.1-28 through 4.1-31 of Section 4.1.7. Support post load response and column element rocking angles, rocking forces, and dowel forces are shown in Figs. 4.6-15 through 4.6-22 for tests 20 and 22. It should be noted that most figures show an artificial transient response at the beginning and end of the excitation; this response came about by starting the input from an off-center position in order to utilize the maximum displacement capacity of the shakers.

Fig. 4.6-13. Vertical resonance - sweep-up, 0.5 g fixture acceleration

Fig. 4.6-14. Vertical resonance - sweep-down, 0.5 g fixture acceleration

Fig. 4.6-15. Support post load - shock 4, 0.5 g

Fig. 4.6-16. Support post load - shock 3, 0.5 g

Fig. 4.6-17. Rocking angles - shock 4, 0.5 g

Fig. 4.6-18. Rocking force - shock 4, 0.5 g

Fig. 4.6-19. Dowel force - shock 4, 0.5 g

Fig. 4.6-20. Rocking angles - shock 4, 0.5 g

Fig. 4.6-21. Rocking force - shock 4, 0.5 g

Fig. 4.6-22. Dowel force - shock 4, 0.5 g

The column support forces shown in Figs. 4.6-15 and 4.6-16 illustrate that the overall load for pure horizontal excitation is much larger than that for vertical excitation of the same g-level. The existence of a 0.125-in. base block gap for the horizontal time history test, therefore, seems to present a severe local load environment for the posts.

The rocking angles, rocking forces, and dowel forces in Figs. 4.6-17, 4.6-18, and 4.6-19 illustrate the response of the column to a vertical input. This is compared to the column response in Figs. 4.6-20, 4.6-21, and 4.6-22 for a horizontal input, which is seen to induce far larger response than does the vertical input.

4.6.6.6. Biaxial Time History Tests. Simultaneous horizontal and vertical time history tests, performed according to Table 4.6-6, represent different boundary conditions such as changes in input excitation phase lag, column gaps, and excitation g-level. Typical response of the relative rocking angle between elements, support post forces, element lateral impact forces, and rocking forces are shown in Figs. 4.6-23 through 4.6-27 for Test 35. This test represents a 0.25/0.5 g (vertical/horizontal) ground acceleration input, zero phase lag, and column gaps of 0.25/0.0/0.125 in. (midcolumn/plenum element/support block).

A summary description of the column response to Tests 30, 32, 35, 37, and 38 is given in Table 4.6-7. The comparison between Tests 30 and 32 illustrates the effect of introducing a phase lag between horizontal and vertical input. Little effect on the response parameters is observed except for the element impact forces at midheight, which are seen to reduce considerably. At other locations along the column, however, no significant change in impact forces was noted. By increasing the g-level of the vertical input from 0.25 to 0.5 g (comparing Tests 35 and 38), the support post load and rocking forces increased by approximately 75% and 40%, respectively. Little change was observed in the dowel force and

Fig. 4.6-23. Rocking angles - shock 4, 0.25/0.5 g

Fig. 4.6-24. Support post load - shock 4, 0.25/0.5 g

Fig. 4.6-25. Dowel forces - shock 4, 0.25/0.5 g

Fig. 4.6-26. Impact force - shock 4, 0.25/0.5 g

Fig. 4.6-27. Rocking force - shock 4, 0.25/0.5 g

TABLE 4.6-7
COMPARISON OF MAXIMUM VALUES (1b)

Test No.	Support Post Load [(y-1) + (y-2)]	Dowel Force (Block 10/11)	Impact Force (Midheight)	Rocking Force (Block 10/11)	Change in Boundary Conditions (a)
30	--	56.0	160	89.0	0.25/0.5 g ^(b) 0.1/0.0/0.0 ^(c) in. gap. } Base 0.0 sec phase lag. } case Support block locked. }
32	--	58.0	110	90.0	1.17 sec phase lag.
33	21.5	45.0	180	92.5	Support block unlocked.
35	21.0	60.0	265	90.0	0.25/0.0/0.125 in. gap.
38	37.5	54.0	265	127.0	0.5/0.5 g. 0.25/0.25/0.125 in. gap.
37	47.0	60.0	> 400 ^(d)	145.0	0.5/0.75 g. 0.25/0.25/0.125 in. gap.

(a) Ref. Table 4.6-6.

(b) Vertical/horizontal.

(c) Mid column/plenum block/support block.

(d) Instrument saturated.

impact force parameters. From these observations, it may be concluded that:

1. Maximum column response occurs for two-axis horizontal and vertical input applied in-phase.
2. The vertical input has little effect on lateral column response parameters such as element impact forces and dowel forces.

Increasing the column gap has a large effect, as expected, on element lateral impact forces and dowel forces. This is demonstrated by Tests 33 and 35.

Comparing Tests 38 and 37, it is seen that an increase in horizontal g-level increased all column response parameters. The element lateral impact forces essentially doubled as a result of increasing the g-level from 0.5 g to 0.75 g.

4.6.7. Error Analysis

Statistical errors in the test data were estimated using the component error analysis derived in Section 4.1.11. The value of component errors associated with digitization, peak holding, signal summation, random noise, and instrument calibration were taken from results in the dowel force test since this instrumentation and associated test equipment were basically the same.

The effect of small geometric deviations in the nominal test configuration was estimated for the dowel strain gage instrumentation using the analytical data in Fig. 4.6-28. Being the only data available, these results were also assumed to apply for the boundary load cells and column rocking force load cells.

SHOCK 4, 0.5 G. ALL BOUNDARY GAPS = 0.25 IN. UNLESS OTHERWISE NOTED
 GAPL (1) = GAPR (1) = GAPL (14) = GAPR (14) = 0.0 IN.

