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MASTER
ONE-FIFTH SCALE FULL-ARRAY
TEST REPORT

FINAL REPORT

by
J. E. RAKOWSKI and B. E. OLSEN

Prepared under
Contract EY-76-C-03-0167
Project Agreement No. 65
for the San Francisco Operations Office
Department of Energy

DECEMBER 1978

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**GENERAL ATOMIC PROJECT 6422
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GENERAL ATOMIC COMPANY

ABSTRACT

A series of horizontal uniaxial seismic tests were performed on a one-fifth scale model of a 3000-MW(t) HTGR reactor core. The purpose was to determine the core characteristic behavior in terms of displacement and frequency and to obtain specific core parameter data such as fuel element and reflector block impact velocities and forces and lateral support (spring pack) forces. These data were obtained for validating analytical models used in the prediction of HTGR core design loads. The test rig was excited in two directions, across-the-flats of the hexagonal core elements and across-the-corners. Both sinusoidal sweep and dwell type excitations were employed and also several simulated earthquakes representing different soil conditions. Two different lateral support stiffnesses representing a soft and a combined soft and hard stop design were also tested.

This report presents the overall description of the tests conducted including test hardware, modeling, instrumentation, and test plan. The detailed test results and conclusions are published elsewhere.

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1. SUMMARY AND CONCLUSIONS

The results from the 1/5-scale full-array core model seismic tests at Wyle Laboratories were obtained for horizontal, uniaxial tests on a 3000-MW(t) reactor core model in the cold and fully irradiated state at the end of life. Results were obtained for two lateral core support designs of different spring rates: a soft spring support and a combined soft spring and stop support. The core was shaken uniaxially in two directions 90° apart, across-the-flats of a hexagonal core element (X-axis), and across-the-corners of an element (Y-axis).

Test conditions included both sinusoidal and time history type input to the test rig. The sinusoidal input was employed to study the core dynamic characteristics and consisted of frequency sweeps at constant g-levels and sine dwells at constant g-level and frequency. The time history input was employed to obtain the core response under earthquake conditions. These were the El Centro and Taft earthquakes and GA-synthesized design basis earthquake generated for different soil conditions and structural damping factors.

A total of 38 tests were run, of which the sinusoidal testing was confined to the low-frequency range of interest below 10 Hz. The core was subjected to more than 200 earthquakes during the test period at g-levels as high as 0.75 g equivalent peak ground acceleration. It is estimated that in this period the core graphite blocks received more than 15,000 significant load cycles from impact and cyclic loading in compression.

The test results and conclusions are documented in Ref. 1. Reference 2 contains a list of those items considered to be of special significance to the program. Sections 1.1 and 1.2 summarize the more important test results and conclusions, which are included in this report for continuity.

1.1. SINUSOIDAL INPUT

1. The reactor core resonance curve exhibits typical nonlinear spring hardening characteristics. It is strongly dependent on the across core accumulative gap and the core lumping factor (mass density).
2. Essentially three resonance frequencies of importance were identified, of which the first and third modes were only detected at the 0.5-g excitation level. At this level, $\omega_1 = 1.6$ to 2.4 Hz, $\omega_2 = 4.0$ Hz, and $\omega_3 = 5.0$ Hz.
3. Table 1-1 gives the second mode resonance frequencies as a function of excitation level, core support spring rate, and excitation axis. It is shown that the resonance frequency is strongly amplitude dependent and increases with an increase in excitation level. A change in support stiffness from 800 to 100,000 lb/in. increased the resonance frequency by less than 10%. The resonance frequency for excitation along the Y-axis was less than 10% lower than along the X-axis.
4. The first mode in the 1.6 to 2.4 Hz core resonance range shows the excitation of one or more column (beam) modes. The second mode at 4.0 Hz is a core mass mode typified by the across-core gap. It has a superimposed beam shape caused by the reflector and core column stiffnesses. The third mode at 5.0 Hz is a core support floor mass mode typified by the smaller across-floor gap.
5. During harmonic core motion the core oscillates as a tightly lumped mass between the reflector boundaries. The core lumping factor increases with increasing frequency up to 4.0 Hz. At 4.0 Hz, the lumping factor is a minimum 79% during travel across the core and reaches 100% during impact with the boundary. The effect on core lumping from a change in core support spring rate is negligible.

TABLE 1-1
CORE RESPONSE FREQUENCIES - SECOND MODE

Excitation g-Level	Excitation Axis		
	X-Axis		Y-Axis
	Soft Spring Support 800 lb/in.	Combined Soft Spring and Stop Support 800/100,000 lb/in.	Soft Spring Support 800 lb/in.
0.15 g	2.5 Hz	2.5 Hz	--
0.3 g	3.5 Hz	3.6 Hz	--
0.50 g	4.0 Hz	4.2 Hz	3.8 Hz

6. Less than 10% cross-core coupling was measured from the uniaxial tests.
7. Satisfactory core damping measurements were not obtained. The quick shutdown procedure employed to construct the core logarithmic decay in free vibrations was not at a sufficiently fast rate. This caused the damping values to be underestimated. However, large core damping was indicated by core element oscillations decaying to less than measurable levels after only two cycles. Estimated equivalent viscous damping values were larger than 30%.

1.2. TIME HISTORY INPUT

1. The fuel element is subjected to two different types of loading, an impact load similar to a two body impact where the face opposite the impact face is load free and a dynamic compression load where opposite faces are equally loaded. The impact load is of very short duration (typically 0.0005 sec), and the dynamic compression is of long duration (typically 0.120 sec). The dynamic compression loads generally represent the maximum fuel element load.
2. Neither fuel element nor reflector element columns were observed to disarray even under the most severe excitation equivalent to 1.25 in. support spring deflection (synthesized earthquake, soft soil, 2% damping at 0.6-g ground acceleration).
3. For an earthquake of approximately 20-sec duration (9 sec for the 1/5-scale model), about 30 significant fuel element load cycles occurred. By establishing a reasonable criteria for superimposing high-frequency peaks from the analog records, the approximate number of significant fatigue cycles was obtained as 100.

4. At maximum time history response, the earthquake causes a core lumping factor of nearly 100%.
5. For uniaxial input the boundary support force distributions show maximum support forces at core mid-elevation along the direction of excitation. Circumferentially the forces conform approximately to a cosine distribution.
6. In-core fuel element force distributions for the soft spring support case show a maximum near the boundary at core mid-elevation.
7. The core response as a function of input g-level is nonlinear and tends to flatten out markedly above 0.5 g.
8. At about 0.2 g a sudden jump in response level occurs, which is caused by the core resonance coinciding with the 3 to 4 Hz harmonic components in the earthquake. Since the resonance frequency increases with decreasing core gap, the transition g-level can be shifted upward by making the core gap smaller. Therefore, it can be concluded that a smaller core gap will have two effects. First, significant boundary response will occur at lower ground acceleration input. Second, since the boundary force response tends to flatten with increasing g-level, smaller forces will likely result at higher ground acceleration input.
9. The soft spring support resulted in larger deflections. A maximum of 0.96 in. occurred at 0.5-g ground acceleration. The combined soft spring and stop support practically limits the deflection of 0.2 in. of the soft spring because of the high spring rate in the stop.
10. The maximum core response was obtained from portions of the earthquake containing strong harmonic waveforms (large sinusoids at 3 to 4 Hz). These waveforms typify the GA-synthesized design bases earthquake.

