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ONE-FIFTH-SCALE DOWEL FORCE TEST REPORT

by
J. E. RAKOWSKI

Work supported in part by
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ABSTRACT

This report presents the results of the second seismic test program conducted on the 1/5-scale, full-array model of the 3000 MW(t) high-temperature gas-cooled reactor (HTGR) core. The test conditions consisted of uniaxial horizontal sine sweeps at 0.5 g fixture acceleration, sine dwells at various g-levels and frequencies, and time history excitations at several g-levels conforming to NRC seismic response spectra for seismic category 1 components.

The main objective of the program was to measure fuel element and reflector block dowel forces. In addition, measurements were taken for core damping, fuel element collision, and fuel element and reflector block rocking angles. These data were required to provide a broader base for validating analytical computer models used to calculate HTGR core design loads.

The extensive data reduction effort that followed the test program produced an array of new data reduction routines applicable to data from other tests; descriptions of these routines are included. A lengthy section of this report is devoted to the identification and calculation of statistical errors in the test data.

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1. SUMMARY

The results of the dowel force test program were obtained by subjecting the 1/5-scale, full-array core model to a series of horizontal uniaxial sine sweeps at 0.5 g, sine dwells, and time history inputs conforming to current NRC design spectra in Ref. 1. The first test program using the 1/5-scale, full-array model employed time histories satisfying early NRC criteria (prior to December 1973). El Centro earthquake data were used to obtain results for comparison to those of the previous test program. The excitation was always input in one direction normal to the flats of the fuel elements.

The model represented the 3000 MW(t) reference design reactor core in its cold and fully irradiated state of life. The overall model fuel element gap and plenum block gap were scaled to be 1.238 in. and 1.012 in., respectively, as described in Ref. 2. However, the actual gaps measured on the model subsequent to the dowel force test averaged 1.197 in. and 0.919 in., respectively.

The lateral supports consisted of a soft spring with an 800 lb per in. modulus backed up by a hard stop of at least 167,500 lb per in., after 0.2 in. of deflection.

The in-core instruments were relocated at a total of four locations in the core for the 26 tests of the program. Although an effort was made to hold the typical model fuel block weight of 2.07 lb for the blocks containing the instrumentation, the block weights actually varied from 2.13 to 2.75 lb.

Summaries of the more important results contained in the program follow.

1.1. CORE DAMPING

The damping associated with the free transient decay of the core from resonance in its lumped mode was 40%. The equivalent viscous damping of the core while forced sinusoidally at 0.5 g in its lumped mode was approximately 18%. The phase angle of the core motion at resonance, relative to the rig displacement, was verified to be 90° by comparing the test model to the viscously damped Duffing model.

1.2. SINUSOIDAL EXCITATION AT 0.5 g

The results below apply only to the instrument locations on the core diameter parallel to the excitation axis. The off-axis response is discussed in Section 2.2.5.

1. The fuel element rocking angle frequency response generally decreased during sweep-up until the core dropped out of the second mode resonance at 4.1 Hz. At this time, the rocking angle experienced a sudden increase to a maximum of about 3.2° . The orientation of rocking was always parallel to the axis of rig excitation to within about 10° . The rocking angle at 4.0 Hz, just prior to core resonance, increased from a minimum of 0.5° at the core center to a maximum of about 1.5° at the periphery, considering all instrumented elevations.
2. The reflector block rocking angle frequency response was similar to that of the fuel elements. The peak reflector block rocking angle was approximately 0.54° and was measured at the core mid-height elevation.
3. The frequency response of the two instrumented spring packs was similar to that recorded in previous full-array tests, with the up-sweep and down-sweep responses essentially identical at frequencies below resonance.

4. The variation of dowel forces with core radius for blocks at a fixed elevation revealed that dowel forces increased more rapidly near the core boundary.
5. Both the X-axis and Y-axis frequency responses of the reflector block dowel forces substantially increased with core elevation. The Y-axis (circumferential) dowel force was always similar to or greater than the X-axis (radial) dowel force.
6. In general, collision forces remained fairly constant with respect to core radius, the only exception being the force measured at core block level 4. This difference was postulated to be caused by block impacts occurring in an unlumped rather than lumped portion of the core vibration period.

1.3. TIME HISTORY EXCITATION

The following results apply only to the instrument locations on the core diameter parallel to the excitation. The peak time history response for each instrument is shown in Table 1-1. The response to shock 4 was presented in more detail since this shock generally produced the greatest response.

1. In contrast to the rocking angle frequency response of fuel elements 001-7 and 007-5, which increased near the core boundary, the time history rocking angle response was essentially constant or even decreased from the core center to the periphery. Since rocking angles measured on other blocks were small compared to the peak angle of 1.75° for the above blocks, they were not presented in the results.
2. While the fuel element dowel force frequency response increased toward the core boundary for all elevations, the time history dowel force response increased toward the boundary only at the floor level. The dowel forces recorded at block elevation 4 in

TABLE 1-1
SUMMARY TIME HISTORY RESPONSE, 0.25 g (GROUND) (REFERENCE)

Instrument	Core Center					Midradius					Core Boundary				
	1	2	3	4	5(a)	1	2	3	4	5(a)	1	2	3	4	5(a)
Eddy current probes 4-11 (deg)	0.54	0.60	0.52	0.90	0.50										
Eddy current probes 1-7	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	1.70	-1.66
Eddy current probes 7-5	0.34	0.25	0.78	1.10	0.34	+0.35	+0.39	-0.76	0.69	+0.32	+0.30	+0.34	+0.42	0.52	0.33
Eddy current probes 596	0.25	0.42	0.34	0.66	0.39										
5 load cells (block) 5-7 (1b)	3.3	0	114	143	19.5	0	0	125	91.2	10.2	17.4	54	180	182	11
2 load cells (block) 6-4	0	0	4.6	12.6	18.5	0	0	3.6	6.3	0	3.6	30.3	62	146	1.5
2 strain gages (block) 4-10	27	46.3	205	320	53	26	29.8	261.3	268	36.4	65.8	101.8	372	457	72
1 strain gage (block) 1-6	13	0	104	184	51	0	32.1	196.5	248	24.2	75.3	29	184	106	67
Strain gage (dowel)-X net 4-10	16	10	6.6	17	14	-8.5	-21.6	7.7	6.4	-13.4	3	-2.9	9.8	-28	2.9
Strain gage (dowel)-Y net 4-10	4	2	6	5.4	4				-5.6					20	
Strain gage (dowel)-X net 7-4	0	0	2.36	8.2	1.0	0	0	1.82	2.33	0	1.9	3.65	5.45	8.4	2.2
Strain gage (dowel)-Y net 7-4	0	0	2.07	3.2	0										
Strain gage (dowel)-X net CSB	2.25	2.4	4.55	4.5	3.0						6.25	5.35	10.8	9.9	3.9
Load cell (dowel)-X net 1-6	10.8	4.5	72.4	73.8	18.0	34	23.7	149.5	160.5	28	18.5	5.70	124	129	33.8
Load cell (dowel)-Y 1-6	0	0	6.6	47.3	0	0	0	21	26.2	0	0	0	76.5	57	0
Load Cell (dowel)-X net 596	68	110.5	159	181	23			101.4	93				55	95	
Load cell (dowel)-Y net 596	63	177	157	383	9.8			78.7	84				15	25.4	
Spring pack 1-5	0	0	2351	2505	0				2781					2781	
Spring pack 19-5	0	0	1179	1474	0				1518					1287	

(a) Shocks 1, 2, 3, 4, 5

the core exhibited a definite trough at the midradius point. The dowel force at block level 10 in the core shows a rather large scatter in the radial distribution and an explanation was given for the large expected error in this particular instrument due to the absence of a signal peak holder in the circuitry.

3. The time history response of the reflector block X-axis and Y-axis dowel forces was similar to the sinusoidal distribution, exhibiting a sharp increase with core elevation and the existence of large Y-axis loads.
4. The fuel element collision force time history response exhibited larger increases from the core center to the periphery in comparison to those for sinusoidal excitation, depending on their elevation in the core.
5. Fuel element rocking angles for blocks 001-7 and 007-5 underwent large overall increases with increasing shock input g-level; however, for block 001-7 the large variations were at the low end of the g-level scale, while for block 007-5 the only variation occurred in the region from 0.18 to 0.24 g (ground).
6. All fuel element dowel forces increased with shock input g-level, with the larger variations occurring at the upper end of the g-level scale. The only exception was the floor block dowel load, which underwent larger variations at the low end of the scale.
7. Of all the data recorded in the test, the collision forces exhibited the greatest increase with input g-level; the variations were consistently greater near the core periphery.

1.4. FUEL ELEMENT COLLISION FORCE ORIENTATION AND NUMBER OF LOAD CYCLES

1. Only shocks 3 and 4 at the reference 0.20 g and 0.25 g levels produced at least several collision force events greater than the 28.5 lb limit, which was an estimate of the collision force fatigue endurance limit in 1/5 scale.
2. The total number of impacts of loads larger than the 28.5 lb limit was approximately 9 at 0.25 g (ground) (reference) and 2 at 0.20 g (ground).
3. Half of the total number of impacts occurring for the shock were corner impacts, with the remainder being equally divided between edge and flat hits. However, a relatively large percentage of the flat hits were probably line or point hits delivered by the blocks in the adjacent staggered control rod column.