Fig. 4.6-28. Maximum dowel shear force as a function of gap, 1/5-scale, single-column analysis

Examination of the data output from accelerometers attached to the shaker table and test rig revealed that control of the rig motion by the biaxial shaker system was less precise than that for the uniaxial system used in the 1/5-scale, dowel force test. In addition, the variation ($\pm 1\sigma$) in the nominal input g-level was estimated at 2.5% in contrast to the 1.0% to 1.8% in the dowel force test. A summary of the component errors contributing to the total is given in Table 4.6-8.

The overall total random error of the test data was calculated by substituting the above component errors into the error propagation equation (Eq. 4.1-13, Section 4.1.11.2).

Total random errors for the instrument data are given in Table 4.6-9. From the table, it is seen that all parameters except the dowel forces were obtained with a reasonable accuracy.

4.7. 1/5-SCALE, FULL-ARRAY TESTS

This section documents in summary the seismic tests on the 1/5-scale, full-array HTGR core model. Further detailed descriptions are obtained in the final test report (Ref. 4.7-1), and all documented test results are presented in Ref. 4.7-2.

The test model represents the HTGR 3000-MW(t) core reference design and its support structures as of late 1972 in the cold and fully irradiated end-of-life condition. Dynamic input to the test rig consisted of constant acceleration sine sweeps, sine dwells, and time histories representing actual and synthesized earthquakes.

Typical test results are presented including resonant frequencies, mode shapes, and in-core and boundary forces and deflections for two different lateral core support designs.

TABLE 4.6-8
COLUMN SHAKE TEST INSTRUMENT COMPONENT ERRORS^(a)

Error Component	Dowel Strain Gages	Load Cells	Eddy Current Probes
$\hat{S}_{G_C} (\%)$	0.025	0.025	0.025
$\hat{S}_{N_R} (\%)$	0.5	3.0	1.5
$\hat{S}_{G_P} (\%)$	0.5	0.5	0.5
$\hat{S}_{G_S} (\%)$	0.5	0.5	0.5
$\hat{S}_{G_A} (\%)$	9.0	6.0	7.5
$\hat{S}_{G_G} (\%)$	20.0	8.0	1.0
$\hat{S}_g (\%)$	2.5	2.5	2.5
$\hat{S}_\omega (\%)$	0.0	0.0	0.0
$\frac{\partial (g, \omega)}{\partial g}$	900.0	2000.0	0.2
$\frac{g}{\bar{u}(g, \omega)} \frac{\partial (g, \omega)}{\partial \omega} \hat{S}_g$	8.3	11.0	2.5
$\frac{\omega}{\bar{u}(g, \omega)} \frac{\partial (g, \omega)}{\partial \omega} \hat{S}_\omega$	0.0	0.0	0.0

(a) Fractional one-sigma errors are expressed in percent.

TABLE 4.6-9
COLUMN SHAKE TEST OVERALL RANDOM ERRORS

Instrument	1 σ Random Error (%)
Rocking Angle	8.0
Uplift	8.0
Dowel Shear Force	23.0
Rocking Forces	15.0
Lateral Support Loads	15.0

4.7.1. Objectives

The overall objectives of the 1/5-scale, full-array tests were to ascertain the behavior of the full-array core model and its support structure when subjected to seismic excitation forces and to provide data for correlation and verification of the computer codes.

The following information was obtained:

1. Core motion characteristics
 - a. Core lumping
 - b. Resonant frequencies and mode shapes
 - c. System damping
2. Forces and deflection at lateral supports
3. Core deflection and forces
 - a. Fuel column and reflector column deflections
 - b. Fuel block impact forces

4.7.2. Description

4.7.2.1. Core Model and Supports. A schematic diagram of a section through the 1/5-scale, full-array model and rig is shown in Fig. 4.7-1. A photograph of the rig is shown in Fig. 4.7-2.

All of the 1/5-scale core elements, including fuel elements, hexagonal and permanent reflector blocks, core support blocks, and the plenum blocks, which are of steel construction in the prototype, were fabricated from graphite. The use of graphite material for the model introduced a distortion in the scaling laws employed for the model; this is discussed in Section 4.1.3.

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Fig. 4.7-1. Test rig and model schematic diagram

Fig. 4.7-2. One-fifth-scale, full-array test rig

One series of tests was run using a soft lateral core support spring pack design (800 lb/in.), and the other series incorporated an essentially rigid hard stop (>100,000 lb/in.) after 0.2 in. of the soft spring compression. The core support floor blocks were supported on recessed roller bearings (see Fig. 4.7-1), which simulated the lateral free motion of core support posts used in the prototype.

4.7.2.2. Test Rig. The test rig structure, shown in Fig. 4.7-2, was designed to hold the boundary spring packs and function as the PCRV in the prototype. The test rig and model assembly weigh approximately 55,000 lb, and are supported by four hydraulic TEAM bearings permitting nearly frictionless uniaxial motion. The rig was designed with a connection to a hydraulic shaker system with a capacity of 75,000 lb force. The shaker was attached to a reaction mass of 750,000 lb.

4.7.2.3. Input Excitation and Test Scope. The input excitation consisted of three types. Constant acceleration sine sweeps in the range of 1.6 Hz to 20 Hz were used to determine core motion characteristics. The acceleration input level was varied from 0.075 g to 0.75 g. Resonant frequencies identified by these tests were further investigated by sweeping up to the resonant frequency and dwelling at that point. Several dwells were terminated abruptly in order to obtain the free transient response of the core.

A set of time history rig displacements which represented real and synthesized earthquakes for a range of soil stiffnesses and ground g-levels were also input. The time history input represents the PCRV displacement response at the core support floor elevation. A more detailed description of the input excitation is given in Section 4.1.7.

Uniaxial tests were performed in the across-the-flats direction of the core element (x-axis) and across-the-corners (y-axis). Excitation of the x and y axes was performed with the soft boundary supports, and the x-axis excitation only with the continued soft support and stop. A summary of all test cases is given in Table 4.7-1.