11. Table 1-2 gives the maximum boundary support and in-core forces for the synthesized earthquake (soft soil, 5% damping at 0.5-g ground acceleration). The combined soft spring and stop support forces are 3 to 4 times higher than those for the soft spring support.
12. The in-core fuel element forces are only moderately sensitive to a change in boundary support spring rate and are 10% to 20% higher for the stop support test case. Excitation along the Y-axis results in in-core forces about 30% lower than for X-axis excitation.
13. The stop support loads were very sensitive to the radial position relative to adjacent stop supports. Design tolerances relative to the core center for radial positioning of a support with high spring rate should therefore be kept as small as possible.
14. The GA-synthesized design bases earthquake produced generally much higher core response than the El Centro and the Taft earthquakes. Boundary support forces for the combined soft spring and stop support were larger by a factor of 2. Thus the GA-synthesized waveform seems to constitute a very conservative design earthquake for the reactor core.
15. The soft soil conditions (65,000 psi modulus) induced lateral support forces approximately two times larger than forces induced by the firm soil (0.9×10^6 psi) and rock (3×10^6 psi) foundations.
16. Increasing the damping factor from 2% to 5% structural damping decreased the support forces by nearly a factor of two for the combined soft spring and stop support. Increased structural damping had a lesser effect on the forces generated for the soft spring support.

TABLE 1-2
 MAXIMUM FORCES AT 0.5-g GROUND ACCELERATION - SYNTHESIZED EARTHQUAKE
 (SOFT SOIL, 5% DAMPING)

Component Load	Excitation Axis		
	X-Axis		Y-Axis
	Soft Spring Support 800 lb/in.	Combined Soft Spring and Stop Support 800/100,000 lb/in.	Soft Spring Support 800 lb/in.
Support Load	700 lb	2,750 lb	704 lb
In-core Fuel Element Load	600 lb	701 lb	420 lb

2. INTRODUCTION

The 1/5-scale full-array test program was started in December 1972. This test was the third in a series which included single-element collision testing and 1/5-scale planar-array seismic testing. The earlier tests provided individual graphite element impact characteristics and some data on the seismic behavior of a loosely packed array of elements.

The full array test was initially planned to prove that the HTGR core design was capable of withstanding the anticipated Zone 2 operating basis earthquake (OBE) and safe shutdown earthquake (SSE) and to determine the maximum intensity OBE and SSE which the design could withstand. However, due to distortions in the scaling of the model and subsequent changes in the prototype design, the original objective could not be met with certainty. A new approach was taken where the information from the test was only obtained for study of core behavior and to provide data for verification of analytical codes. As a result, the codes will accomplish the original test objectives. Full core response behavior was obtained from sinusoidal sweep and dwell excitation, whereas preliminary design data were based on GA-synthesized random displacement time history input formulated to agree with design response spectra recommended by the U.S. regulatory agency for Class 1 nuclear components prior to December 1973 (Ref. 3).

The tests were carried out in the fall of 1973, and the results were published in a third interim test report (Ref. 1). The report contains results for separate cases of soft and hard lateral core supports, in terms of lateral spring pack deflections and forces, and in-core and boundary core block deflections, accelerations, and forces. Core damping, resonant frequencies, and mode shapes are also given. Several test results are also summarized in the first and second interim test reports (Refs. 4 and 5).

3. TEST OBJECTIVES

The purpose of the test was to determine the seismic response of the nuclear core and its support structure and to use the results to verify analytical codes developed to predict prototype HTGR design data. Specifically, the 1/5-scale test objectives were to obtain the following information:

1. Core motion characteristics.
 - a. Core lumping.
 - b. Resonant frequencies and mode shapes.
 - c. System damping.
2. Force and deflection of lateral supports.
3. Core deflection and forces.
 - a. Fuel column and reflector column deflections.
 - b. Fuel block impact forces.
 - c. Fuel block dowel pin forces.
4. Number of repetitious loadings of fuel blocks.

4. DESCRIPTION OF TEST MODEL AND HARDWARE

The assembled 1/5-scale full-array model and test rig are shown in Fig. 4-1.

4.1. MODELING AND SCALING LAWS

A set of scaling laws was prepared prior to the design of the 1/5-scale full-array test which was also used subsequently for all other test models (Ref. 6).

A number of independent parameters which were important for predicting the dynamic response of the core and core supports were defined. These parameters and their basic variables are listed in Table 4-1. These variables were reduced to the following nondimensional relationship,

$$\pi = \phi \left(e, \mu, \frac{l}{t_g^2}, \frac{l^3 \rho}{t_k^2}, \frac{l^2 \rho}{t_k^2} \right), \quad (4-1)$$

from which the scaling laws summarized in Table 4-2 were driven.

The following design restrictions were then applied to the model:

1. A model scaling factor of 1/5 was employed.
2. Graphite was chosen for the core elements.
3. Acceleration input level equaled prototype level.

By examining the similitude requirements in Eq. 4-1, based on these design restrictions, the observations discussed below were made.

Fig. 4-1. 1/5-scale full array model and test rig

TABLE 4-1
LIST OF VARIABLES

Parameter	Basic Variable	Dimension
Model length, displacement of PCRV, reflector, fuel element and column gaps	l	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 4-2
SCALING LAWS FOR TEST MODELS

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 first design condition states that the coefficient of restitution of the model elements must equal that of the prototype elements. Since graphite is employed, this is easily achieved if exact geometric similitude in element modeling exists with respect to the prototype. However, on a 1/5 scale some 200 fuel and coolant holes were impractical and uneconomical to model, and seven-hole and one-hole models were experimented with until the required coefficient of restitution was obtained. This required that some weight compensation be made, which was achieved with tubular steel inserts. As a result the block stiffness characteristics were changed, as discussed further below. The coefficient of restitution was regarded as an important parameter since the core motion comprises a very large number of collisions and a small change in it could cause significant velocity changes between colliding elements and hence distort overall core motion characteristics.

The second design condition stipulates equal coefficients of friction in the 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 was probably a lower coefficient of friction in the model core compared to the prototype, which results in a conservatively lower damped structure.

Design condition three compares the time scale to the length scale and gravitational field. Since the latter two variables are fixed, the time scale for the model becomes

$$t_m = \frac{t_p}{\sqrt{5}} \quad , \quad (4-2)$$

which means the events will transpire faster in the model.

The fourth design condition 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

$$k_m = 25 k_p \quad . \quad (4-3)$$

It is now apparent that even if the model block is a faithful reproduction in graphite, the result would be a stiffness which is higher than the scaling laws require, since there has been no attempt to scale the elastic modulus E. By introducing the one- and seven-hole patterns in the 1/5-scale elements, the across-the-flat stiffness was adjusted but, as it turned out, not sufficiently. This has an effect on the contact time for the impacting elements. Interblock collision forces consequently were also affected since these forces vary in direct proportion to the contact time. Since the use of graphite tended to produce an element stiffness larger than the scale value, the impact forces would become conservatively high. This does not concern the side support forces since they are not affected by the element stiffness. They are only a function of the spring pack coil stiffness, which can be modeled accurately.

The last design condition relates the core column pressure drop to the material property, length, and time scale. Since the core design was to represent the reactor in a cold and shutdown state at end of life, this variable was ignored altogether in the design. However, for other reactor conditions, the pressure drop adds a possible significant stiffening and restoring effect to the core column which may influence the element forces. This variable can be modeled without difficulty. A further discussion of the scaling analysis for the present 1/5-scale full-array model is contained in Refs. 6 and 7.

4.2. GRAPHITE CORE MODEL

A general description of the graphite core model assembly is given below. Model details are shown in drawings listed in Table 4-3.