1.5. SPECIAL COMPARISONS

1. Simultaneous rocking angle and dowel force events were recorded. Approximately 25% of these were of mutually large values. However, the maximum rocking angle (with a simultaneous dowel force) was 1.38°.
2. There was no observable correlation between fuel block collision forces and dowel forces. Only 21% of the simultaneous block and dowel force events contained loads greater than 33% of the peak values.
3. For sinusoidal excitation below core resonance, the single-pin X-axis dowel loads (in the direction of the excitation) varied between 15% and 50% of the total X-axis load (3 pins). The average percentage (over the four largest events) of the total X-axis

dowel load taken by dowel pins 1, 2, and 3 was 37%, 31%, and 32%, respectively.

4. The total Y-axis dowel load in sinusoidal excitation was shared by dowel pins 1, 2, and 3 according to an average (over the four peak events) of 59%, 22%, and 19%, respectively.
5. For sinusoidal excitation, the largest single dowel pin modulus (computed from the X-axis and Y-axis component forces) was 24% greater than the single pin X-axis load. Averaged over the three dowel pins, the peak modulus was only 9% greater than the single pin X-axis loads.
6. For time history excitation, the single pin X-axis load varied between 5% and 70% of the total; however, the averages for pins 1, 2, and 3 calculated over six peak events were 23%, 39%, and 40%, respectively.
7. The single pin Y-axis load in time history excitation varied between 4% and 90% of the total. The average percentages for pins 1, 2, and 3 calculated over six peak events were 17%, 47%, and 36%, respectively.
8. For time history excitation, the largest single dowel pin modulus was 11% greater than the single pin X-axis load. Averaged over three dowel pins, the peak modulus was only 6% greater than the single pin X-axis loads.
9. The data supported use of one-half of the total X-axis dowel load on the block for strength analysis of a single dowel pin (as if only two dowels always share the total X-axis load).
10. The frequency distribution of the dowel pin moduli was obtained and compared to that for the individual dowel X-axis forces and the half-total X-axis dowel forces. The results showed that

inclusion of the Y-axis forces in the moduli shifted the dowel load frequency distribution to higher levels, which is more severe from a fatigue standpoint; however, the total number of load cycles remained essentially unchanged. It turned out that the frequency distribution of the half-total dowel loads was similar to the moduli distribution in terms of both total load cycles and load magnitude. Hence, the data supports use of the half-total loads for dowel fatigue analysis in addition to dowel strength analysis.

11. The rocking angle frequency response and time history response at the core 45° position (instrument position 4) was similar in shape and magnitude to the response on the main core diameter, in line with the excitation, at the periphery (instrument position 3). The orientation angle response indicated rocking parallel to the X-axis, and absence of the circular movement, which was previously observed in the plenum blocks.
12. Although the magnitudes of the fuel element dowel forces at position 4 were in the range of 45% to 68% of those at position 3, the response at the lower core elevations showed a dramatic resonance peak at about 4.3 Hz, which was absent in all instrument positions on the main diameter. Reflector block dowel forces were about 38% of those at position 1 and exhibited similar resonance behavior.

The frequency response of the fuel element collision forces at position 4 also exhibited the 4.3 to 4.5 Hz peak at the lower core elevation as shown by dowel force response. Collision forces at position 4 ranged from 62% to 107% of those at position 3.

13. The X-axis time history dowel force response at position 4 contained about the same number of events as those at position 3

for the same shock; however, the magnitude varied from about 20% to 120% of those at position 3.

14. The X-axis time history reflector block dowel forces at position 4 were approximately 30% of those measured on the main core diameter.
15. The time history fuel element collision forces at position 4 varied widely from those measured at position 3 for the same shock in that one instrumented block received no impacts compared to a 36 lb peak load at position 3, while the second instrumented block registered a peak load 34% larger than the peak at position 3.

1.6. SUMMARY OF ERRORS IN THE DATA

The dowel force test error analysis included error identification, statistical treatment of data from repeated tests, and summation of component errors to form an estimate of the total error for the in-core instrument data. Systematic errors were subtracted from the data prior to making statistical calculations.

A summary of the overall two-sigma random error in the test data appears in Table 1-2. The predominant sources of these errors were, in descending order, instrument calibration, core geometry, and rig input motion.

Several other kinds of calibration errors were not specifically included in the error calculations. These were: (1) block force strain gage response to a pure dynamic dowel load, (2) dowel instrument response to dowel inertia loading during a block impact, particularly for the relatively heavy two-component dowel load cells, and (3) crosstalk in the two-component dowel load cells found during dynamic verification testing. Although these errors were found to be small enough not to affect the

errors in Table 1-2^{*}, they should be evaluated during instrument calibration in future core seismic tests.

The final error, which was discovered late in the data reduction effort, was the 35% dowel strain gage error resulting from relatively fast loading transients and the absence of peak holders on these instruments. This error was included in Table 1-2.

* The 38% cross-talk error in the reflector block dowel load cell does not affect the peak X-axis loads as long as the X and Y loads do not act simultaneously, a condition found for the fuel elements.

TABLE 1-2
DOWEL FORCE TEST ONE-SIGMA RANDOM ERRORS

Response	One-Sigma Random Error (%)
Boundary spring pack force	4.1 to 8.1
Reflector block velocity	6.0
Reflector block displacement	3.0
Net fuel element dowel force ^(a)	6.0 to 11.0
Floor support block dowel force	10.0
Reflector block dowel force	11.5
Fuel element collision force (strain gage)	55.0
Fuel element collision force (load cell)	6.0 to 10.0
Rocking angle	14.0

^(a) Fuel element 004-10 dowel force: 11% to 16%.

2. CONCLUSIONS AND RECOMMENDATIONS

2.1. CONCLUSIONS

Based on the results of the test, including the error analyses, the following conclusions were made:

1. The test objectives were satisfied to within the limits of the data error presented in Table 1-2.
2. The transducers and their applications proved successful for the measurement of core element loads and displacements.
3. Load cell washers were successfully applied to measure fuel element collision forces, but strain gages failed in this application due to calibration problems.
4. A method was developed and successfully used to determine core damping for sinusoidal sweep excitation of the core using the phase lag of core displacements with respect to the rig.
5. The damping factor determined from the free transient decay of the core was about twice that calculated from the forced motion.
7. The same resonant frequencies found in previous full-array tests were reproduced in this test program. However, the data recorded by instruments at the core 45° position indicated an additional core or core support floor mode, which controlled the peak response in this region, and which was not observed in the past.
7. GA synthesized shocks 3 and 4 [soft soil, safe shutdown earthquake (SSE) and operational basis earthquake (OBE), respectively] produced the greatest core response.

8. No possibility of core disarray was shown at the test g-levels since the maximum rocking angle, approximately 1.75° , occurring in the lower half of the core, was far less than the value of 5° below which disarray cannot occur per Ref. 2a.
9. Although fuel element Y-axis dowel forces were generally lower than X-axis forces, permanent side reflector block Y-axis forces were similar to and often greater than the X-axis forces when the block was located on the main core diameter in line with the excitation. This behavior was believed to be due to tangential block forces in the reflector ring since negligible Y-axis reflector block dowel forces were measured when the instrument was located on an axis normal to the main core diameter.
10. The increase in response with increasing g-level was consistently greatest at the core boundary.
11. The test data showed no correlation between peak dowel forces and rocking angles or dowel forces and block collision forces.
12. Computation of dowel force moduli showed that peak X-axis and Y-axis dowel force components did not occur simultaneously.
13. The dowel force data supported use of one-half the total across-face dowel force for both static and fatigue strength analysis of a single dowel.
14. A component error model was developed which could be used for identification and estimation of errors from similar tests.

2.2. RECOMMENDATIONS

Based on the results and conclusions of the 1/5-scale dowel force test, the following recommendations are made for future core seismic

testing, in particular with the full-array model:

1. The test specification should require an error bound on the rig input motion since it was found that in some cases unacceptable deviations from the nominal occurred.
2. Bounds on the maximum cross-talk error of two-component load cells, as calibrated, should be specified.
3. Dowel strain gage response to a block impact and block load cell response to dynamic dowel loading should be evaluated during calibration testing.
4. At least one five-load-cell block should be located adjacent to a fuel element column as opposed to a control rod column since the blocks in the latter columns are staggered vertically with respect to those of the former columns.
5. Instrumenting fuel elements with strain gages to measure collision forces should be avoided, although strain gages were preferred over load cells for dowel force measurement.
6. An investigation should be made into the newly available compact load cells to develop a good alternative to dowel strain gages.
7. The low frequency response of the load cell charge amplifiers should be verified in calibration. Only Kistler Corporation microdot cable should be used between the transducer and charge amplifier to prevent loss of signal.
8. All strain gages and load cell assemblies should be calibrated and verified.
9. The test laboratory should be required to verify the calibration factors transmitted in the log sheets, particularly where signal conditioners have been used. This is paramount.