TABLE 4.7-1
SUMMARY OF 1/5-SCALE, FULL-ARRAY TESTS

Test ID No.	Test Type	Excitation G-Level(a)	Excitation Frequency	In-Core Instrument Position/ Level(b)	Support Boundary Instrument Plan(c)
X-Axis Excitation without Stops					
-	Sine sweep Sine dwell	0.15 g	0.8-22 Hz 2.0 Hz	1/8	1
1	Sine sweep Sine dwell and decay	0.30 g	1.25-22 Hz 2.0, 3.0 3.5 Hz		
2	Time history	0.15 g	--	1/8	
3	Time history	0.10 g 0.25 g	-- --		
4	Sine sweep Sine dwell and decay	0.50 g	1.6-22 Hz 2.0, 3.0 3.5, 3.8 Hz		
5	Time history	0.35 g	--		
6	Time history	0.50 g	--		
7	Sine sweep Sine dwell and decay	0.50 g 0.50 g	1.6-22 Hz 4.0, 4.4 Hz	2/8	2
8	Time history	0.25 g	--	3/8	3
9	↓	0.25 g	--	1/8	1
2M		0.15 g	--		
3M		0.10 g 0.25 g	-- --		
4M		0.3 g 0.35 g	-- --	1/8	1
5M		0.50 g	--		
9M	↓	0.25 g	--	3/8	3
12		0.25 g	--	1/4	4
13		0.25 g	--	1/10	5
14		0.25 g	--	1/13	6
15		0.15, 0.25 g 0.35 g	-- --	1/8	1
16		0.5, 0.6 g	--		
17		0.65, 0.7 g 0.75 g	--		

TABLE 4.7-1 (Continued)

Test ID No.	Test Type	Excitation G-Level (a)	Excitation Frequency	In-Core Instrument Position Level (b)	Support Boundary Instrument Plan (c)
<u>Y-Axis Excitation without Stops</u>					
18	Sine sweep	0.15 g	0.8-22 Hz	5/8	1
19	Sine sweep Sine dwell and decay	0.30 g	1.25-22 Hz 9.0, 7.0, 4.1, 3.7, 3.3, 1.8		
19A	Time history	0.15 g	--		
20	↓	0.25 g	--		
21		0.50 g	--		
22	↓	0.70 g	--		
23	Sine sweep Sine dwell and decay	0.50 g	1.6-22 Hz 3.0, 3.5, 3.75, 4.0, 4.5	5/8	1
24	Time history	0.25 g	--	7/8	1
<u>X-Axis Excitation with Stops</u>					
25 (No digital data)	Sine sweep	0.15, 0.20 g 0.25, 0.30 g		1/8	1
26	Sine sweep Sine dwell Sine sweep Sine dwell	0.3 g 0.3 g 0.5 g 0.5 g	1.21 Hz 2.8 Hz 1.6 Hz 1.6, 4.0, 4.5, 4.7 Hz	1/8	1
27	Time history	0.25, 0.35 g 0.5 g	-- --	1/8	2
28		0.65, 0.75 g	--		
29		0.5 g	--	1/4	2
30			--	1/11	3
31			--	2/8	2
32	↓		--	3/8	

TABLE 4.7-1 (Continued)

Test ID No.	Test Type	Excitation G-Level(a)	Excitation Frequency	In-Core Instrument Position Level(b)	Support Boundary Instrument Plan(c)
33 (No digital data)	Sine sweep Sine dwell	0.5 g 0.5 g	-- 1.60 Hz 3.0 Hz	1/8	
34	Time history	0.5 g	--	4/8	1,2,3 new
26R	Sine sweep Sine dwell Sine sweep Sine dwell	0.3 g 0.5 g	-- 2.78 Hz 1.56 Hz 1.6, 4.0, 4.7, 5.0 Hz	1/8	2R
27R	Time history ↓	0.25, 0.35 g 0.5 g	-- --		
28R		0.67, 0.75 g	--		
30R		0.5 g	--	1/11	
31R			--	2/8	
32R			--	3/8	
33R	Sine dwell	0.5 g	-- 3.0 Hz	1/8	

(a) G-level refers to peak ground acceleration for time history excitation and to fixture acceleration for sinusoidal excitation.

(b) See Fig. 4.7-5.

(c) See Fig. 4.7-3 and 4.7-4.

4.7.2.4. Instrumentation. The test instruments were categorized into three groups: rig, boundary, and in-core transducers. Pertinent electronic hardware is discussed in Section 4.7.2.5.

The rig instruments consisted of two accelerometers placed at the base and top of the rig and one linear variable displacement transducer (LVDT) to measure the rig motion relative to ground.

Boundary transducers included LVDTs mounted in the permanent side reflector blocks to measure displacements relative to the hexagonal core blocks on one side and the lateral spring pack supports on the other. The LVDTs also measured support floor deflections and spring pack deflections.

Calibrated LVDTs and strain gages mounted on the spring packs measured spring pack forces. The LVDTs were used in the tests with the soft support design. The majority of these were relocated during testing to obtain a wide distribution of support forces, as shown in Fig. 4.7-3. The strain gage instrumentation, used only in tests with the hard stop support, was relocated as shown in Fig. 4.7-4.

The in-core instruments, concentrated in a group of three adjacent elements as described in Section 4.1.5, consisted of the following:

1. Capacitive displacement gages (DEES gages) for fuel block relative displacement measurements.
2. Accelerometers.
3. Fuel block strain gages calibrated to measure element collision forces.
4. Fuel block contact gages for determining the impact configuration of two colliding fuel elements.

Fig. 4.7-3. Boundary plan for spring pack LVDTs (x-axis and y-axis excitation, soft core support)

Fig. 4.7-4. Boundary plan for spring pack load cells (x-axis excitation with stops)

Fig. 4.7-5. In-core instrument locations - plan view

The group of three elements was located at several vertical and planar locations during testing as shown in Table 4.7-1 and Fig. 4.7-5. The in-core test results therefore can be expressed as a function of core position.