TABLE 4-3
DRAWINGS FOR 1/5-SCALE MODEL DESIGN^(a)

Drawing Number	Title
12676	Proposed Test Rig and Core Model
12659	Model of Fuel Element
12734	Model of Inner Core Support Block
12735	Model of Outer Core Support Block
12736	Model of Outer Core Support Block
12737	Model of Outer Core Support Block
12738	Model of Outer Core Support Block
13072	Model of Outer Core Support Block
13598	Model of Outer Core Support Block
12739	Model of Side Reflector Blocks
12740	Model of Side Reflector Blocks
12741	Model of Side Reflector Blocks
12742	Model of Side Reflector Blocks
12743	Model of Side Reflector Blocks
12744	Model of Side Reflector Blocks
13755	Plenum Element Assembly
13072	1/5-Scale Model Core Support Block
13333	1/5-Scale Model Fuel Element Dowel Pin
13334	1/5-Scale Model Fuel Element Sleeve
Q13218	Dowel-Fuel and Reflector Blocks
Q12678	Block, Control Fuel Element
13577	1/5-Scale Model Dowel and Sleeve
13578	1/5-Scale Model Dowel and Sleeve
13168	1/5-Scale Model Core Barrel Plates
13583	Spring Pack Assembly
13592	Spring Pack Assembly Components
13593	Spring Pack Assembly Components
13594	Spring Pack Assembly Components
13595	Spring Pack Assembly Components
13596	Spring Pack Assembly Components

^(a) The drawings listed are GA proprietary information.

4.2.1. General

The model was designed by GA to represent the equilibrium core under refueling conditions. The fuel elements, reflector elements, control rod elements, core support blocks, and plenum elements were fabricated from graphite. The graphite specifications (Ref. 8) require all components in the test model to be commercial grade H321 graphite. Numbers and weights of the graphite elements are given in Table 4-4. All other components were metallic. Other geometric design details of the model are described in Ref. 9.

4.2.2. Fuel Elements

The model fuel elements were full-height elements (Drawing 12659).^{*} These elements were 6.24-in.-long prismatic bodies with a hexagonal base 2.83 in. across flats. Each element had a cylindrical hole parallel to its axis. To achieve the properly scaled weight, a steel tube was placed inside the hole (during assembly) (Drawing 12676).

All fuel elements had three dowel pins in the top face and three dowel holes in the bottom face. Design and analysis of the 1/5-scale fuel blocks are discussed in Ref. 10.

4.2.3. Reflector Elements

The full-height model reflector elements were identical to the model fuel elements. The half-height elements (Drawing 12659) were used as half-height reflector elements. The irregular side reflector blocks were as shown in Drawings 12739 through 12744.

4.2.4. Control Rod Elements

In the model there were full-height and three-quarter-height control elements. The full-height control elements were identical to the fuel

^{*} Drawings referred to in text are GA proprietary information.

TABLE 4-4
SUMMARY OF GRAPHITE COMPONENTS
IN SEISMIC TEST MODEL

Component	Number of Components	Spares	Weight of Component (lb)
Hexagonal element (with steel tubes)	5,132	51	2.07
3/4-height element	146	2	1.58
1/2-height element	2,138	65	1.07
Plenum elements	583	9	0.83
Average side reflector block	224	10	26.15
Hexagonal support block	73	1	9.94
Outer support block (maximum)	36	6	8.25

Approximate Total Weights (lb) (Steel Tubes Included)

All hexagonal elements	13,170
Side reflector	5,640
Core support blocks	1,210
Keys, dowels, sleeves, studs, and lock plates	170
Total	<u>20,190</u>

elements, and the three-quarter-height control elements were the three-quarter-height elements in Drawing 12659. All control elements have dowel holes and tube inserts to achieve correct geometric and mass scaling.

4.2.5. Plenum Elements

The model plenum elements were graphite elements of similar outside dimensions to the half-height reflector elements except that the across flats dimension was 0.015 in. larger. The plenum elements have keyways on the side faces, a large through-hole, and three dowel holes in the bottom face (Drawing 13755).

4.2.6. Dowels

The steel dowels and their mating sleeves are as shown in Drawings 13333 and 13334.

4.2.7. Core Support Blocks

There were two kinds of core support blocks in the model, hexagonal support blocks and irregular outer support blocks. (Drawings 12734 through 12738, 13072, and 13598). The hexagonal support blocks had a few large through-holes and 21 dowel holes in the top face. There were two configurations of irregular outer support blocks. Both types were of the same height as the hexagonal support blocks and also had dowel holes.

4.2.8. Assembly of Model Core

The model core consisting of fuel elements, reflector elements, control rod elements, plenum assemblies, side reflector blocks, core support blocks, dowels, and steel tubes was assembled as shown in Drawing 12676. The elements were stacked on top of each other to form columns. There were four kinds of columns: fuel columns, control columns, hexagonal

reflector columns, and side reflector columns. The columns were stacked in the following manner:

1. The hexagonal reflector columns consisted, from the bottom up, of three half-height elements, eight full-height elements, one half-height element, one full-height element, and one plenum element, totaling 14 elements.
2. The control columns consisted, from the bottom up, of one three-quarter-height element, one half-height element, eight full-height elements, one half-height element, one full-height element, and one plenum element.
3. The fuel columns consisted, from the bottom up, of three half-height hexagonal elements, eight full-height elements, one half-height element, one full-height element, and one plenum element, totaling 14 elements.
4. The irregular side reflector columns all had 16 elements of equal height. There were two types of side reflector columns, owing to the irregular geometry.

A mean gap of 0.03 in. was maintained between all the columns, based on design dimensions for the graphite elements. This gap was achieved automatically and no control was required during assembly. A further detailed distribution of gaps between core columns is given in Ref. 11.

The core support floor was assembled from the hexagonal and irregular support blocks. Each hexagonal block supported one fuel region, which consisted of six fuel columns surrounding one control rod column. Each irregular block supported one side reflector column.

The steel dowels were used to connect the columns to the support blocks and to connect each element in the model to the element beneath it. There were three dowels per element.

At the level of the plenum elements the fuel columns were keyed to the other fuel columns in that region by inserting steel keys into matching keyways.

In total, the model consisted of 420 fuel columns, 73 control rod columns, 84 hexagonal reflector columns, and 36 side reflector columns.

The overall height of the model core, including the plenum elements and the core support blocks, was 6 ft 4.4 in.

Figure 4-2 is an internal view of the core arrangement showing permanent reflector columns, fuel element columns, and core support blocks.

4.3. CORE SUPPORTS

The model core was supported by spherical roller bearings embedded in the core support blocks in place of support posts used in the prototype. The roller bearings permitted lateral movement of the core floor, simulating roll-out of the prototype post.

The tests incorporated two spring pack designs. First, a soft spring design consisting of a single coil of 800 lb/in. stiffness was tested. Later tests were conducted with a combined soft spring and hard stop of stiffness 800 lb/in. and 100,000 lb/in., respectively. The latter spring pack design was incorporated after test results with the soft spring showed deflections to be too large. Two-hundred and fifty-two spring packs were arranged in vertical rows (seven in each row) at 10° intervals around the core, each spring pack being located at the corners of adjoining reflector blocks. Details of the model spring packs are given in Drawing 12676; Refs. 12 through 14 present the design basis for these supports. In the test model the spring packs are attached to steel core barrel plates covering the surrounding permanent reflector blocks. The lateral seismic forces, therefore, are transmitted through the core barrel plates to the spring packs.

Fig. 4-2. Internal view of the 1/5-scale core arrangement

4.4. TEST RIG

The test fixture consisted of a reinforced steel barrel designed to contain the graphite core and act as a vibration structure (Fig. 4-1). The design basis for the fixture specified a maximum rig deflection of 0.02 in., considering 1000-lb loads on each of three rows of adjacent spring pack supports. Also, all natural frequencies of the structure were required to be above 50 Hz, significantly above the range of test frequencies.

The design requirements were verified from a finite element analysis employing NASTRAN which showed static deflections of 0.006 in. and a fundamental natural frequency of 190 Hz (Ref. 15).