10. Repeated tests should be required in order to bypass the component error method and more easily compute data random errors including mean values.
11. Peak holders should be used on all force transducers.
12. The 45° position of the full-array model should be instrumented and more carefully tested to obtain force data. The lower section of these regions should be instrumented with displacement transducers to check for a new mode of vibration in this region which was indicated by a new resonance peak in the data.
13. The test lab should be required to prove the sign of the drift on instruments where peak holders are used (or hold the drift to within some small value).
14. All block collision force load cell assemblies should have summing circuits leading to a separate channel. The channels picking up the separate load cell data and the summed data should all be adjacent to each other in the data acquisition system to facilitate determination of block impact orientation.
15. If different designs of dowel and block force instrumentation are present, the blocks should be moved to different core elevations and the tests repeated since the variation of mass among these instrumented blocks precludes direct comparison of the response with respect to core elevation.

3. INTRODUCTION

In 1973 a 1/5-scale, full-array model of a 3000 MW(t) HTGR core was seismically tested. The test objectives were to ascertain the behavior of the core to seismic excitation and to provide basic data for correlation of analytical codes which provide design loads for the core elements and lateral core supports. The description, objectives, data, and results of these full-array tests are given in Refs. 3 through 7.

While the 1/5-scale, full-array test data were being analyzed, much attention was given to the design and analysis of the fuel element dowel and socket system aligning the blocks in the core. Early analytical models of the core columns predicted seismic forces on the dowels which were too large for the reference design but which also contained excessive conservatism. This information led to a formal request for additional data from the full-array test model such that the analytical models could be better correlated with the test data and more accurate load predictions made.

Of primary concern was the maximum dowel load vector and its variation as a function of location within the core. Information was also required for the distribution of loads among the three dowels on a single fuel element. Since the function of the dowel and socket system was to prevent element disarray, core block rocking angles were also required including the dowel load versus rocking angle. Finally, since dowel-socket failure could depend on the superposition of both fuel element body loads and dowel loads, these loads were required to be recorded simultaneously on a single element.

In response to the requirement for this data, a test specification (Ref. 10) was written in August 1974 describing requirements for the 1/5-scale dowel force test. Since this test was an add-on to the previous 1/5-scale, full-array tests, the essential changes included (1) the design of

dowel force instrumentation, (2) fuel element rocking angle instrumentation, (3) new block force instruments replacing those showing poor performance in previous tests, and (4) the use of new time history excitation satisfying the latest NRC seismic response spectra for seismic category 1 components (Ref. 1).

A portion of the test plan was devoted to measurement of data for correlation with data from the earlier full-array tests and for replacing erroneous data. Examples of the latter case are core element impact forces and core displacement decay transients for damping estimates.

All aspects of the 1/5-scale dowel force test are covered in the following sections of this report and its references.

4. TEST OBJECTIVES

The overall objectives of the 1/5-scale dowel force test were to measure and record the dynamic response of the full-array core model subjected to uniaxial horizontal sinusoidal and time history excitation. The response parameters measured as a function of core location were:

1. The magnitude and direction of fuel element dowel forces.
2. The magnitude and direction of reflector block and core support block dowel forces.
3. The fuel element horizontal collision forces and impact orientation.
4. The fuel element and reflector block rocking angles.

The additional response components measured for correlation with previous 1/5-scale, full-array test data were:

1. Resonant frequencies and mode shapes.
2. Horizontal core boundary forces.

Finally, decay transients and the phase angle of the response components were measured for evaluation of the equivalent viscous damping of the core.

5. DESCRIPTION OF TEST MODEL AND HARDWARE

The 1/5-scale, full-array core model and test rig are shown in Figs. 5-1 and 5-2.

5.1. GRAPHITE CORE MODEL

A general description of the graphite core model assembly is given in Appendix A of Ref. 10, while the model details are illustrated in Refs. 11 through 22.

A complete description of the core model requires a presentation of the scaling laws defining its relationship with the prototype core. These laws are discussed in Ref. 23; a summary of the scaling laws is given in Table 5-1.

The seventh and ninth relationships in the table illustrate that the test model is not ideal, as all scaling laws are not satisfied by the model. For a graphite model, the density ρ_m is equal to ρ_p ; hence the elastic modulus E_m does not equal λE_p as given by scaling law number 7. The elastic modulus of the blocks in the model is therefore five times the correct scale value. In addition, the coefficient of friction of graphite in air is known to be less than that for graphite in a hot helium environment; as a result, scaling law number 9 in the table is not satisfied. On the other hand, the coefficient of restitution was made to fit that of the prototype block by optimization of the size and geometry of the holes in the 1/5-scale element.

The distortion in the elastic modulus tends to produce element contact times that are too small in relation to scaled prototype contact times. This has an effect on element impact forces, which are recorded too large. However,

Fig. 5-1. One-fifth-scale, full-array model

Fig. 5-2. Test rig for one-fifth-scale, full-array model

TABLE 5-1
SCALING LAWS FOR THE ONE-FIFTH-SCALE 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	$F_m = \lambda^3 (\rho_m / \rho_p) F_p$
6.	Stiffness	$K_m = \lambda^2 (\rho_m / \rho_p) K_p$
7.	Modulus	$E_m = \lambda (\rho_m / \rho_p) E_p$
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 effect on overall core motion characteristics would be negligible since the contact time is approximately two orders of magnitude smaller than the block travel time between impact events. For this reason, the 1/5-scale model will adequately represent the behavior characteristics of a prototype case. The test results therefore provide valid data for code correlation and unification.

Other noteworthy factors placing the model out of conformance with the scaling laws were:

1. The weight of the hexagonal reflector elements was not to scale.
2. The dowel/socket stiffness was not to scale for the core in general; however, careful scaling was maintained in the regions where dowel loads were measured.
3. The floor support structure varied from the prototype as explained below.

These effects, however, were accounted for in the analytical models used for code correlation.

5.2. CORE SUPPORTS

5.2.1. Floor Support Structure

The model core was supported below the floor by roller bearings in the core support blocks rather than by support posts used in the prototype. The roller bearings permitted lateral movement of the core floor without the residual vertical travel that accompanied support post rocking motion in the prototype. The vertical travel, however, was concluded to have an insignificant effect on the overall core response.

5.2.2. Lateral Supports

Horizontal support of the model core was provided within the steel test rig by 252 spring packs simulating the prototype design. These spring packs have a hard stop to limit seismic movement of the core relative to the rig, and a soft spring that in the prototype permits core and PCRV differential movement due to temperature and pressure changes, creep, and PCRV prestress. The spring packs were connected to the corners of four core barrel plates, which was a feature of the early 3000 MW(t) reference design. Details of the model spring packs are given in Refs. 25 through 27. The total cross-core gap of the model was constant at 1.24 in., with the gap in the plenum block layer equal to 1.01 in.

5.3. TEST RIG

The test rig shown in Fig. 5-2 consists of a rigid reinforced steel barrel designed to contain the graphite core model and simulate the prestressed concrete reactor vessel (PCRV). The rig is supported by four hydrostatic bearings allowing unrestrained motion along one axis. A connector was located on the rig approximately in line with the composite CG of the model and rig. Attached to this connector was a hydroshaker, which was programmed to execute sinusoidal or other time history displacement input.

5.4. TEST HARDWARE

In addition to the graphite core model and test rig, other equipment was required in order to perform the test. Primarily, this was the instrumentation, fixtures for calibrating the instruments, and equipment for data acquisition, including a Varian 600 computer for automatic data storage. Descriptions of these items are given in the references or subsequent sections of this report. A list of equipment is given in Ref. 28.

6. INSTRUMENTATION

6.1. GENERAL

All instrumentation used in the 1/5-scale dowel force test is described in this section. Most of the in-core instruments were newly designed although a portion of the instruments from previous 1/5-scale, full-array tests were recalibrated for reuse.

6.2. INSTRUMENTATION PLAN

The test instrumentation was made up of the 51 transducers listed in Table 6-1. These were categorized into separate groups of rig instrumentation, core boundary instrumentation, and in-core instrumentation. The identification, number, and function of each transducer are summarized in Table 6-2.

6.2.1. Rig Instrumentation

For this test, one linear variable differential transformer (LVDT) was used to measure rig displacement and provide feedback control for the hydraulic shaker servomechanism. LVDT instrumentation is shown in Fig. 6-1. Previous 1/5-scale, full-array tests employed additional accelerometers at the base and top of the rig to check for overturning motion. Since little difference in the signals was found for these instruments, the measurements were not repeated in the dowel force test.