4.7.2.5. Data Acquisition. The signal from each transducer varied in the range of 0 to 10 volts, and was digitally sampled for computer tape storage using a multiplexer circuit having a period of 5 msec. The test data were stored on magnetic tape for later data processing using predetermined calibration factors. Peak holding circuits were used for each transducer such that response of duration less than the multiplexer period could be captured. Further details are given in Section 4.1.6.

4.7.2.6. Data Reduction. Processing of the raw digital test data into final test results was accomplished by applying the transducer calibration factors to convert the data to engineering units.

The data were then extracted from the tapes by a number of computer programs which produced transducer frequency response, rates of change, peak values, and statistical parameters, including graphical representation of the results. A summary description of the data reduction software is given in Table 4.7-2. These data reduction programs are further described in Section 4.1.8.

4.7.3. Results and Conclusions

Typical test results for the soft core support and combined soft and hard stop support for both sinusoidal and time history excitation are presented in this section. The complete results are contained in Ref. 4.7-2.

TABLE 4.7-2
ONE-FIFTH-SCALE, FULL-ARRAY TEST DATA REDUCTION SOFTWARE

Program Name	Task	Function
1. DATAT	I	Conversion from Varian to UNIVAC system. Input of instrument calibration factors, and storage in UNIVAC 1108
2. DUMP	I	Varian to UNIVAC conversion system check
3. DATAP	II	Plots instrument output versus time (UNIVAC 1108, SC4020 plots)
4. DATA C	II	Plots core contact gages output versus time
5. BINGO		
a. VEL	II	Calculates time rate of change of instrument output
b. LUMP	II	Calculates degree of lumping of core elements
c. MAX	II	Calculates statistical parameters (i.e., standard deviation, range, etc.) for given set of calculated data
d. PEAK	II	Calculates maximum value, minimum value, time at max value, time at min value from a set of raw data
e. LVDT	II	Checks input waveform (sinusoidal)
6. PICCOR	II	Calculates and displays gaps and velocities for horizontal cross section of core
7. OGIVE	II	Statistical analysis of a set of data (i.e., probability distribution, ogive, etc.)
8. BMD02T	II	Power spectral density, autocorrelation, cross correlation analyses for one or more time series

4.7.3.1. Sinusoidal Input. The dynamic core characteristics were obtained using constant acceleration sinusoidal sweep excitation at the rate of 0.5 decade per min. Figure 4.7-6 gives the resonance characteristics of the model core for the soft spring support condition. As shown in the figure, the resonance behavior is typically nonlinear, characterized by the sudden drop-off in response. During sweep-up, the resonance occurs at a higher frequency than during sweep-down, which characterizes a spring-hardening system. This observation is consistent with the characteristics generated for the planar core sections of 73 elements tested (Section 4.4). Figure 4.7-6 also shows that the resonance is strongly amplitude dependent, and increases with excitation level. From tests with the combined soft spring and hard stop support, the change in lateral support stiffness (800 lb/in.^2 to greater than $100,000 \text{ lb/in.}^2$) increased the resonant frequency by less than 10% as shown in Fig. 4.7-7. Tests along the core x-axis (across-flats) and y-axis (across-corners) did not reveal any significant changes in the core resonance characteristics.

Essentially three resonant frequencies of importance were identified. These are summarized in Table 4.7-3. The first mode is in the 1.6 Hz to 2.4 Hz frequency range and has been identified as a column "beam" mode. The resonance is indicated from fuel element impact force measurements as shown in Fig. 4.7-8. The second mode at 4.0 Hz is a lumped core mass mode dependent on the across-core gap. The third mode, at 4.5 to 5.0 Hz, is a core support floor lumped mass mode dependent on the floor gap. The column and core support floor resonances were only detected at an excitation level of 0.5 g.

During sinusoidal motion, the core oscillated as a tightly lumped mass between the reflector boundaries, and the core lumping parameter increased with increasing frequency up to the 4.0 Hz resonance. At 4.0 Hz, the core lumping factor was a minimum 79% during travel across the core and reached 100% during impact with the boundary. The effect on core lumping from a change in core support spring rate was negligible.

Fig. 4.7-6. Core resonance characteristics, soft boundary support

Fig. 4.7-7. Core resonance characteristics, combined soft support and hard stop

TABLE 4.7-3
CORE RESONANT FREQUENCIES

Excitation (g-level)	Soft Spring Support (800 lb/in.)	Combined Soft Spring and Hard Stop
0.15 g ^(a)	2.5 Hz/2nd mode	2.5 Hz/2nd mode
0.30 g ^(a)	3.5 Hz/2nd mode	3.6 Hz/2nd mode
0.50 g	1.6 - 2.4 Hz/1st mode 4.0 Hz/2nd mode 4.5-5.0 Hz/3rd mode	2.0 Hz/1st mode 4.2 Hz/2nd mode 4.5-5.0 Hz/3rd mode

(a) First and third modes not measured at these g-levels.

Fig. 4.7-8. Core resonance characteristics (full element forces), soft boundary support

Core structural cross coupling was measured for uniaxial input as a function of the boundary support force response at 90° to the direction of excitation. Figure 4.7-9 shows that the spring pack axial support force at this position was less than 10% of the axial support force recorded in the direction of excitation. However, larger across-core response could occur under simultaneous two-axis excitation in the x and y directions.

Satisfactory core damping measurements were not obtained in this test because the quick shutdown procedure employed to produce the core logarithmic decay in free vibrations was too slow. Hence, the damping values were underestimated. Larger core damping was indicated by core element oscillations decaying to less than measurable levels after only two cycles, which leads to estimates of equivalent viscous damping values above 30%. Further tests of this kind were performed under the dowel force test program described in Section 4.8.