The total weight of the core and test fixture was 65,000 lb.

The entire core and fixture assembly was mounted on four long-stroke hydrostatic "Team" bearings. These bearings only allowed motion in the direction of test rig excitation. They were designed to minimize any undue side loading to the hydraulic actuator as a result of overturning moment of the core and fixture.

4.5. SHAKER SYSTEM

An electrohydraulic shaker was built according to the test requirements, which specified a force of approximately 75,000 lb and a peak-to-peak displacement of 5 in. The shaker was built with an effective piston area of 26 in.² and operated at a hydraulic air pressure of approximately 2000 psi.

The hydroshaker was designed to execute sinusoidal time history and random motion. The driving force was transmitted to the test fixture through a "stinger" attachment located approximately at the core and test fixture center of gravity. The reaction forces were taken up by a large concrete mass weighing ~750,000 lb.

4.6. TEST HARDWARE

In addition to the graphite core model and test rig, other test equipment included instrumentation, fixtures for calibrating the instruments, and equipment for data acquisition including a Varian 620 computer for automatic data storage. Descriptions of these items are given in subsequent sections of this report.

5. INSTRUMENTATION

5.1. GENERAL

All instrumentation used in the 1/5-scale full-array test is described in this section. These descriptions are divided into two sections, one identifying the instruments and the overall instrumentation plan and the other describing the particular instrument features including methods and results of calibrations. A separate section is devoted to data acquisition.

5.2. INSTRUMENTATION PLAN

The test instrumentation was made up of 68 transducers and 8 contact gages; the identification and function of this instrumentation are given in Table 5-1. The instrumentation is described by categories which include rig, core boundary, and in-core instrumentation.

5.2.1. Rig Instrumentation

Five transducers were used to measure the motion of the test rig. Three of these were linear variable differential transformers (LVDTs), all of which were at the base of the rig, and two measured the slave and piston displacement of the hydroshaker.

Two rig accelerometers were mounted at the top and base of the rig to detect overturning motion resulting from impact of the core with the rig during excitation. Only small differences were observed in the response of these instruments, and it was concluded that no significant overturning occurred.

TABLE 5-1
1/5-SCALE FULL-ARRAY TEST - TRANSDUCER IDENTIFICATION

Instrument	Number	Function
I. RIG INSTRUMENTATION		
1. LVDT ^(a)	1	Measure test rig displacements and provides feedback rig control
2. Hydroshaker Displacements	2	
3. Accelerometers	2	Measures test rig linear and overturning accelerations
II. CORE BOUNDARY TRANSDUCERS		
1. Spring Pack Strain Gages	2	Records force on the hard stop of the core horizontal boundary restraints
2. Spring Pack LVDT	18	Measures spring pack displacements
3. Reflector Block LVDT	15	Measures reflector block displacements relative to the core barrel plate. Data for core lumping and transient decay motion
III. INCORE INSTRUMENTATION		
1. Reflector Block LVDT	15	Measures reflector block displacements relative to core hexagonal reflector blocks. Data for core lumping, core damping and mode shapes
2. Core Support Block LVDT	6	Measures relative displacement of core support blocks
3. Fuel Element DEES ^(b) Gages	2	Measures relative horizontal displacements between fuel elements. Used for velocity calculation at impact
4. Accelerometer	3	Measures fuel element accelerations
5. Block Force Strain Gages	2	Measures (after calibration) fuel element collision forces, 2 locations
6. Contact Gages	8	Register fuel element contact. Data used to determine collision time and orientation

(a) Linear Differential Variable Transformer.

(b) Capacitive Displacement Device.

5.2.2. Core Boundary Instrumentation

Core boundary instrumentation included strain gaged spring packs to measure boundary forces, spring pack displacement LVDTs to measure the boundary support deflections in the case of the soft supports, and LVDTs to measure reflector block displacements with respect to the core barrel plates. Additional LVDTs were mounted in the reflector blocks facing the core. These devices are covered under in-core instrumentation.

Strain gages were applied to the hard stop of two boundary spring packs. These gages were calibrated to measure force when the spring reached its limit of travel. Locations of the gages are specified in Table 5-2 for X-axis testing and in Table 5-3 for Y-axis testing. The designations follow the column/elevation numbering scheme given in Fig. 5-1.

Spring pack deflections were monitored by spring pack LVDTs, also identified in Tables 5-2 and 5-3; however, the location of these instruments was varied according to the six arrangements illustrated in Fig 5-2 in order to more fully cover the boundary. Spring pack LVDT data were used to obtain soft spring force data by multiplying by the spring constant.

The locations of the reflector block LVDTs are also given in Tables 5-2 and 5-3. Each instrument interfacing with the barrel plate is designated as RB. The following three digits represent the column number as shown in Fig. 5-3, and the final number represents the block elevation as shown in Fig. 5-4.

Several LVDTs were located in the core support floor elements. The floor block numbering scheme is given in Fig. 5-5.

5.2.3. In-core Instrumentation

The in-core instrumentation was designed to measure displacements, accelerations, forces, and impact force orientation among the fuel elements

TABLE 5-2
X-AXIS INSTRUMENTATION TABLE

Word	Instrument/Measurement	Location	Measure- ment Number	Wyle S/N	Equip. Rack to Comp. Room	F-2 Boom
1	In-Core Accelerometer	EL302	CA3028	W45207	75	62
2	In-Core Accelerometer	EL245	CA2458	W45206	74	63
3	In-Core Accelerometer	EL194	CA1948	W45205	73	61
4	Strain Gage	EL245 T	CS245T	W45272	72	Pin 1-2 66
5	Strain Gage	EL245 B	CS245B	W45273	71	Pin 4-5 66
6	Zero	DNA	Zero		Short Plug	DNA
7	Fixture Accelerometer	Fixture (Top)	TFAX-2	W45283	80	65
8	Fixture Displacement	Fixture Base (Ext)	TFDX	W45284	1	1
9	Fixture Accelerometer	Fixture (Stinger End)	TFAX-1	W7124	79	64
10	Input	Input to Exciter	Input		28 Control	DNA
11	Slave Displacement	Hydrashaker	Slave		Control	DNA
12	Piston Displacement	Actuator Element	Piston		Control	DNA
13	DC $\propto$ Frequency	DNA	DNA		29 Control	DNA
14	Start/Stop	DNA	DNA		27 Control	DNA
15	In-Core Displacement (Dees)	EL302	CD3028	W45274	97	Coax 1
16	In-Core Displacement (Dees)	EL194	CD1948	W45275	98	Coax 2
17	Load Cell	Spring Pack 1-4	LC0014	W45276	83	81
18	Load Cell	Spring Pack 3-4	LC0034	W45277	84	82

TABLE 5-2 (Continued)