6.2.2. Core Boundary Instrumentation

The core boundary instrumentation consisted of LVDTs measuring displacements of the permanent side reflector blocks relative to the core

TABLE 6-1
TRANSDUCER LIST

Word	Instrument/Measurement	Location	Measurement Number
1	Fixture displacement	Fixture base (Ext)	TFDX
2	DC α frequency	DNA	DNA
3	Strain gage	Spring pack 1-5	LC0191
4	Displacement (LVDT) ^(a)	SB001	SB001
5	Displacement (LVDT)	SB088	SB088
6	Strain gage	Spring pack 19-5	LC0195
7	Displacement	Ref1. block 595-1	RB5951
8	Displacement	Ref1. block 595-6	RB5956
9	Displacement	Ref1. block 613-6 ^(b)	RB6136
10	Displacement	Ref1. block 434-13	HR434N
11	Displacement	Ref1. block 434-3	HR4343
12	Displacement	Ref1. block 398-13 ^(c)	HR398N
13	Load cell (dowel, XY)	Ref1. block 596-5	DF5965
14	Displacement (vertical)	Ref1. block 596-6	PA5966
15	Displacement (vertical)	Ref1. block 596-6	PA5966
16	Displacement (vertical)	Ref1. block 596-6	PA5966
17	Load cell (dowel bar, XY)	EL 001-6	DB0016
18	Strain gage (block)	EL 001-6	BF0016
19	Strain gage (block)	EL 004-10	BF004N
20	Strain gage (block)	EL 004-10	BF004N
21	Displacement (vertical)	EL 004-1	PA004N
22	Displacement (vertical)	EL 004-1	PA004N
23	Displacement (vertical)	EL 004-1	PA004N
24	Strain gage (dowel)	EL 004-10	DF004N
25	Strain gage (dowel)	EL 004-10	DF004N
26	Strain gage (dowel)	EL 004-10	DF004N
27	Strain gage (dowel)	EL 004-10	DF004N
28	Strain gage (dowel)	EL 004-10	DF004N
29	Strain gage (dowel)	EL 004-10	DF004N
30	Load cell (block)	EL 006-4	BF0064
31	Load cell (block)	EL 006-4	BF0064

TABLE 6-1 (Continued)

Word	Instrument/Measurement	Location	Measurement Number
32	Displacement (vertical)	EL 001-8	PA0018
33	Displacement (vertical)	EL 001-8	PA0018
34	Displacement (vertical)	EL 001-8	PA0018
35	Load cell (block)	EL 005-7	BF0057
36	Load cell (block)	EL 005-7	BF0057
37	Load cell (block)	EL 005-7	BF0057
38	Load cell (block)	EL 005-7	BF0057
39	Load cell (block)	EL 005-7	BF0057
40	Displacement (vertical)	EL 007-5	PA0075
41	Displacement (vertical)	EL 007-5	PA0075
42	Displacement (vertical)	EL 007-5	PA0075
43	Strain gage (dowel)	EL 007-4	DF0074
44	Strain gage (dowel)	EL 007-4	DF0074
45	Strain gage (dowel)	EL 007-4	DF0074
46	Strain gage (dowel)	EL 007-4	DF0074
47	Strain gage (dowel)	EL 007-4	DF0074
48	Strain gage (dowel)	EL 007-4	DF0074
49	Strain gage (dowel)	SB 001-1	SD0011
50	Strain gage (dowel)	SB 001-1	SD00N
51	Strain gage (dowel)	SB 063-470	SD063N
52	Strain gage (dowel)	SB 063-470	SD063N
53	Start/stop	DNA	DNA

- (a) Block SB001 instrumented with LVDT mating with block SB005.
- (b) This instrument taken from its original location RB595-2. Block RB613-2.
- (c) This instrument interfaces with reflector block RB613-6.

TABLE 6-2
ONE-FIFTH-SCALE DOWEL FORCE TEST TRANSDUCER IDENTIFICATION

Instrument	Number	Function
Rig LVDT	1	Measure test rig displacements and provide feedback control
Core boundary transducers		
Reflector block LVDT	3	Measure reflector block displacement relative to core barrel plate. Data used to evaluate degree of core lumping and transient decay motion
Spring pack strain gages	2	Provide spring pack forces
In-core instrumentation		
Reflector block LVDT	3	Measure reflector block displacement relative to core hexagonal reflector blocks. Data used to evaluate degree of core lumping.
Core support block LVDT	2	Measure displacements between core support blocks at locations where dowel forces are measured
Eddy current sensors	12	Measure separation distance at 3 points on each of 3 interfaces of vertically adjacent fuel elements, and 1 reflector block interface.
Dowel strain gages	16	Measure (after calibration) X and Y dowel shear forces in 2 fuel elements and 2 core support blocks
Two component load cells	2	Measure dowel force on one fuel element and one permanent side reflector block
Block force strain gages	3	Measure (after calibration) fuel element collision forces, 2 locations
Block force load cells	7	Measure fuel element collision forces, 2 locations

Fig. 6-1. Rig, boundary, and in-core LVDT instrumentation

barrel plate, and strain gages calibrated to measure forces on two lateral spring packs. The locations of these instruments are shown in Fig. 6-1.

The LVDTs were employed to determine the centerline motion of the core as described in Section 9. In addition, these devices were used to record the response of the core following quick shutdown of the rig from resonance, and to determine the phase angle of the core motion with respect to the rig for estimating the overall core damping. Satisfactory core damping measurements were not achieved in previous full-array tests because the shutdown of the rig was not sufficiently rapid.

The use of two instrumented spring packs was repeated in the dowel force test to determine the loads during impact of the core with the boundary, for the new time history motion discussed in Section 7.

6.2.3. In-core Instrumentation

The in-core instrument package is shown in Fig. 6-2. Since a test objective was to record data at several core elevations and radial positions, it was more efficient and cost effective to design an instrument package with the required transducers spanning the full elevation of the core, and move this package to several radial locations within the core for repeated testing. This was accomplished by the instrument layout shown in Fig. 6-2. A group of five columns was used to hold the instruments in order to decrease the number of wires per column and hence the resistance to the block rocking motion. The instrumented columns were removed from the core using a nylon cord fastened to the bottom block in each instrumented column. The vertical distribution of the instruments was based on previous test results, rough analytical predictions of dowel forces and rocking angles, and the specific objective that data be taken at more than one elevation.

In regard to dowel forces, preliminary analysis predicted the largest values occurring near the bottom of the core, and in particular near the

Fig. 6-2. Dowel force test instrument locations

core periphery, in line with the excitation. Thus, dowel force instrumentation was located in a fuel element near the bottom of the core and in a core support block as shown in Fig. 6-2.

Results from previous 1/5-scale, full-array tests indicated that peak fuel element collision forces and boundary spring pack forces occurred near the core midheight (Ref. 7). Consequently, dowel force and block collision force instrumentation was placed in this region.

Finally, dowel force, rocking angle, and block force instrumentation was positioned in the top one-quarter of the core since this region was not instrumented in previous tests. LVDTs near the core boundary were located near this elevation to measure core centerline displacements (Section 9).

The center of the core, half-radius position, and peripheral regions on the line of rig excitation and at approximately 45° to the excitation received the fuel block instrumentation. The latter position was chosen since a circular motion of the blocks at the 45° points was visible in earlier tests; however, maximum loads were expected to occur in line with the excitation.

For each radial location shown in Fig. 6-2, the five instrumented columns rest on a common floor support block in order to avoid a gap discontinuity within the instrumented group, i.e., the gap between two columns located on the edge of adjacent floor blocks is 0.080 in. compared to 0.030 in. between columns on the same floor block.

Dowel force instrumentation was duplicated in two hexagonal core support blocks, one at the core center (SB004) and one adjacent to the periphery (SB063), instead of moving the instruments during the test. Only one instrumented block was recorded at a time. Additional dowel force instrumentation was placed in a permanent side reflector block, and this block was moved in elevation and once in column position during the test program. Table 7-1 of Section 7 identifies instrumented column positions

as well as the instrumented floor block and reflector block positions for each test in the program. Table 6-3 lists, for core position number 1, the in-core instrumentation located at each block interface in the core.

6.3. DATA ACQUISITION

All transducers used in the test operated within a 0- to 10-volt signal range. The continuous signal output from each transducer was digitally sampled by using a multiplexer circuit with a fundamental period of 5 ms. Hence, the signal from each of the 51 transducers in Table 6-1 (78 channels), plus a dc-proportional-to-signal channel and a start-stop signal channel, was recorded and stored on magnetic tape at an interval no longer than 5 ms. A Varian 600 computer was used to digitize the analog transducer data, converting voltage to digital counts at a digitization factor of 409.7 counts per volt.

Where it was determined that a particular transducer would have a high frequency response such that the 5 ms sampling period would effectively act as a filter, two methods were employed for obtaining an accurate record of the signal. This would be the case, for example, for a fuel element collision force load cell responding in as little as 0.5 ms as opposed to the rig LVDT responding to rig frequencies no larger than 20 Hz (in a time history rig input).

The first method allowed the absolute value of the peak 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 at 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 accurately determine the peak value of the transducer and the shape of the response for time intervals less than 5 ms, the transducer signal was allocated to more than one multiplexer channel, equally spaced within the cycle. Thus, a finer distribution of the transducer signal was obtained.

TABLE 6-3
INSTRUMENTED BLOCK END CONDITIONS

Block	Bottom Surface	Top Surface	Comments
SB-001	--	New dowel + soft contacts	Dowel has 3k stiffness
SB-063	--	New dowel + soft contacts	Dowel has 3k stiffness
4-1	Sockets for SB-001	Existing dowels	No dowel strain gages here
470-1	Sockets for SB-063	Existing dowels	
4-9	Existing sockets	New dowels	
4-10	New sockets	Instrumented dowels	
4-11	New sockets + FEAG	New sockets	
4-12	New dowels	Existing dowels	Dowel forces measured at 7/8
5-6	Existing sockets	New dowels	
5-7	New sockets	New sockets	
5-8	New dowels	Existing dowels	
1-5	Existing sockets	New dowels	
1-6	New sockets	New sockets	
1-7	New dowels + FEAG	New sockets	
1-8	New dowels	Existing dowel	
6-3	Existing sockets	New dowels	
6-4	New sockets	New sockets	
6-5	New dowels	Existing dowels	
7-3	Existing sockets	New dowels	
7-4	New sockets	Instrumented dowels	
7-5	New sockets + FEAG	New sockets	
7-6	New dowels	Existing dowels	
596-5	Existing sockets	Socket plate load cell + 2 sockets	
596-6	3 dowels + RBAC		

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. For example, since the stiffness of the instrumented dowels was design-controlled and the block mass was known, the element vibration period subsequent to a collision could be no smaller than 0.0058 s. Therefore, four channels were allocated to each dowel strain gage to bring the sampling period to 0.00125 s, which results in at least 4 to 5 samples per dowel vibration period.*

An additional instrument utilized to acquire data was the summing circuit by which certain signals were algebraically combined before being recorded on tape. Summed signals were also peak held in some cases. Summing circuits were employed for recording the net dowel force in both the X-axis and Y-axis directions at a given block interface, obtaining the torque transmitted to a fuel element via the dowels and obtaining the net collision force on a fuel element instrumented with several load cells in parallel.