4.7.3.2. Time History Input. From instrument analog output and fuel element contactor data, a study was performed to determine the types of fuel element loading. It was found that the fuel elements were basically subjected to two different types of loading: (1) a shock load similar to a two-body impact where the face opposite to the impact face was relatively load free, and (2) a dynamic compression load where opposite faces were equally loaded. The impact load was of very short duration (typically 0.0004 sec), and the dynamic compression was of long duration (typically 0.120 sec). The dynamic compression loads generally represented the maximum fuel element load.

In uniaxial excitation the boundary support force distributions showed maximum support forces at the core mid-elevation along the direction of excitation. Circumferentially, the forces conformed approximately to a cosine distribution. This is demonstrated in Fig. 4.7-10. The soft spring support case resulted in larger deflections. A maximum of 0.96 in. occurred at 0.5 g ground acceleration. The combined soft spring and hard stop support practically limits the deflection to the 0.2 in. of the soft

Fig. 4.7-9. Core coupling

1/5 SCALE FULL ARRAY TEST

Fig. 4.7-10. Core support force distribution

spring because of the high spring rate of the hard stop. The support forces for this design are therefore much higher. In-core fuel element force distributions are shown in Fig. 4.7-11 for the soft spring support case and show a maximum near the boundary slightly above the core mid-height. The combined soft spring and hard stop support case showed a more even distribution of in-core forces.

The core response as a function of input g-level was nonlinear and tended to flatten out markedly above 0.5 g. This is demonstrated in Fig. 4.7-12, which shows both the GA design earthquake and the El Centro earthquake. It is observed that the GA design earthquake generally produced much larger core response than the El Centro earthquake. It was also found that the maximum core response was obtained from portions of the GA design earthquake containing strong harmonic waveforms (large sinusoids at 3 Hz to 4 Hz). These waveforms typified the GA synthesized design basis earthquake prior to December 1973, when new NRC seismic design spectra were issued.

The core response was also sensitive to the plant soil conditions employed to generate the excitation input. Figure 4.7-13 demonstrates that soft soil conditions (65,000 psi modulus) induce lateral support forces approximately two times larger than forces induced by the rock (3×10^6 psi) foundation. This figure also shows that the forces generated from excitation along the y-axis are about 30% lower than those obtained for x-axis excitation.

4.7.4. Errors in the Test Data

An error analysis to determine the total random error in the test data was performed in conjunction with the dowel force test. Since the test configuration and most of the instrumentation were identical for both tests, the dowel force test data errors in Section 4.8.5 also apply to the 1/5-scale, full-array test.

Fig. 4.7-11. In-core force distribution

1/5 SCALE FULL ARRAY TEST
HARD SUPPORT (100,000 LB/IN.)

Fig. 4.7-12. Core support forces as a function of g level

Fig. 4.7-13. Core support forces for two site soil stiffnesses

4.8. DOWEL FORCE TEST

This section documents in summary the follow-on series of seismic tests on the 1/5-scale, full-array model, which was primarily run for the purpose of measuring core element dowel pin shear forces. Improved instrumentation designs also made it possible to reevaluate the impact forces on the fuel element. The complete test report is documented in Ref. 4.6-2. The development of the 1/5-scale full-array model and test program is described in Section 4.7 and Ref. 4.7-1.

4.8.1. Test Objectives

The dowel force test objectives were to measure the following as a function of core radial location and elevation:

1. Magnitude and direction of core element dowel forces.
2. Core element collision forces and orientation of the elements at impact.
3. Core element rocking angles.
4. Boundary loads.

Core displacements were also measured during the test for use in the determination of resonant frequencies and the overall core damping. The test data provided a further base for analytical code correlation with the 1/5-scale, full-array model.

4.8.2. Description

4.8.2.1. Core Model and Test Rig. The core model and test rig were basically the same as for the 1/5-scale, full-array tests except for new

instrumentation designs for measuring dowel forces and interblock collision forces. A schematic diagram of the full-array model and rig is shown in Fig. 4.7-1 in Section 4.7, while the actual test rig is shown in Fig. 4.7-2.

The core elements were fabricated from graphite, which included all fuel elements, hexagonal and permanent reflector blocks, core support blocks, and keyed plenum blocks. The core element scaling analysis and design are described in Section 4.1.3, including a discussion of model distortions.

All tests in the program were performed with core lateral spring pack supports having a combined soft spring of 800 lb/in. and a hard stop of a minimum of 100,000 lb/in. stiffness. The stop was designed to activate after 0.2 in. of soft spring compression. The core support floor blocks were supported by roller bearings (Fig. 4.7-1, Section 4.7), which allowed the same freedom as the floor support posts used in the prototype.

4.8.2.2. Input Excitation and Test Scope. The model response was measured for three kinds of excitation. Resonance characteristics were determined by constant acceleration sine sweeps in the range of 1.6 Hz to 10 Hz, performed at peak test rig fixture accelerations of 0.5 g. Several tests were run at fixture g-levels in the range of 0.15 g to 0.5 g and consisted of a sweep-up to the resonant frequency followed by a brief dwell and then automatic termination with the use of a special quick-shutdown device. These tests were used to measure the free transient core decay from which overall damping was evaluated. Core damping was also calculated from the phase angle relationship between the damped core and the test rig displacement during sine sweep excitation.

A set of time history rig displacement was also input which represented real (El Centro) and synthesized earthquakes (GA design earthquakes) for a range of soil stiffnesses and ground g-levels. These are described further in Section 4.1.7. As opposed to the 1/5-scale input in

Section 4.7, these time histories satisfied the NRC seismic design spectra after December 1973. A summary of all the tests performed showing type of input, excitation level and frequency, and location of instrumentation is given in Table 4.8-1.

4.8.2.3. Instrumentation. The test instruments were categorized into groups of rig, boundary, and in-core transducers. Pertinent electronic hardware is discussed in the section covering data acquisition.

The rig instrumentation consisted of a single LVDT, which monitored the rig motion and provided position feedback to the rig control unit.

Boundary transducers consisted of spring pack strain gages calibrated for load measurements and LVDTs, which measured displacements of the permanent side reflector relative to the lateral supports.