Word	Instrument/Measurement	Location	Measure- ment Number	Wyle S/N	Equip. Rack to Comp. Room	F-2 Boom
19	Displacement	Spring Pack 19-4	SP0194	W45227	2	2
20	Displacement	Spring Pack 18-4	SP0184	W45260	3	3
21	Displacement	Spring Pack 17-4	SP0174	W45261	4	4
22	Displacement	Spring Pack 16-4	SP0164	W45268	5	5
23	Displacement	Spring Pack 9-4	SP0094	W45230	6	6
24	Displacement	Spring Pack 3-4	SP0034	W45264	7	7
25	Displacement	Spring Pack 2-4	SP0024	W45232	8	8
26	Displacement	Spring Pack 1-4	SP0014	W45236	9	9
27	Displacement	Spring Pack 36-4	SP0364	W45231	10	10
28	Displacement	Spring Pack 28-4	SP0284	W45235	11	11
29	Displacement	Spring Pack 19-5	SP0195	W45267	12	12
30	Displacement	Spring Pack 19-3	SP0193	W45266	13	13
31	In-Core Displacement	EL302	CD3028	W45274	97	Coax 1
32	In-Core Displacement	EL194	CD1948	W45275	98	Coax 2
33	Displacement	Spring Pack 19-6	SP0196	W45234	14	14
34	Displacement	Spring Pack 19-7	SP0197	W45263	15	15
35	Displacement	Spring Pack 19-2	SP0192	W45228	16	16
36	Displacement	Spring Pack 19-1	SP0191	W45265	17	17
37	Displacement	Spring Pack 36-1	SP0361	W45233	18	18
38	Displacement	Spring Pack 9-1	SP0091	W45229	19	19
39	Displacement	Ref1. Block 595-4	RB5954	W45240	20	20
40	Displacement	Ref1. Block 595-4	RB5944	W45253	21	21
41	Displacement	Ref1. Block 593-4	RB5934	W45237	22	22
42	Displacement	Ref1. Block 592-4	RB5924	W45250	23	23
43	Displacement	Ref1. Block 585-4	RB5854	W45255	24	24
44	Displacement	Ref1. Block 605-4	RB6054	W45242	25	25
45	Displacement	Ref1. Block 613-4	RB6134	W45256	26	26
46	Displacement	Ref1. Block 578-4	RB5784	W45257	27	27

TABLE 5-2 (Continued)

Word	Instrument/Measurement	Location	Measure- ment Number	Wyle S/N	Equip. Rack to Comp. Room	F-2 Boom
47	In-Core Displacement	EL302	CD3028	W45274	97	Coax 1
48	In-Core Displacement	EL194	CD1948	W45275	98	Coax 2
49	Displacement	Ref1. Block 579-4	RB5794	W45245	28	28
50	Displacement	Ref1. Block 580-4	RB5804	W45251	29	29
51	Displacement	Ref1. Block 595-5	RB5955	W45215	30	30
52	Displacement	Ref1. Block 595-3	RB5953	W45241	31	31
53	Displacement	Ref1. Block 595-6	RB5956	W45219	32	32
54	Displacement	Ref1. Block 595-1	RB5951	W45216	33	33
55	Displacement	Ref1. Block 595-2	RB5952	W45223	34	34
56	Displacement	Support Block 106	SB106F	W45218	35	35
57	Displacement	Support Block 88	SB088F	W45222	36	36
58	Displacement	Support Block 96	SB096F	W45225	37	37
59	Displacement	Ref1. Block 434-8	HR4348	W45239	38	38
60	Displacement	Ref1. Block 502-8	HR5028	W45214	39	39
61	Displacement	Ref1. Block 555-8	HR5558	W45238	40	40
62	Displacement	Ref1. Block 554-8	HR5548	W45249	41	41
63	In-Core Displacement	EL302	CD3028	W45274	97	Coax 1
64	In-Core Displacement	EL194	CD1948	W45275	98	Coax 2
65	Displacement	Ref1. Block 543-8	HR5438	W45258	42	42
66	Displacement	Ref1. Block 569-8	HR5698	W45248	43	43
67	Displacement	Ref1. Block 398-8	HR3988	W45252	44	44
68	Displacement	Ref1. Block 472-8	HR4728	W45254	45	45
69	Displacement	Ref1. Block 536-8	HR5368	W45243	46	46
70	Displacement	Ref1. Block 540-8	HR5408	W45244	47	47
71	Displacement	Ref1. Block 434-11	HR434N	W45220	48	48
72	Displacement	Ref1. Block 434-6	HR4346	W45211	51	51
73	Displacement	Ref1. Block 434-3	HR4343	W45212	52	52

TABLE 5-2 (Continued)

Word	Instrument/Measurement	Location	Measure- ment Number	Wyle S/N	Equip. Rack to Comp. Room	F-2 Boom
74	Displacement	Ref1. Block 434-1	HR4341	W45202	53	53
75	Displacement	Ref1. Block 434-13	HR434T	W45217	54	54
76	Displacement	Support Block 75	SB075F	W45221	55	55
77	Displacement	Support Block 63	SB063F	W45224	56	56
78	Displacement	Support Block 68	SB068F	W45200	57	57
79	In-Core Displacement	EL302	CD3028	W45274	97	Coax 1
80	In-Core Displacement	EL194	CD1948	W45275	98	Coax 2

TABLE 5-2 (Continued)

Bit No.	Instrument/Measurement	Location	Measurement Number	Wyle S/N	Equip. Rack to Comp. Room	F-2 Boom
1	Contact Gage	EL245	CC245A	DNA	61	71
2	Contact Gage	EL245	CC245B	DNA	62	71
3	Contact Gage	EL245	CC245C	DNA	63	71
4	Contact Gage	EL245	CC245D	DNA	64	71
5	Contact Gage	EL245	CC245E	DNA	65	72
6	Contact Gage	EL245	CC245F	DNA	66	72
7	Contact Gage	EL245	CC245G	DNA	67	72
8	Contact Gage	EL245	CC245H	DNA	68	72
9	Contact Gage (Inverted)	EL245	CI245A	DNA	61	71
10	Contact Gage (Inverted)	EL245	CI245B	DNA	62	71
11	Contact Gage (Inverted)	EL245	CI245C	DNA	63	71
12	Contact Gage (Inverted)	EL245	CI245D	DNA	64	71
13	Contact Gage (Inverted)	EL245	CI245E	DNA	65	72
14	Contact Gage (Inverted)	EL245	CI245F	DNA	66	72
15	Contact Gage (Inverted)	EL245	CI245G	DNA	67	72
16	Contact Gage (Inverted)	EL245	CI245H	DNA	68	72

TABLE 5-3
Y-AXIS INSTRUMENTATION TABLE

Word	Instrument/Measurement	Location	Measure- ment Number	Wyle S/N	Equip. Rack to Comp. Room	F-2 Boom
1	In-Core Accelerometer			W45207	75	62
2	In-Core Accelerometer			W45206	74	63
3	In-Core Accelerometer			W45205	73	61
4	Strain Gage			W45272	72	Pin 1-2 66
5	Strain Gage			W45273	71	Pin 4-5 66
6	Zero	DNA	Zero		Short Plug	DNA
7	Fixture Accelerometer	Fixture (Top)	TFAX-2	W45283	80	65
8	Fixture Displacement	Fixture Base (Ext)	TFDX	W45284	1	1
9	Fixture Accelerometer	Fixture (Stinger End)	TFAX-1	W7124	79	64
10	Input	Input to Exciter	Input		28	DNA
11	Slave Displacement	Hydrashaker	Slave		Control	DNA
12	Piston Displacement	Actuator Element	Piston		Control	DNA
13	DC $\propto$ Frequency	DNA	DNA		29	DNA
14	Start/Stop	DNA	DNA		Control 27	DNA
15	In-Core Displacement (Dees)			W45274	97	Coax 1
16	In-Core Displacement (Dees)			W45275	98	Coax 2
17	Load Cell	Spring Pack 28-4	LC0284	W45276	83	81
18	Load Cell	Spring Pack 30-4	LC0304	W45277	84	82
19	Displacement	Spring Pack 10-4	SP0104	W45227	2	2

TABLE 5-3 (Continued)