The allocation of channels, peak holders, and summing circuits to the instruments is given in Table 6-4. The specific instrument/channel breakdown based on in-core instrument location is given in Ref. 29.

6.4. DOWEL FORCE TEST INSTRUMENTATION DESIGN

This section describes the design of the individual instruments employed in the 1/5-scale dowel force test. Instrument calibration is the topic of the next section. Figures and sketches of the instrument designs are presented. Actual detail drawings of all in-core instruments are given in Ref. 30. Design requirements for the instruments are given in Ref. 10.

* It was later determined that this low number was inadequate for accurate measurements.

TABLE 6-4
INSTRUMENT CHANNEL ALLOCATION

Signal	No. of Channels	Sample Period (s)	No. of Peak Holders	No. of Σ Circuits
Rig instrumentation	12	0.005	2 ^(a)	3
1 FE dowel bar instr.	2	0.005	2	
1 block - FEDG, 6 gages	24	0.00125		
1 block - FEDG with Σ circuit	3	0.005	3	
2 dowel gages CSFB	2	0.005	2	
1 dowel load cell SRB, 2 comp.	2	0.005	2	
1 blk - 5 load cells	5	0.005	5	
1 blk - 2 load cells	2	0.005	2	
1 blk - 2 strain gages	2	0.005	2	
1 blk, FEDB with strain gages	2	0.005	1	
9 FE pitch < sensors	18	0.0025		
3 SRB pitch < sensors	6	0.0025		
1 start/stop	1			
Total	80		21	3

(a) Peak holders for spring packs

6.4.1. Boundary Load Cells

The spring packs at locations 1-5 and 19-5 on the rig shown in Fig. 6-3 were instrumented with strain gages for measurement of the core seismic lateral boundary force. The design, shown in Fig. 6-4, consisted of a strain gage applied to the hard stop of the spring pack and calibrated for a compressive load applied by the spring pack shaft.

6.4.2. Rig, Boundary, and In-core Displacement Sensors (LVDTs)

All LVDTs for the 1/5-scale dowel force test, listed in Table 6-2, were previously employed in the 1/5-scale, full-array tests. The instruments are best described as linear displacement transducers with a range of ± 1 in. (± 3 in. for the rig LVDT), and were typically placed on the rig or recessed in permanent side reflector blocks and core support blocks for measurement of the relative deflection between adjacent core blocks. Figure 6-5 contains the instrument characteristics and a sketch of a typical application.

6.4.3. Pitch Angle and Block Uplift Instrumentation

Three eddy current displacement sensors were mounted in each of three fuel elements and one permanent side reflector block as shown in Figs. 6-6 and 6-7. The purpose of the instrumentation was to measure the vertical gaps at the top surface of the elements during seismic response of the core. Simultaneous gap measurements from three sensors at a block interface were resolved into rocking angle, rocking axis orientation and net block uplift using the subroutine ANGLES, which is described in Section 8.

Each eddy current sensor had an effective range of approximately 0.16 in., which permitted accurate pitch angle measurements up to 10° . Estimates of larger angles, which could be made by extrapolation using the measurements of the unsaturated sensors, were not necessary.

Fig. 6-3. Boundary load cell locations

Fig. 6-4. Instrumented spring pack with hard stop

Fig. 6-5. Permanent side reflector block LVDT installation

Fig. 6-6. Fuel element eddy current probe installation

Fig. 6-7. Reflector block dowel and gap sensor locations

Calibration and performance of the instruments are covered in Section 6.5. Prior to their use in the dowel force test, these transducers, along with the strain gaged dowels and block force measuring load cells, received a preliminary evaluation (Ref. 31).

6.4.4. Dowel Strain Gage Instrumentation

The baseline dowel force instrumentation consisted of three dowels equipped with strain gages and recessed into the face of a model fuel element, as shown in Figs. 6-8 and 6-9. A modified version of this design was used in two core support blocks as illustrated in Fig. 6-10.

Recessing the dowel resulted in the following advantages:

1. Adequate bending strain at the base of the dowel for horizontal shear loads in the range of interest (less than 50 lb). Hence, the gages had an adequate signal for a high signal-to-noise ratio.
2. The change in bending moment at the gages was small due to a maximum possible ± 0.125 in. excursion of the dowel shear force over the protruding end. This resulted in only a small difference (less than 10%) in strain measurement over the full range of excursion.
3. The stiffness of the dowel was not sensitive to a change in point of application of the shear load on the protruding end, satisfying the requirement for a dowel of properly scaled stiffness with respect to the prototype, as discussed below.

6.4.5. Dowel Stiffness Design

A design requirement for the dowels was that the stiffness be scaled to 1/25 of the prototype. Since earlier full-array tests showed that the motion characteristics of the core were sensitive to an across-core gap but

Fig. 6-8. Strain gaged dowel

Fig. 6-9. Fuel element dowel strain gage instrumentation

Fig. 6-10. Floor support block dowel instrumentation

not to the boundary spring pack stiffness (although the boundary forces themselves were sensitive to spring pack stiffness), it was concluded that dowel stiffness would not affect the core motion but would influence the dowel force.

Each block where dowel forces were measured had scaled dowels located at both the upper and lower surfaces. The surface configuration of each instrumented core block is given in Table 6-3.

The required dowel stiffness was achieved by first applying the cantilever beam equation,

$$l^3 = 3EI/K \quad , \quad (6-1)$$

where l = dowel effective length,
 E = dowel modulus of elasticity,
 I = dowel section modulus,
 K = desired dowel stiffness.

The effective length of the steel dowels was measured from the base of the necked-down portion to the midpoint of the exposed portion (Fig. 6-9). The section modulus was known based on the requirement for a scaled dowel diameter equal to 0.312 in.

The desired dowel stiffness was scaled using a prototype value of 200,000 lb/in. This updated value primarily resulted from use of a finite element analysis on a full-scale fuel element socket.

Since fuel and cooling hole penetrations surrounded both dowels and sockets of a full-scale block, and the dowels were glued and threaded into the block, it was estimated that both dowel and sockets deflect with similar stiffness. It followed that since the graphite model fuel elements were solid, except for a center hole, the stiffness of the model dowel

should scale (by 1/25) the combination of full-scale dowel and socket as two equal springs in series. Hence the result for the model dowel was

$$K_D = 1/25 \times 1/2 \times 200,000 = 4,000 \text{ lb/in.}$$

A test was made, referenced in the next section, confirming that only the dowels deflected sufficiently to control dowel stiffness in the model.

Equation 6-1 led to an effective dowel length of 2.16 in. However, after building a dowel to this design, it was found to be somewhat more flexible than required, probably due to lack of the proper controlled end constraint and variations in material modulus and/or machining tolerances. With some iteration, an effective length of 2.0 in. was chosen. When accounting for the upper half of the protruding end and the chamfer, a value of 2.14 in. resulted as shown in Fig. 6-9.

The core support block dowel design (Fig. 6-10), a single strain gaged dowel, had three times nominal stiffness representing the overall interface stiffness. The remaining two dowels were designed to be relatively soft and served only to maintain torsional alignment at the interface.

6.4.6. Dowel Socket Design

Figure 6-11 shows the scaled prototype socket design. This pattern was not reproduced to scale, but modified as shown in the figure. The change resulted from concern that the chamfer on the model fuel blocks might lead to a socket failure during testing at high excitation levels, and that more distance away from the block edge was necessary for location of the sockets. Rather than reinforcing the sockets with aluminum inserts, a test was performed (Ref. 32) qualifying the sockets to a minimum shear load of 225 lb, more than four times the seismic test load estimated by existing analytical codes.

Fig. 6-11. Reference and modified socket locations

The socket strength test also determined the model socket stiffness to be approximately 24,000 lb/in. This was essentially rigid in comparison to the model dowel stiffness of 4000 lb/in., therefore verifying that the dowels alone controlled the flexibility of the model dowel-socket combination.