The in-core instruments consisted of:

1. LVDTs to measure displacements between permanent and replaceable reflector elements and between core support floor blocks.
2. Eddy current probes to measure vertical displacements between core elements, subsequently providing element lift-off and rocking angles.
3. Dowel strain gages and dowel load cells for dowel shear force measurements.
4. Strain gages and load cells for determination of fuel element collision forces and impact orientation.

Further descriptions of these instruments are given in Section 4.1.5, which gives design details of the eddy current probe, dowel pin strain

TABLE 4.8-1
ONE-FIFTH-SCALE DOWEL FORCE TEST SEQUENCE

Test No.	Test Type	Fixture ^(a) g	Ground g	Frequency Range (Hz)	Core Column Location	Side Reflector Pos./Elev.	Floor Structure ^(a) Block Location
1	Sine sweep	0.50	--	1.6-10-1.6	1-7	RB596/5,6	SB004
2	Dwell and decay	0.15	--	1.6-2.5	1-7	RB596/5,6	SB004
-	Data reviewed		--				
3	Dwell and decay	0.30	--	1.6-3.5	1-7	RB596/5,6	SB004
4	Dwell and decay	0.50	--	1.6-1.7	1-7	RB596/5,6	SB004
5	Dwell and decay	0.50	--	1.6-2.4	1-7	RB596/5,6	SB004
6	Dwell and decay	0.50	--	1.6-4.1	1-7	RB596/5,6	SB004
7	Dwell and decay	0.50	--	1.6-5.1	1-7	RB596/5,6	SB004
8	Time history	0.20	0.10	--	1-7	RB596/5,6	SB004
9	Time history	0.30	0.15	--	1-7	RB596/5,6	SB004
10	Time history	0.40	0.20	--	1-7	RB596/5,6	SB004
11	Time history	0.50	0.25	--	1-7	RB596/5,6	SB004
-	Data reviewed						
-	Modified setup	(Relocated instrumented elements)					
12	Sine sweep	0.50	--	1.6-10-1.6	92-171	RB596/3,4	Not recorded
13	Repeat test No. 8	0.20	0.10	--	92-171	RB596/3,4	Not recorded
14	Repeat test No. 9	0.30	0.15	--	92-171	RB596/3,4	Not recorded
15	Repeat test No. 10	0.40	0.20	--	92-171	RB596/3,4	Not recorded
16	Repeat test No. 11	0.50	0.25	--	92-171	RB596/3,4	Not recorded
-	Modified setup						
17	Repeat test No. 12	0.50	--	1.6-10-1.6	332-411	RB596/1,2	SB470
18	Repeat test No. 8	0.20	0.10	--	332-471	RB596/1,2	SB470
19	Repeat test No. 9	0.30	0.15	--	332-471	RB596/1,2	SB470
20	Repeat test No. 10	0.40	0.20	--	332-471	RB596/1,2	SB470
21	Repeat test No. 11	0.50	0.25	--	332-471	RB596/1,2	SB470
-	Data reviewed						
-	Modified setup						
22	Repeat test No. 12	0.50	--	1.6-10-1.6	405-478	584/3,4	Not recorded
23	Repeat test No. 8	0.20	0.10	--	405-478	584/3,4	Not recorded
24	Repeat test No. 9	0.30	0.15	--	405-478	584/3,4	Not recorded
25	Repeat test No. 10	1.40	0.20	--	405-478	584/3,4	Not recorded
26	Repeat test No. 11	1.50	0.25	--	405-478	584/3,4	Not recorded
27	Repeat test No. 11	1.50	0.25	--	405-478	584/3,4	Not recorded

(a) Approximate in the case of time history tests.

gage, and element load cell applications (see Figs. 4.1-6, 4.1-9, and 4.1-10). The vertical and radial distribution of the instruments in the core is illustrated in Fig. 4.1-5. All in-core instrumentation was located in a cluster of five columns positioned at four radial core locations as shown in Fig. 4.1-5. In the cluster, similar instrumentation was concentrated at three elevations. This scheme provided a fair distribution of instrumentation throughout the core.

Signals were digitally sampled for computer tape storage by a multiplexer circuit having a period of 5 msec. Predetermined calibration factors for the instruments were subsequently used to convert the data from digital counts to engineering units. Two electronic instrumentation units were specially designed to process the data. These included:

1. Peak holding circuits, which held the maximum peak signal during the time interval for sampling by the multiplexer, since some maxima were known to respond in much less than one multiplexer period.
2. Summing circuits for measurement of the instantaneous sum of forces on three instrumented dowels or forces from five fuel element load washers.

Further descriptions of the data acquisition hardware are presented in Section 4.1.6.

4.8.2.4. Data Reduction. The data reduction processes that were applied to the dowel force test data and that are also applicable to data from other tests in the core seismic test program are described in Section 4.1.8.

The data were received from the test laboratory in the form of magnetic tapes containing digital data, and data packages containing tape

logs and calibration factors applicable to each data channel. Programs DATAT and NEWTEN were used to convert these data into engineering units and to reorganize the data into records compatible with the Univac 1110 computer at GA. Various other programs and routines listed in Section 4.1.8 were used to manipulate the engineering data into formats from which the response of the core could be interpreted.

4.8.3. Results and Conclusions

The more important results of the test and the conclusions are summarized below.

4.8.3.1. Core Damping. The equivalent viscous damping factor of the model core was calculated to be approximately 40% from an analytical damping model correlating with the experimental free vibration decay of the core at resonance. An alternative method, which compared the phase angle frequency response of the core to that of a linear, single-degree-of-freedom system, resulted in a damping ratio of approximately 20%. These results are shown in Figs. 4.8-1 and 4.8-2.

The difference in the results illustrates damping properties in two different modes of core vibration. The lower damping value represents core vibration in a tightly lumped mass, while the higher value occurs when the core is not specifically lumped and exhibits a larger number of interelement collisions (higher energy loss) during vibration.