Word	Instrument/Measurement	Location	Measure- ment Number	Wyle S/N	Equip. Rack to Comp. Room	F-2 Boom
20	Displacement	Spring Pack 9-4	SP0094	W45260	3	3
21	Displacement	Spring Pack 8-4	SP0084	W45261	4	4
22	Displacement	Spring Pack 7-4	SP0074	W45268	5	5
23	Displacement	Spring Pack 36-4	SP0364	W45230	6	6
24	Displacement	Spring Pack 30-4	SP0304	W45264	7	7
25	Displacement	Spring Pack 29-4	SP0294	W45232	8	8
26	Displacement	Spring Pack 28-4	SP0284	W45236	9	9
27	Displacement	Spring Pack 27-4	SP0274	W45231	10	10
28	Displacement	Spring Pack 19-4	SP0194	W45235	11	11
29	Displacement	Spring Pack 10-5	SP0105	W45267	12	12
30	Displacement	Spring Pack 10-3	SP0103	W45266	13	13
31	In-Core Displacement			W45274	97	Coax 1
32	In-Core Displacement			W45275	98	Coax 2
33	Displacement	Spring Pack 10-6	SP0106	W45234	14	14
34	Displacement	Spring Pack 10-7	SP0107	W45263	15	15
35	Displacement	Spring Pack 10-2	SP0102	W45228	16	16
36	Displacement	Spring Pack 10-1	SP0101	W45265	17	17
37	Displacement	Spring Pack 27-1	SP0271	W45233	18	18
38	Displacement	Spring Pack 36-1	SP0361	W45229	19	19
39	Displacement	Refl. Block 595-4	RB5954	W45240	20	20
40	Displacement	Refl. Block 594-4	RB5944	W45253	21	21
41	Displacement	Refl. Block 593-4	RB5934	W45237	22	22
42	Displacement	Refl. Block 592-4	RB5924	W45250	23	23
43	Displacement	Refl. Block 585-4	RB5854	W45255	24	24
44	Displacement	Refl. Block 605-4	RB6054	W45242	25	25
45	Displacement	Refl. Block 613-4	RB6134	W45256	26	26
46	Displacement	Refl. Block 578-4	RB5784	W45257	27	27

TABLE 5-3 (Continued)

Word	Instrument/Measurement	Location	Measure- ment Number	Wyle S/N	Equip. Rack to Comp. Room	F-2 Boom
47	In-Core Displacement			W45274	97	Coax 1
48	In-Core Displacement			W45275	98	Coax 2
49	Displacement	Refl. Block 580-4	RB5804	RB5804	29	29
50	Displacement	Refl. Block 580-4	RB5804	W45251	29	29
51	Displacement	Refl. Block 595-5	RB5955	W45215	30	30
52	Displacement	Refl. Block 595-3	RB5953	W45241	31	31
53	Displacement	Refl. Block 595-6	RB5956	W45219	32	32
54	Displacement	Refl. Block 595-1	RB5951	W45216	33	33
55	Displacement	Refl. Block 595-2	RB5952	W45223	34	34
56	Displacement	Support Block 106	SB106F	W45218	35	35
57	Displacement	Support Block 88	SB088F	W45222	36	36
58	Displacement	Support Block 96	SB096F	W45225	37	37
59	Displacement	Refl. Block 434-8	HR4348	W45239	38	38
60	Displacement	Refl. Block 502-8	HR5028	W45214	39	39
61	Displacement	Refl. Block 555-8	HR5558	W45238	40	40
62	Displacement	Refl. Block 554-8	HR5548	W45249	41	41
63	In-Core Displacement			W45274	97	Coax 1
64	In-Core Displacement			W45275	98	Coax 2
65	Displacement	Refl. Block 534-8	HR5438	W45258	42	42
66	Displacement	Refl. Block 569-8	HR5698	W45248	43	43
67	Displacement	Refl. Block 398-8	HR3988	W45252	44	44
68	Displacement	Refl. Block 472-8	HR4728	W45254	45	45
69	Displacement	Refl. Block 536-8	HR5368	W45243	46	46
70	Displacement	Refl. Block 540-8	HR5408	W45244	47	47
71	Displacement	Refl. Block 434-11	HR434N	W45220	48	48
72	Displacement	Refl. Block 434-6	HR4346	W45211	51	51
73	Displacement	Refl. Block 434-3	HR4343	W45212	52	52

TABLE 5-3 (Continued)

Word	Instrument/Measurement	Location	Measure- ment Number	Wyle S/N	Equip. Rack to Comp. Room	F-2 Boom
74	Displacement	Ref1. Block 434-1	HR4341	W45202	53	53
75	Displacement	Ref1. Block 434-13	HR434T	W45217	54	54
76	Displacement	Support Block 75	SB075F	W45221	55	55
77	Displacement	Support Block 63	SB063F	W45224	56	56
78	Displacement	Support Block 68	SB068F	W45200	57	57
79	In-Core Displacement			W45274	97	Coax 1
80	in-Core Displacement			W45275	98	Coax 2

Fig. 5-1. Boundary load cell locations

Fig. 5-2. Boundary plan for spring pack LVDTs

Fig. 5-3. Instrument locations - plan view

Fig. 5-4. In-core instrumentation locations - side view

Fig. 5-5. Floor support block layout

in the core. The number and function of the in-core instruments designed to meet these objectives are noted in Table 5-1.

The 15 LVDTs in the permanent side reflector blocks measured displacement relative to the hexagonal reflector blocks. These instruments are identified by the letters HR in Tables 5-2 and 5-3, the numbers referring to the hexagonal reflector column location and elevation, as shown in Fig. 5-4. One other function of the data from these instruments was to determine the core lumping results reported in Ref. 1.

A primary test objective was to obtain in-core force, acceleration, velocity, and displacement response at several locations in the core. This was accomplished by configuring the in-core transducers in three fuel blocks, as shown in Fig. 5-6, and relocating this set at different radial positions and elevations of the core during the test series. The contactor gages served as a means of determining collision orientation between the blocks.

Since the core analysis codes were relatively undeveloped at the time of this test, confident predictions of peak core response locations could not be made prior to the testing. Relocations of the in-core instruments were therefore made on an arbitrary basis.

5.3. DATA ACQUISITION

All transducers used in the test operated within a 0 to 10 V signal range, except for the contactors which operated in a 3 to 5 V range. The continuous signal output from each transducer was digitally sampled by using a multiplexer circuit with a fundamental period of 5 msec. Hence, the signal from each of the 68 transducers listed in Table 5-1 (excluding the contactor), plus a DC-proportional-to-frequency and start/stop signal, was recorded and stored on magnetic tape at an interval no larger than 5 msec. A Varian 620 computer was used to digitize the data.

Fig. 5-6. In-core instrumentation package

Since the contactors provided analog data, they were recorded via a separate circuit and recorded directly and taped, bypassing the computer. A zero voltage record was associated with an open contactor, any voltage record in excess of 3 V (up to 5 V maximum) was interpreted as a closed contactor.

For some transducers it was determined that they would have a high frequency response such that the 5 msec sampling period would merely act as a filter. This was the case, for example, for a fuel element collision force strain gage responding in as little as 0.5 msec, as opposed to the rig LVDT responding to rig frequencies no larger than 15 Hz (corresponding to 30 msec).

Two methods were employed for obtaining an accurate record of the signal. The first method allowed the true peak value of the signal occurring in the multiplexer pass to be recorded, using only one channel. This was accomplished by a "peak holder" circuit, which holds the absolute value of the peak positive or negative transducer signal and dumps it onto the tape during the following multiplexer pass. In most cases the peak value (force or displacement) occurring in one multiplexer pass was sufficient.

Where it was desired to determine the peak value at a more precise time than inside 5 msec, as well as its true shape, the transducer signal was allocated to more than one multiplexer channel, equally spaced over the multiplexer sweep interval. Thus, a finer distribution of the transducer signal could be obtained.

The amount of extra channels necessary for a transducer was based on an estimate of the highest frequency to which it would be subjected during the test, as well as the requirement for smoothness of the data which depended on how it was to be subsequently processed. For example, the in-core (DEES) displacement gages were sampled five times per multiplexer pass, or every 1 msec. This was based on the existence of higher in-core

fuel block frequencies due to collisions, as well as the requirement for differentiation of the data to determine fuel block approach and rebound velocities during collision.