6.4.7. Net Dowel Force and Torque Instrumentation

Strain gaging individual dowels on a fuel element permits summation of the gage signals to produce the net dowel shear force across the interface and the torque transmitted between two blocks via the dowels. These methods were used in the test on blocks where individual dowel loads were not desired, therefore saving instrument channels. Referring to Fig. 6-12, the net force and torque equations are, in terms of the strain gage signals:

$$\begin{aligned}\sum F_x &= R_{1X}S_{1X} + R_{2X}S_{2X} + R_{3X}S_{3X} \quad , \\ &= R (S_{1X} + S_{2X} + S_{3X})^* \quad ;\end{aligned}$$

$$\begin{aligned}\sum F_y &= R_{1Y}S_{1Y} + R_{2Y}S_{2Y} + R_{3Y}S_{3Y} \quad , \\ &= R (S_{1Y} + S_{2Y} + S_{3Y})^* \quad ;\end{aligned}$$

$$\begin{aligned}\sum M_z &= -0.939 R_{1Y}S_{1Y} + 0.761 (R_{2X}S_{2X} - R_{3X}S_{3X}) \quad , \\ &\quad + 0.670 (R_{2Y}S_{2Y} + R_{3Y}S_{3Y}) \quad ; \\ &= R [-0.939 S_{1Y} + 0.761 (S_{2X} - S_{3X}) + 0.670 (S_{2Y} + S_{3Y})] \quad .\end{aligned}$$

* This holds when the strain gages are of the same sensitivity and mounted in close alignment with the reference axes.

Fig. 6-12. Dowel strain gage locations, plan view

where S_{1X} , S_{2Y} , . . . are the signals from the X-axis strain gage on dowel number 1, the Y-axis strain gage on dowel number 2, . . ., and R_{1X} , R_{2Y} , . . . are the calibration constants taken in the same manner. These equations were implemented in the summing circuits referred to in Section 6.3.

6.4.8. Dowel Load Cell Instrumentation

As an alternative to the dowel strain gages, two-component, shear-sensitive load cells were arranged into a design for measuring the net dowel shear force in two directions on a model fuel element and one permanent side reflector block.

The mechanics of the Kistler Instruments Limited two-component load cell are illustrated in Ref. 33. In summary, two shear strain sensitive quartz wafer rings were contained in the unit and aligned with their sensitive axes at 90° .

The dowel load cell design in the permanent side reflector block is shown in Fig. 6-13. In this case, the load cell measures the shear force on the socket exerted by the central dowel in the mating element. As in the case of the core support block dowel design, the total interface dowel shear load is taken at this location, and the two remaining dowels have relatively low stiffness and serve only to keep the torsional alignment of the mating blocks. The central dowel stiffness was designed to have three times the stiffness of an individual fuel block dowel in order to represent the net interface dowel stiffness. Photographs of the reflector block load cell design are found in Ref. 28.

The fuel element dowel load cell design (referred to as the "dowel bar") is illustrated in Fig. 6-14. The two-component load cell is similarly used but in this case the preload plate covers the block and contains the standard socket pattern. Dowels of scaled stiffness mate with the plate, transferring loads to the cell.

Fig. 6-13. Two-component shear load cell application with permanent side reflector block

Fig. 6-14. Fuel element dowel load cell

The main advantage in the use of the dowel load cell was that it provided an alternative to the strain gage concept; however, there were disadvantages that affected its successful operation. Foremost were (1) machining complexity (the necessity for holding close tolerances and alignments for proper seating and preloading), (2) ringing during high frequency impact forces (Section 6.5.6), and (3) the relatively large weight of the finished unit. Instrumented block weights are given in Table 6-5.

It was concluded that all disadvantages of this device were attributed to its excessive size and weight compared to the graphite fuel element.

6.4.9. Fuel Element Collision Force Instrumentation

Two methods used to measure fuel element collision forces were (1) the use of strain gages mounted on internal surfaces of a block, calibrated for block impact forces, and (2) use of precalibrated load cells mounted on the side of a block behind a preload plate coated with a layer of graphite.

6.4.9.1. Block Force Strain Gage Design. The two-strain gage design illustrated in Fig. 6-15 was previously used in the 1/5-scale, full-array test; however, the results were not held with confidence because of large scatter in the calibration data. The instrument was retained for use in the dowel force test for the following reasons:

1. It was anticipated that the data from a block force strain gage mounted in the dowel bar instrument (Ref. 30) would provide a correction factor applicable to all block force strain gages by comparison of the loads from this gage with those recorded by an adjacent block equipped with load cells.
2. There was no assurance that the load cell method would ultimately be successful because it had not been used previously.

TABLE 6-5
INSTRUMENTED BLOCK WEIGHTS

Instrumented Block	Weight (lb)
Dowel strain gages, 7-4	2.390
Pitch angle sensors, 1-7	2.132
Dowel strain gages and block gages, 4-10	2.240
Dowel bar, 1-6	2.753
Block force load cells, 5-7	2.511
Pitch angle sensors, 4-11	2.181
Pitch angle sensors, 7-5	2.159
Block force load cells, 6-4	2.560

Fig. 6-15. Model fuel block with strain gages for collision force measurement

3. The design was convenient for simultaneous measurement of block forces and dowel forces on the same element.
4. The response of this instrument may be used to compare the relative intensity of the new time history forcing functions with those used previously.

The large scatter in the calibration data for this instrument was primarily due to interpreting an external impact force on the block from an internal strain measurement. Subsequent to the full-array tests, it was theorized that the size and shape of the strain wave through the block depend on the magnitude and location of the impact force, and hence the strain gage signals could vary considerably for very slight changes in the loading conditions.

Moreover, the loading condition is extended here to include the boundary restraints on the block during impact. In earlier calibration tests, different calibration factors were obtained in the case of free block impacts as opposed to backed-up impacts such as those occurring when the core blocks lump together and impact the boundary.

The use of the two-strain-gage design shown in Fig. 6-15 provides no direct information to distinguish which of the two kinds of impacts has occurred, and therefore which of two calibration curves apply for determination of the force. However, earlier full-array tests demonstrated that long duration impacts, on the order of 0.01 to 0.05 s, were associated with a lumped core boundary collision and that short duration impacts, on the order of one sampling period (0.005 s) or less, are most probably free impacts between two fuel elements. Although exceptions could always be postulated, it was believed that these trends were sufficient to predict the appropriate calibration curve for the data.

6.4.9.2. Block Force Load Cell Design. Two model fuel elements were designed to accommodate load cells for direct measurement of block

collision forces on one surface. The advantages of this design were as follows:

1. In this application, the load cells are precalibrated and measure force directly, regardless of the impact configuration. This statement depends on results of tests to confirm the precalibrated behavior of the individual load cells, as explained in Section 6.5.
2. Information can be obtained about the orientation of the applied impact.

Two applications of load cells for block force measurement are illustrated in Fig. 6-16. In each case, part of the block is machined away and the load cells are mounted and preloaded by a plate covered with a 1/8-in.-thick graphite slab. The purpose of the slab was to restore the proper impacting surface material.

The two-load-cell block contained Kistler number 903A load washers, which were 1.1 in. in diameter. Theoretically, this device identifies impacts misaligned about the pitch axis of the block, and measures the total force on the block, which was equal to the instantaneous sum of the two load cell measurements.

Use of the peak holding circuit described in Section 6.3, however, complicated interpretation of the collision forces having a duration of less than 5 ms. Since the circuit records and holds the absolute value of the signal obtained at some point within the sampling period, definition of the signal within the period was lost.

It was determined during calibration and from analog records during previous tests that with blocks that are slightly misaligned during the impact event, the process often proceeds as follows: (1) significant loads are delivered to the top and bottom load cells, (2) there is a small time

lag between these loadings, and (3) the whole process occurs in less than 1 or 2 ms. In this case, the peak load on the block is equal to the (largest) load on one load cell, which is in contrast to a flat hit where the total block load is equal to the sum of the forces on the individual load cells.

This discrepancy was resolved on the five-load-cell block by applying a special summing circuit to the load cell signals which, in addition to retaining the individual (peak held) signals, records the instantaneous sum of the load cell signals on a separate peak held channel. Comparison of this sum to the individual load cell response during the impact allows interpretation of the impact orientation in most cases.*

All previous discussion on block force load cell operation applies to the five-load-cell design, which was equipped with the summing device discussed above. This instrumented block was incorporated into the test when finite element analyses predicted fuel block edge and corner loads to be the controlling design loads.

During the design of this instrumented block, the Kistler No. 9001 load cell became available. Being only 0.380 in. in diameter, it allowed practical design for measuring block corner forces as depicted in Fig. 6-16. One additional load cell (Kistler 901A) was positioned in the center of the block face to stiffen the preload plate and eliminate plate resonance during impact. As explained in Section 9.6, the center load cell was instrumental in distinguishing flat hits from corner and edge hits.

Instrumenting for corner and edge loads on a fuel block represents a minor deviation from the basic test objective of obtaining data solely for correlation of the analytical codes. The relative magnitudes of the corner, edge, and flat impacts, and their number associated with a particular earthquake excitation, were useful in determining fatigue usage

* One additional problem in the interpretation of impact orientation is associated with the spacing of the summing channel relative to the individual load cell channels and is discussed in Section 9.6.

FIVE-LOAD-CELL BLOCK

TWO-LOAD-CELL BLOCK

Fig. 6-16. Block load cell instrumentation

factors for the fuel blocks and as a guide for the proper impact orientations imposed in full-scale fuel block fatigue failure tests.

The same reasoning applies to the use of individual versus overall X-axis and Y-axis dowel force instruments discussed in Sections 6.4.4 and 6.4.7.

6.4.10. Instrumented Block Parameters

Since it was desirable to correlate with data from a model most accurately representing the ideal scale, the instrumented blocks were designed to conform to the scaling laws where possible. Therefore, perforations were made in the blocks to lower their weight toward the properly scaled value of 2.07 lb, and post-tests were conducted to verify the properly scaled values of coefficient of restitution and impact duration. The results of these tests are given in Ref. 34.