4.8.3.2. Sine Sweep Excitation. The frequency response represented by the core and boundary forces exhibited nonlinear characteristics similar to those in Figs. 4.8-3 and 4.8-4. At 0.5 g excitation, the resonance curves show a column mode at 2.0 Hz, a core lumped mass mode at 4.1 Hz, and a core support floor mode at about 5.0 Hz.

Fuel element rocking angles gradually decreased approaching the 4.1 Hz resonance, and then increased abruptly to a maximum of 3.2° as the lumped

Fig. 4.8-1. Core decay and damping model

Fig. 4.8-2. Phase angle versus frequency response (core second mode)

Fig. 4.8-3. Boundary force frequency response

Fig. 4.8-4. Dowel force frequency response

core mode subsequently dissipated. The rocking angle frequency response of a fuel element at block level 11 in the center of the core is shown in Fig. 4.8-5.

4.8.3.3. Time History Excitation. Maximum peak values for in-core and boundary parameters are given in Table 4.8-2 for time history input at 0.25 g. The data are organized according to instrument type and location, and values are indicated where data reduction was performed. Shock 4, the GA design earthquake representing soft soil and OBE conditions, generally produced the maximum response.

Fuel element rocking angles remained approximately constant from the core center to the boundary along the excitation direction (x-axis). The rocking angles were largest in the lower half of the core model, approaching 1.75° (element 001-7). The rocking angle of this element as a function of core radius is depicted in Fig. 4.8-6.

The core support block dowel forces were largest at the core boundary. Fuel element dowel forces generally increased toward the boundary. A typical distribution of forces is shown in Fig. 4.8-7 for element 007-4 located in the lower section of the core. Dowel forces at higher core elevation were also recorded, but were not validated due to a problem in the instrument applications. Reflector block dowel forces increased sharply with core elevation (Fig. 4.8-8). The data also showed that the y-axis forces were larger than the x-axis dowel forces in the upper half of the core.

The time history responses of the fuel element collision forces were also maximum at the core boundary, as shown in Fig. 4.8-9. These forces were obtained with the Kistler load cell design employing load washers as described in Section 4.1.3. The data from the strain gage design were not found to be reliable since calibrations of strain versus force could not be accurately obtained. Only shocks 3 and 4 produced fuel element collision forces above a minimum recorded load level of 28.5 lb for 1/5-scale

Fig. 4.8-5. Rocking angle frequency response

TABLE 4.8-2
MAXIMUM TIME HISTORY RESPONSE, 0.25 g GROUND ACCELERATION

Parameter	Instrument and Location (a)	Core Center					Mid Radius					Core Boundary				
		Shock No.					Shock No.					Shock No.				
		1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
Rocking Angle (Deg)	EC4-11	0.54	0.60	0.52	0.90	0.5										
	EC1-7	0.99	0.68	1.27	1.38	1.30	0.34	0.79	1.74	1.32	1.10	0.65	0.52	1.74 ^(b)	1.70	1.66
	EC7-5	0.34	0.23	0.78	1.10	0.34	0.35	0.39	0.76	0.69	0.32	0.32	0.34	0.42	0.52	0.33
	EC613-6											0.25	0.42	0.34	0.66 ^(b)	0.39
Element Impact Force (lb)	5LC5-7	3.3	0.0	114.0	143.0	19.5	0.0	0.0	125.0	91.2	10.2	17.4	54.0	180.0	182.0 ^(b)	11.0
	2LC6-4	0.0	0.0	4.6	12.6	18.5	0.0	0.0	3.6	6.3	0.0	3.6	30.3	62.0	146.0	1.5
Element Dowel Force (lb)	DSGX4-10	16.0	10.0	6.6	17.0	14.0	8.5	21.6	7.7	6.4	13.4	3.0	2.9	0.8	28.0 ^(b)	2.9
	DSGY4-10	4.0	2.0	6.0	5.4	4.0				5.6					20.0 ^(b)	
	DSGX7-4	0.0	0.0	2.4	8.2	1.0	0.0	0.0	1.8	2.3	0.0	1.9	3.7	5.5	8.4 ^(b)	2.2
	DSGY7-4	0.0	0.0	2.1	3.2	0.0										
	DSGXCSB	2.2	2.4	4.6	4.5	3.0						6.3	5.4	10.8 ^(b)	9.9	3.9
	DLCX613-5													55.0	95.0 ^(b)	
Lateral Support Force (lb)	DLCY613-5													15.0	25.4 ^(b)	
	SP1-5														2781.0 ^(b)	
	SP19-5														1287	

(a) See Fig. 4.1-5.

(b) Indicate maximum values.

Fig. 4.8-6. Rocking angle versus core radius for time history excitation, 0.25 g (ground)

Fig. 4.8-7. Dowel force versus core radius, time history excitation, 0.25 g (ground)

Fig. 4.8-8. Permanent side reflector block dowel force versus core elevation, time history excitation, 0.25 g (ground)

Fig. 4.8-9. Element collision force versus core radius, time history excitation, 0.25 g (ground)

elements. An average of nine significant impacts per shock occurred with one-half of these being corner impacts. Of these, one or two flat impacts per shock occurred with the maximum collision force of 181 lb. Table 4.8-3 shows collision force frequency distribution typically for the five-load-cell element.

The rocking angles, dowel forces, and collision forces all increase with input g-level. This is demonstrated from Figs. 4.8-10, 4.8-11, and 4.8-12, respectively, where three core radial positions are represented for each response parameter. It is observed that the relationship between response and g-level is nonlinear.

4.8.3.4. Data Correlations. During an earthquake, the peak values of element impact forces were compared with the dowel forces as shown in Fig. 4.8-13. Here the significant dowel forces on two dowels for the time history case of shock 4 at 0.25 g were plotted against simultaneous collision loads on the same element. No apparent correlation between impact forces and dowel forces was observed.