Allocation of instrument channels and peak holders is given in Table 5-4, while previous Tables 5-2 and 5-3 give the specific instrument channel allocation.

5.4. INSTRUMENT DESIGN

This section describes the basic design of the instrumented elements installed in the model core.

5.4.1. Reflector Block and Core Support Block LVDTs

These instruments simply consisted of an induction coil which changes inductance as a function of the position of a sliding plunger. The instruments accurately measured displacements of adjacent elements relative to their parent (reflector or core support) element for frequencies less than 30 Hz. Displacement records from these probes were also differentiated for velocity in subsequent data analysis. The LVDTs were restricted to the large boundary blocks because of their relatively large size and spring-loaded plunger. Several of these LVDTs attached to reflector blocks can be seen in Fig. 4-2.

5.4.2. Boundary Spring Pack Instruments

Eighteen boundary spring packs (Drawing 13583) were equipped with an LVDT to measure spring pack deflection for subsequent calculation of spring pack force. The hard stop design was instrumented with strain gages in two cases to record the impact load applied to the hard stop after the soft spring deflected to the limit of 0.2 in.

The soft spring in the latter design was rated at 800 lb/in. No spring pack LVDTs were incorporated into the bilinear spring pack design.

TABLE 5-4
INSTRUMENT CHANNEL ALLOCATION

Signal	No.	No. of Channels	Sample Period, Sec.	No. of Peak Holders
Fixture Displacement	1	1	0.005	
Actuator Displacement	2	2	0.005	
Fixture Acceleration	2	2	0.005	2
Incore Acceleration	3	3	0.005	3
Boundary Force	2	2	0.005	2
Fuel Element Force	2	2	0.005	2
Spring Pack Displacement	18	18	0.005	
Reflector Block Displacement	30	30	0.005	
Floor Support Block Displacement	6	6	0.005	
Fuel Element Displacement	2	10	0.001	
Zero	1	1	0.005	
Input	1	1	0.005	
DC $\propto$ Frequency	1	1	0.005	
Start/Stop	1	1	0.005	
Total	72	80		9

5.4.3. In-core Instrument Package

In-core displacements, velocities, accelerations, collision forces, and collision orientations were measured throughout the core using the three-element instrument package illustrated in Fig. 5-6. The package contained three types of transducers: capacitive displacement gages (DEES gages), accelerometers, and strain gages. Contact gages consisting of thin brass strips were also located in the corners of opposing faces on two blocks in line with the excitation. These gages were used to determine the orientation of an adjacent element impact by the registering of an open or closed signal during an impact event. Each gage was insulated from the parent element and a ground connection was closed during adjacent element contact.

5.4.3.1. Displacement (DEES) Gages. Two capacitive DEES gages were mounted in the outer elements of the instrumentation package to measure the displacement of the element relative to an adjacent element. These gages were considerably smaller and lighter than the boundary LVDTs. An inherent limitation of the gages was their inability to measure displacements beyond 0.1 in. However, their main function was the subsequent determination of the relative impact and rebound velocity with the neighboring elements.

5.4.3.2. Accelerometers. Three accelerometers were distributed in the in-core package to provide data which could be integrated for absolute element velocity. Block collision forces were not calculated from the accelerometer data because of the uncertainty of the effective element mass (due to core lumping) during an impact event.

5.4.3.3. Fuel Block Strain Gages. Two strain gages were attached to interval surfaces of one fuel element in the in-core instrument package as shown in Figs. 5-6 and 5-7. The gages were calibrated with respect to a force corresponding to the collision of another fuel element on the face nearest the strain gages.

Fig. 5-7. 1/5-scale fuel element collision force instrumentation

5.5. INSTRUMENT CALIBRATION

Instrument calibration methods are described in this section. All calibration data are contained in the calibration data package in GA storage under the full-array test. For the most part, these data have not been published in any preceding report by either GA or Wyle Laboratories.

5.5.1. LVDT Displacement Gages

All LVDT displacement gages were checked statically and verified to agree with the manufacturer's calibration constants. The actual data log sheets from the manufacturer were retained in storage.

The rig displacement LVDT and exciter LVDT were calibrated at least once daily prior to each test sequence at a given position of the in-core instrumentation. The calibration data were recorded on the visicorder output.

5.5.2. Accelerometers

No known verification tests were employed for the rig and in-core accelerometers other than the DC insert calibration tests prior to test startup. Calibration factors were taken from manufacturer's specifications.

5.5.3. DEES Gages

DEES gages measuring relative fuel element displacements were subjected to a static calibration using another model graphite fuel block separated by a known gap.

5.5.4. Spring Pack Strain Gages

Strain gages mounted on the spring pack hard stop were statically calibrated using a hydraulic actuator. The spring pack was loaded axially

in increments of 1000 lb to a maximum load of 7000 lb. Dynamic verification tests of the static calibration factors were not performed since the load application mode was the same as for the spring pack mounted in the test fixture and dynamic amplification was not expected due to very stiff support structures.

5.5.5. Element Force Strain Gage Calibration

By far more effort was expended obtaining calibration factors for the internal fuel element strain gages. Initially, the gages were subjected to a quasi-static calibration test using the hydraulic actuator to deliver a sinusoidal input load over a static preload. This technique was abandoned when it was realized that the impact loading and variable impact configuration of the elements occurring during the actual testing was not taken into consideration (i.e., flat, edge, or corner hits between two blocks).

At this point a pendulum rig was constructed where the model fuel element containing the strain gages was swung into a semirigid boundary instrumented with load cells. The initial data exhibited a large scatter indicating a significant variation in the load recorded by the strain gages for small misalignments of the blocks at impact. After extensive testing, calibration factors were determined for this method in the categories of "aligned" and "misaligned" impacts. The calibration curves are shown in Fig. 5-8.

After 1/5 scale full-array testing commenced, it was observed that the fuel elements in the core assumed a lumped configuration over a wide range of sinusoidal and time history excitation. A decision was made to recalibrate the fuel element strain gages, taking account of the backed-up restraint offered by adjacent blocks when being dynamically loaded in this mode. The results of this final instrument calibration are also shown in Fig. 5-8. These calibrations were documented in Ref. 16, concluding that the calibration factor for the free-face condition was approximately double that for the backed-up configuration.

Fig. 5-8. 1/5-scale fuel element strain gage calibration

6. TEST PLAN AND RIG EXCITATION

The 1/5 scale core model was tested using a series of sine sweeps and earthquake inputs at different g-levels. After initial sinusoidal tests were run and the core resonance frequencies were identified, sine dwell tests followed by a manual rig shutdown were run in an attempt to determine core damping from the core free vibration decay data records.

Separate test series were run along the X- and Y-axes corresponding to the across-the-flat and across-the-corner directions of a fuel element, respectively. Many tests were also repeated after changing the initial soft boundary spring design to one incorporating a hard stop after 0.2 in. of soft spring compression. Tables 6-1 and 6-2 are included to describe the complete testing program and instrument locations (refer to Fig. 5-3).

6.1. SINE SWEEP TESTING

Sine sweep tests were executed in the range of 0.8 to 15 Hz and varied in g-level from 0.3 to 1.0 g (fixture). The frequency response characteristics of the instruments based on these tests were used to establish the dwell points for dwell and decay testing.

6.2. DWELL AND DECAY TESTING

Starting with the known core resonance frequencies, dwell tests were conducted in both the X- and Y-directions. Initial tests were repeated after failure to achieve the proper response amplitude at resonance due to the nonlinear resonance characteristics of the core. This situation was corrected by first sweeping to the resonance frequency and then conducting the dwell. Rig shutdown was achieved manually after about 10 cycles of dwell at the instant the test rig achieved a peak amplitude (zero velocity).