6.5. INSTRUMENT CALIBRATION

The test specification (Ref. 10) presents all instrument calibration requirements. The contractor documents (Refs. 35-39) contain calibration procedures. Reference 40 contains calibration data and an evaluation of the results.

The scope of this section is to present the purpose of calibration tests as described in the above references and supplement the discussion of calibration results presented in Ref. 40.

6.5.1. Nominal Calibration Factors

The final objective in calibration was to determine a factor which, when multiplied by the recorded data in counts (Section 6.3), gave the transducer response in the correct engineering units (EU). Hence, calibration factors have so many EU per count.

Various methods of instrument calibration are discussed in the following sections. For each method and for each transducer, the test laboratory established a linear nominal calibration factor that was documented in a log associated with each test in the program (Ref. 41). For a transducer yielding a nonlinear voltage output to a calibrated input, the calibration factor in the test log would typically be the tangent to the curve at the origin.

For the displacement LVDTs yielding linear calibration data (constant slope) and block force load cells where the manufacturers calibration factor was used,* the test log value was used to reduce the digital data. Variations in these factors from test to test in the program are due to changing the transducer sensitivity by way of the transducer amplifier gain in order to keep the instrument from saturating during the test. Saturation occurs when the measured transducer response reaches 4097 counts since the data acquisition system has a total range of 0 to 10 V, or 4097 counts.

From Ref. 30, the overall channel sensitivity, which is equal to the nominal calibration factor, is defined by the equation

$$NCF = \frac{1}{\text{Transducer Sensitivity} \left(\frac{V}{EU} \right) \times \text{Channel Gain} \left(\frac{\text{Counts}}{V} \right) \times G_S}, \quad (6-2)$$

where G_S = gain of the signal conditioning filter presented in the LVDT circuits (= 0.746); otherwise G_S is unity.

The gain G_S was included in the equation to derive the nominal calibration factor (NCF) given by the test lab. However, interpretation of the end-to-end calibration procedure described in Ref. 40 indicates that the gain was already absorbed into the transducer sensitivity. The rig LVDT measurements were finally resolved by the measurement of the oscillograph data as discussed in Section 10.4.

* Load cells were subjected to dynamic verification, which resulted in new factors in some cases as explained later.

6.5.2. New Calibration Factors

For the transducers exhibiting either nonlinear calibration data or generally linear data with significant scatter, as determined by the calibration techniques discussed in the following sections, calibration factors more accurate than the linear nominal were used to reduce the test data. The two separate techniques used were:

1. For the eddy current probes statically calibrated in plus and minus block rocking, and uplift, the -X-axis rocking calibration data, representing a median, was input to the unit conversion program DATAT (Section 8.1) in tabular form in place of the constant value given in the test log.
2. For the force transducers having significant scatter in the calibration data, a straight line RMS fit was performed and the equation of this line used to reconvert the data in engineering units using program NEWTEN (Section 8.2).

Details of the calibration methods for all transducers are given in the following sections.

6.5.3. Static Versus Dynamic Calibration

While setting calibration requirements and in calibrating the instruments, it was determined that significant variations in the data resulted depending on whether a static or dynamic input was used. Two separate phenomena were postulated for this occurrence:

1. Amplification of the dynamic input by the instrument structure.
2. Distortion of the transient output signal by the instrument electronics.

In each case, the amount of amplification or distortion depended on the frequency response of the component. For nearly all the instruments, the structural natural frequencies were high compared to the load input frequencies, and the frequency range of the signal amplifiers exceeded the expected frequency of the instrument response. Special considerations for dynamic calibration are discussed below as they apply to the particular instruments.

6.5.4. Displacement LVDT and Spring Pack Load Cells

The LVDT instrumentation was statically recalibrated after prior use in the 1/5-scale, full-array tests. The boundary force transducers were calibrated by loading with a hydraulic oscillator at a relatively low frequency. Since no impacts occurred with this method, it was classified as a static calibration.

6.5.5. Eddy Current Probe Calibration

The eddy current probes were statically calibrated in each of the following displacement modes:

1. +X-axis rocking
2. -X-axis rocking
3. Uplift

Rocking calibration modes are shown in Fig. 6-17. Calibration was performed by recording the voltage output of the probes for increments of elevation G in the figure. The calibration data in Figs. 6-18 through 6-22 were determined from dimension G and the probe locations. The remainder of the data are given in Ref. 40.

Fig. 6-17. Eddy current probe calibration modes

GAP	+X VOLTS	GAP	-X VOLTS	GAP	UPLIFT VOLTS
.0079	-.09	+.037	-2.22	0	-.09
.016	-.48	.073	-4.56	-.01	-.34
.024	-.99	.110	-6.00	.02	-1.15
.031	-1.59	.146	-6.78	.04	-2.74
.039	-2.13	.183	-7.14	.06	-4.20
.047	-2.68	.219	-7.32	.08	-5.20
.055	-3.22	.255	-7.40	.10	-6.00
.062	-3.70	.291	-7.45	.12	-6.55
.070	-3.99	.327	-7.47	.14	-6.91
.074	-4.18	.344	-7.48	.16	-7.13
				.18	-7.27
				.20	-7.37

Fig. 6-18. Calibration of ECP No. 7307, FE 001-7, position 1

GAP	+X VOLTS	GAP	-X VOLTS	GAP	UPLIFT VOLTS
.033	-2.71	.014	-1.36	0	-0.61
.067	-4.88	.029	-2.31	.01	-1.36
.100	-6.87	.043	-3.30	.02	-2.10
.133	-7.35	.057	-4.03	.04	-3.48
.166	-7.89	.071	-4.96	.06	-4.82
.199	-8.15	.086	-5.56	.08	-5.93
.232	-8.28	.100	-6.26	.10	-6.81
.264	-8.36	.114	-6.73	.12	-7.38
.296	-8.38	.128	-7.39	.14	-7.79
.312	-8.41	.135	-7.52	.16	-8.04
				.18	-8.18
				.20	-8.28

Fig. 6-19. Calibration of ECP No. 7308, FE 001-7, position 2

GAP	+X VOLTS	GAP	-X VOLTS	GAP	UPLIFT VOLTS
0	-8.8	0	-8.3	0	-9.2
.033	-2.99	.014	-1.81	.01	-1.68
.067	-5.16	.029	-2.77	.02	-2.36
.100	-6.55	.043	-3.17	.04	-3.74
.133	-7.42	.057	-4.56	.06	-5.11
.166	-7.87	.071	-5.44	.08	-6.15
.199	-8.11	.086	-6.00	.10	-6.92
.232	-8.22	.100	-6.66	.12	-7.46
.264	-8.28	.114	-7.14	.14	-7.84
.296	-8.31	.128	-7.34	.16	-8.05
.312	-8.32	.135	-7.59	.18	-8.18
				.20	-8.27

Fig. 6-20. Calibration of ECP No. 7309, FE 001-7, position 3

GAP	+X VOLTS	GAP	-X VOLTS	GAP	UPLIFT VOLTS
0	-1.02	0	-1.03	0	-1.00
.0079	-1.45	.037	-3.59	.01	-1.89
.016	-1.98	.073	-5.58	.02	-2.50
.024	-2.50	.110	-6.81	.04	-3.86
.031	-3.10	.146	-7.39	.06	-5.09
.039	-3.51	.183	-7.70	.08	-6.04
.047	-4.02	.219	-7.81	.100	-6.72
.055	-4.57	.255	-7.88	.120	-7.19
.062	-4.90	.291	-7.91	.140	-7.48
.070	-5.22	.327	-7.93	.160	-7.67
.074	-5.57	.344	-7.93	.180	-7.79
				.200	-7.86

Fig. 6-21. Calibration of ECP No. 7310, FE 004-11, position 1

6-47

GAP	+X VOLTS	GAP	-X VOLTS	GAP	UPLIFT VOLTS
0	-1.00	0	-1.03	0	-1.03
.033	-3.17	.014	-2.00	.01	-1.80
.067	-5.21	.029	-2.96	.02	-2.65
.100	-6.58	.043	-3.87	.04	-4.10
.133	-7.58	.057	-4.73	.06	-5.32
.166	-7.79	.071	-5.43	.08	-6.31
.199	-7.97	.086	-6.20	.10	-6.99
.232	-8.08	.100	-6.49	.12	-7.45
.264	-8.12	.114	-7.02	.14	-7.75
.296	-8.15	.128	-7.16	.16	-7.91
.312	-8.16	.135	-7.50	.18	-8.02
				.20	-8.09

Fig. 6-22. Calibration of ECP No. 7311, FE 004-11, position 2

Because the rocking angles reached in calibration did not exceed 10° , the difference between uplift and angular mode data lies within 20%. Examination of the data and probe locations resulted in the following observations:

1. For a given gap, an inclined surface below a probe tends to decrease its output voltage.
2. For eddy current probe (ECP) No. 1, the largest effect of rocking angle on output occurs during a positive X-axis rotation (Figs. 6-18 and 6-21). This occurs because it lies close to the rocking axis and undergoes the largest rotation per unit displacement.
3. When the probes are located away from the rocking axis, the data approximates an uplift calibration because a relatively small angle occurs up to saturation.
4. The rocking mode data converge to the uplift mode data as the rocking angle decreases.