Figure 4.8-14, which shows the correlation between dowel forces and rocking angles, indicates that a dowel force may occur at rocking angles other than zero. This means that the point of load application is shifted toward the end of the dowel pin, which tends to reduce the dowel system structural strength. This could be an important consideration for the design.

From the analysis of the broad spectrum of tests, it was found that the total x-axis dowel shear force (in the direction of the rig excitation) was shared by the three dowels in average proportions of 23%, 39%, and 40%. The total y-axis dowel force distribution was less uniform, but collectively the study showed that the load on any one dowel was never larger than one-half the total load. Furthermore, the largest modulus force on a single dowel composed of simultaneous x- and y-axis loads, was on the average 6% larger than the single x-axis load, which means that the

TABLE 4.8-3
IMPACT ORIENTATION AND COLLISION FORCE FREQUENCY DISTRIBUTION, (a)
FIVE-LOAD-CELL BLOCK, SHOCK 4, 0.25 g (GROUND)

Orientation	Core Center		Core Midradius		Core Periphery	
	No. of Events	Load Range (lb)	No. of Events	Load Range (lb)	No. of Events	Load Range (lb)
Top right corner	1	33.4	3	43.4	1	128.0
Top left corner	1	53.5				
Bottom right corner	1	49.4	1	28.0	1	48.0
Bottom left corner			2	43.0-74.5		
Top side	3	31.3-46.9				
Bottom side			2	70.2-99.5		
Right side	1	47.9				
Left side						
Flat	2	91.8-142.5	2	54.8-65.0	2	138.6-148.9
					5 ^(b)	40.1-182.1
Total hits/peak load	9	142.5	10	99.5	9	182.1

(a) Minimum recorded load (FLIMIT) = 28.5 lb.

(b) Center and one corner hit simultaneously.

Fig. 4.8-10. Rocking angle versus g level for three core locations

Fig. 4.8-11. Dowel force versus g level for three core locations

Fig. 4.8-12. Element collision force versus g level for three core locations

Fig. 4.8-13. Element impact forces versus dowel forces, 0.25 g (ground)

Fig. 4.8-14. Rocking angle versus block and dowel force, 0.25 g (ground)

peak x and y component dowel loads do not act simultaneously. This was considered to be a critical observation because it supports the use of one-dimensional (horizontal) analytical models for predicting maximum fuel element dowel forces.

From measurements at the 45° position (instrument position 4, Fig. 4.1-5, Section 4.1.5), it was found that the rocking angles, dowel forces, and element collision forces were generally smaller than those on the main core diameter.

4.8.4. Test Data Error Analysis

Analysis of the test data errors focused on the areas of (1) error identification within the instrument and test hardware systems, (2) statistical treatment of data from repeated tests, and (3) the combining of component errors to form an estimate of the total error for the data from in-core instruments which were not subjected to repeated testing. The general method of error analysis is outlined in Section 4.1.11.

The component errors contained in each instrument reading are summarized in Table 4.8-4. The table shows that the deviations in instrument calibration, core geometry, and rig input excitation from nominal values were the largest contributors to errors in the in-core instrument data. The other error sources in the table are negligible. The calibration error was prominent in the blocks instrumented with strain gages for collision force measurements and these data were therefore not considered useful.

The overall total random errors represented as a one-standard deviation are given in Table 4.8-5. The errors in the in-core response parameters were calculated by substituting the component errors into the error propagation equation (Eq. 4.1-13, Section 4.1.11.2). The boundary parameter error values were derived from the statistical analysis of data

TABLE 4.8-4
ERROR COMPONENTS (a)

Component	Instrumentation									
	DF4-10	DF7-4	DF1-6	DF596	DF-CSB	SG4-10	SG1-6	LC6-4	LC5-7	ECP(a11)
$\hat{S}_{G_c} (\%)$	0.025	0.025	0.025	0.025	0.025	0.025	0.025	0.025	0.025	0.025
$\hat{S}_{N_R} (\%)$	0.41	0.5	0.14	0.5	0.3	0.5	(b)	2.6	0.28	1.7
$\hat{S}_{G_P} (\%)$	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.0
$\hat{S}_{G_S} (\%)$	0.0	0.50	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$\hat{S}_{G_A} (\%)$	8.5	8.5	9.0	10.0	8.5	13.0, 55.0	45.0	6.0	2.0	7.7
$\hat{S}_{G_G} (\%)$	5.0	5.0	5.0	5.0	5.0	4.0	4.0	4.0	4.0	1.0
$\hat{S}_g (\%)$	1.0	1.0	1.0	1.0	1.0	1.0	(b)	1.0	1.0	1.0
$\hat{S}_w (\%)$	0.0	0.0	0.0	0.0	0.0	0.0	(b)	0.0	0.0	0.0
$\frac{\partial \bar{U}(g, \omega)}{\partial g}$	248.0	137.0	456.0	893.0	45.0	1986.0		937.0	1944.0	0.19
$\frac{\partial \bar{U}(g, \omega)}{\partial g} \frac{\bar{g}}{\bar{U}(g, \omega)} \hat{S}_g (\%)$	3.5	4.7	1.5	2.1	1.4	1.6	(b)	6.4	3.3	1.5

(a) Fractional one-sigma errors are expressed in percent.

(b) Data contains excessive error; no further consideration given.

TABLE 4.8-5
TOTAL DOWEL FORCE TEST RANDOM ERRORS (a)

Response	Random Error (%)
Boundary spring pack force	4.1 to 8.1
Reflector block velocity	6.0
Reflector block displacement	3.1
Fuel element dowel force	10.5 to 11.0
Floor support block dowel force	10.0
Reflector block dowel force	11.4
Fuel element collision force (strain gage)	55.0
Fuel element collision force (load cell)	5.6 to 10.0
Rocking angle	14.0

(a) Represented as one standard deviation.

from repeated tests. Since these are generally much lower than the in-core error values, it is thought that the component error method is conservative.

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