TABLE 6-1
X-AXIS TEST PROGRAM

Test No.	Test Type	Fixture g Level	Ground g Level	Frequency Range (Hz)	Pos./ Level Block Loc. (a)	Boundary Plan (b)	Remarks
1	Sine Sweep, Dwell, Decay	0.30		0.8-22	1/8	1	Minimum Data Review Between Runs
2	Time History	0.30	0.15	--	1/8	1	Run Sequentially
3	Time History	0.50	0.25	--	1/8	1	Run Sequentially
4	Sine Sweep, Dwell	0.50		0.8-22	1/8	1	Minimum Data Review Between Runs
5	Time History	0.70	0.35	--	1/8	1	Run Sequentially
6	Time History	1.00	0.50	0.8-22	1/8	1	Run Sequentially
--	Data Review (Verify Waveform, Assess Instrument Locations, Plot Control Information and Assess Fail Safe and Location)						
--	Modify Setup (Relocate Instrumented Elements, Boundary Instruments, Recalibrate)						
7	Sine Sweep, Dwell	0.50		0.8-22	2/8	2	Minimum Data Review Between Runs
8	Time History	0.50	0.25	--	2/8	2	Run Sequentially
--	Modify Setup (Relocate Instrumented Elements, Boundary Instruments, Recalibrate)						
9	Time History	0.50	0.25	--	3/8	3	Run Sequentially
10	Repeat Test No. 9 with New Filter						
2M	Repeat Test No. 2 with New Filter						
3M	Repeat Test No. 3 with New Filter						
5M	Repeat Test No. 5 with New Filter						

TABLE 6-1 (Continued)

Test No.	Test Type	Fixture g Level	Ground g Level	Frequency Range (Hz)	Pos./Level Block Loc. (a)	Boundary Plan (b)	Remarks
6M	Repeat Test No. 6 with New Filter						
--	Modify Setup (Relocation Instrumented Elements, Boundary Instruments, Recalibrate)						
11	Sine Sweep, Dwell	0.50		0.8-22	1/4	4	Minimum Data Review Between Runs
12	Time History	0.50	0.25	--	1/4	4	Run Sequentially
--	Modify Setup (Relocate Instrumented Elements, Boundary Instruments, Recalibrate)						
13	Time History	0.50	0.25	--	1/10	5	Run Sequentially
--	Modify Setup (Relocate Instrumented Elements, Boundary Instruments, Recalibrate)						
14	Time History	0.50	0.25	--	1/13	6	Run Sequentially
--	Data Review (Verify Waveform, Assess Instrument Locations, Plot Control Information)						
--	Modify Setup (Relocate Instrumented Elements, Boundary Instruments, Recalibrate)						
15	Time History	1.30	0.65	--	1/8	1	Run Sequentially
16	Time History	1.50	0.75	--	1/8	1	Run Sequentially
17	Time History	TBD	TBD	--	1/8	1	

(a) Reference Figs. 6-3 and 6-4.

(b) Reference Fig. 6-2.

(c) Adjusted dwell frequency in the event natural frequency is not achieved in the above tests.

TABLE 6-2
Y-AXIS TEST PROGRAM

Test No.	Test Type	Fixture g Level	Fixture g Level	Frequency Range (Hz)	Block Loc./ Level	Remarks
1	Exploratory Sine Sweep	0.05		0.8-22	5/8	
2	Sine Sweep, Steady State, Decay	0.15	0.75	.8-11, TBD TBD	5/8	Minimum data review between runs.
3	Time History	0.30	0.15	--	5/8	Run sequentially.
4	Sine Sweep, Steady State	0.25		TBD	5/8	Minimum data review between runs.
5	Time History	0.50	0.25	--	5/8	Run sequentially.
6	Sine Sweep, Steady State	0.35		TBD	5/8	Minimum data review between runs.
7	Time History	0.70	0.35	--	5/8	
8	Sine Sweep, Steady State	0.50		TBD	5/8	Minimum data review between runs.
9	Time History	1.00	0.50	--	5/8	Run sequentially.
--	Major Data Review (Verify waveform, assess instrument locations, plot control information)					
--	Setup Modification (Relocate instrumented blocks)					
10	Sine Sweep, Steady State	0.25		TBD	6/8	Minimum data review between runs.
--	Relocate Instrumented Blocks					
11	Sine Sweep, Steady State	0.25		TBD	7/8	Minimum data review between runs.
--	Date Review (Assess instrument locations, plot control information, etc.)					
--	Major Test Setup Modification (Relocate instruments, recalibrate, etc.)					
12-16	TBD	TBD	TBD	TBD	TBD	Maximum of 2 data review periods.

6.3. DISPLACEMENT TIME HISTORY EXCITATION

Synthesized displacement time history motions for the reactor PCRV satisfying the USAEC design spectra prior to December 1973 were used to excite the test rig. Two actual earthquakes, Taft and El Centro, were also input to obtain data for correlation with analytical codes even though these motions were less severe (at the same ground g-level) than the synthesized motions. All earthquake time histories are identified in Table 6-3 and are shown in Figs. 6-1 through 6-9.

The curves in the figures represent the shocks at a level of 1.0-g ground acceleration, on a 1/5-scale basis. Per Tables 6-1 and 6-2, these motions were actually input at lower g-levels, which involved proportional lowering of the earthquake amplitude. (Representation of the time coordinate in 1/5-scale was accomplished by decreasing the full-scale time frame by the factor $\sqrt{5}$.)

All the shocks identified in Table 6-3 were arranged in series on magnetic tape and run sequentially through the test rig control unit. These were referred to as "time histories." G-level control of the input was accomplished simply by adjustment of a potentiometer which changed the gain of the control amplifier, and hence the input amplitude. The overall constraint on the input motion was that the double amplitude of the input did not reach 4 in.

TABLE 6-3
1/5-SCALE FULL-ARRAY TEST TIME HISTORY SEISMIC INPUT

Shock Number	Type	Soil Condition (modulus psi)	Structural Damping
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	Supersoft 10,000	5%
9	El Centro	Soft 65,000	5%

Fig. 6-1. Shock 1, 1.0-g ground

Fig. 6-2. Shock 2, 1.0-g ground

Fig. 6-3. Shock 3, 1.0-g ground

Fig. 6-4. Shock 4, 1.0-g ground

Fig. 6-5. Shock 5, 1.0-g ground

Fig. 6-6. Shock 6, 1.0-g ground

Fig. 6-7. Shock 7, 1.0-g ground

Fig. 6-8. Shock 8, 1.0-g ground

Fig. 6-9. Shock 9, 1.0-g ground

7. 1/5-SCALE FULL-ARRAY TEST DATA REDUCTION

Subsequent to recording the raw test data on magnetic tape as described in Section 5.4, procedures were carried out by GA for converting these data into engineering units and organizing the data into interpretable formats. This process typically involved converting from the data in counts by the use of data channel sensitivities which were determined from instrument calibration data and the gain settings used on the instrument amplifiers during testing. All required information for making this data conversion was given on the test laboratory log sheets accompanying each data tape forwarded to GA from the test laboratory.

Once the data were processed into engineering units at GA, the Univac 1100 computer was utilized to analyze the data. A major effort was completed in development of computer programs which performed both classical and specialized mathematical operations on the data, such as frequency analyses, peak value analysis, and number of events.

A complete description of the data reduction programs is given in Ref. 17. Table 7-1 is included to summarize the routines covered.

TABLE 7-1
1/5-SCALE FULL-ARRAY TEST DATA REDUCTION PROGRAMS

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 1 or more series.

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