Because rocking angle response with little or no uplift was expected in the test due to the horizontal excitation, the -X-axis rocking data were used for reducing the data. For probes No. 7307 and No. 7310, the +X-axis rocking data were incorporated to reduce the test data because the knee of the curve, when unaccounted for, caused obvious errors in the rocking angle and uplift data during +X-axis rocking.

6.5.6. Dowel Strain Gage Calibration

Static calibration was specified for the dowel strain gages (Ref. 10) because no structural amplification of the input load could occur during test. This conclusion was based on a cantilevered dowel natural frequency of 1100 Hz compared to a maximum dowel-fuel element natural frequency (one block and six active dowels) of 330 Hz. It was desirable, however, to

verify the fuel element dowel strain gage calibration with a dynamically applied load. The method and results of the static calibration and dynamic verification tests are described below.

6.5.6.1. Dowel Strain Gage Static Calibration. Static calibration of all strain gaged dowels was performed by clamping the block and hanging calibrated weights from the midpoint of the protruding end as shown in Fig. 6-23. The calibration data for all dowels are given in Ref. 40, and the data for dowel pin 1 of fuel element 007-4 are plotted in Fig. 6-24. During the procedure, all dowel strain gage amplifiers were adjusted for a calibration constant of 0.2 V/lb, resulting in saturation voltage at a load of 50 lb.

Although the dowel strain gages were not generally mounted exactly in line with the reference XY-axes, the cross-axis calibration constants that result from this misalignment can be used to accurately determine the gage orientation. Although accurate alignment was not absolutely necessary for reducing dowel forces, it simplified and reduced error in the reduction, and eliminated the need for feedback loop circuitry in the data acquisition hardware.

As a guide to setting dowel strain gage alignment tolerances in future tests, Ref. 30 gives the method for determining gage orientation and the dowel force data reduction equations using calibration data from this test.

For each dowel strain gage utilized in the test, the alignment was sufficient to neglect the cross-axis terms, yielding the single static calibration factor of 0.2 V/lb.

6.5.6.2. Dowel Strain Gage Dynamic Verification. Dynamic loads were applied to strain gaged dowels on two fuel elements as shown in Figs. 6-25 and 6-26. Load conditions are summarized in Table 6-6.

These loads were specified to test the high and low ends of the expected load range (0 to 50 lb) for two separate loading frequencies.

Fig. 6-23. Fuel element dowel static calibration

Fig. 6-24. Static calibration, pin no. 1, FE 007-4

Fig. 6-25. Dynamic load verification of dowel strain gages

Fig. 6-26. Dowel strain gage dynamic loading

TABLE 6-6
INSTRUMENTED DOWEL DYNAMIC LOAD CONDITIONS

Peak Load (lb)	Half-Sine Pulse Duration (s)
10	0.050
10	0.004
40	0.05
40	0.004

The 0.05 s pulse simulated a compression load occurring when the core lumps together and impacts the boundary, as observed from previous full-array data. The 0.004 s load pulse corresponds to an impact load from an adjacent block, assuming the restraint of two dowels at the lower and upper surface.

The required load levels were achieved in calibration by adjustment of the pendulum mass shown in Fig. 6-25. Application of an impact medium to the transfer bar, such as a sheet of rubber or paper, permitted adjustment of the load duration.

The results of the dowel strain gage dynamic verification are shown in Figs. 6-27 and 6-28. For each of the two blocks tested, dynamic loading resulted in a calibration factor (in pounds per volt) 25% lower than for static loading.

Before plotting in the figures, the raw calibration data in Ref. 40 were adjusted to account for the inaccuracy of the pendulum load cells at the 50 ms load duration, which originated from the low frequency response characteristic of Endevco Corporation charge amplifier No. 4477.2. The remaining difference in results for static and dynamic loading was attributed to hysteresis deformation in the strain gage loading material.

The following excerpt from Ref. 40 gives a more detailed description.

The response of the strain gauges seems to indicate that the gauges have greater sensitivity (more output voltage per unit load), under dynamic load conditions than under static load (calibration) conditions. This dynamic amplification is nominally about 40 percent and at first brush would imply that the data should be adjusted downward to compensate for this amplification. Several factors, however, argue for utilization of the static calibration sensitivity (without adjustment). Study of the pictures representing the input load and output response for the longer duration, approximately 50 ms, dynamic loads (Fig. 6-29A) suggests at least a partial accounting for the apparent amplification. This was found to be a consistent pattern illustrating two of the factors mentioned above.

Fig. 6-27. Fuel element 004-10 dowel strain gage dynamic calibration

Fig. 6-28. Fuel element 007-4 dowel strain gage dynamic calibration

First, the load cell response (input load), exhibits an "undershoot" (negative direction load) which cannot be easily explained from the test fixture (parallel pendulum) which was designed to apply only unidirectional loads. This type of undershoot waveform is, however, characteristic of the charge amplifier electronics when a long duration pulse is applied.* The undershoots have significant magnitudes (typical between 20% and 30% of the magnitude of the primary pulse on the input load cell), and on these long duration pulses are responsible, in part, for both understating the input load, and therefore, overstating the "amplification." As a "rule of thumb" approximately 50% of the undershoot should be added to the primary pulse amplitude to properly reflect the actual applied load.

The second factor illustrated in these pictures is that the strain gauge output also exhibits an undershoot. The conclusion easily jumped to is that it is merely following the input, but as explained above, there is no capability for negative load application. The next easy conclusion is that the dowel is simply "ringing." This conclusion cannot be substantiated because the natural period of the dowel is approximately one millisecond and the undershoot period, as shown in the figure, is about 50 - 100 milliseconds. The test program did not allow indepth testing to prove the following hypothesized source of this strain gauge dowel undershoot, but it appears that some plastic deforming is occurring (perhaps in the strain gauge bonding material) which has a stretch/contract period approximately 50 ms. On long duration pulses the stretching has time to occur; and the strain gauge output value closely corresponds to the static calibration. On short duration pulses (Fig. 6-29B) the material does not have time to stretch and an additional strain is placed on the gauge. It exhibits an output which is larger than that produced under long-term steady-state loading. Upon load release from long duration loads (when the material has had time to stretch) an apparent negative load is created (due to the stretch), until the material has contracted to its original position. The above hypothesized characteristic can, in part, explain the overstatement of the output load (strain gauge output "amplification") for the short duration pulses.

Although the test lab concluded that the conservative static calibration data should be used in data reduction, the procedure followed was to accept the dynamic calibration on the basis that it more nearly approximated the test loads, being dynamic in nature, and was valid because it was obtained under controlled conditions. Furthermore, the actual calibration curve was calculated by a least squares fit to the data, and the standard deviation of the data fit was calculated in order to give a statistical basis from which an overall error analysis of the test results could be performed, as described in Section 10.

* For background on these shock measurement undershoots, refer to Piezoelectric Accelerometer Manual, by Dale Pennington, Environmental Publications, Inc., 1963, and Ref. 42.

The equations of the least squares calibration lines are shown in the figures along with the standard deviation of the line with respect to the data field. The equations are valid for all dowel loads in the 3 to 50 ms duration range. The equation for block 004-10 was also applied to the floor block dowels, which did not receive a separate verification, on the basis that the six fuel dynamic element dowels that were tested established the dynamic behavior of the gages as being characteristic of this instrument design.

6.5.6.3. Summing Circuit Calibration Factor. Data acquisition circuitry for fuel element 007-4 contained a circuit to sum up the strain gage signals for the net X- and Y-axis dowel forces and the dowel moment about the Z-axis.* The calibration factor NCF in Eq. 6-2 for net dowel force, assigned by the test lab, was 0.0667 V/lb, or the reciprocal of the sum of static factors (5 lb/V) for the three gages. Performing the same operation on the dynamic calibration factor results in

$$\text{NCF} \Big|_{007-4 \text{ Dowels}} = 0.00866 L + 0.296 \text{ (lb)} \quad .$$

This factor was employed to reduce dowel forces on block 007-4 as explained in Section 6.5.2.

6.5.6.4. Block Strain Gage Coupling. During dynamic verification testing of the dowels on block FE 004-10, a check was made on the response of the top block strain gage (Fig. 29). A relatively large strain response of this gage from the reaction moment at the base of the dowels would introduce error in the reduction of block forces when dowel forces were acting simultaneously. Reference 10 specifies that the block force gages shall be insensitive to dowel load.

The largest block gage response measured in dowel gage calibration is shown in Fig. 6-30. From the free swing calibration data for this gage (Fig. 6-31) (giving the largest calibration factor), the apparent load in

* In subsequent data reduction, it was found that the moment data were obtained incorrectly.

LOAD CELL INPUT LOAD
(6 lb/cm)

STRAIN GAGE OUTPUT
(10 lb/cm)

A. TYPICAL LONG DURATION (50 ms) PULSE

LOAD CELL INPUT LOAD
(6 lb/cm)

STRAIN GAGE OUTPUT
(10 lb/cm)

B. TYPICAL SHORT DURATION (4 ms) PULSE

Fig. 6-29. Dowel strain gage dynamic load response

Fig. 6-30. Illustration of block strain gage response to a dynamic dowel load

Fig. 6-31. Block force strain gage calibration data, FE 004-10, free impact

the gage was estimated to be about 15 lb for this case. Since this load is less than 5% of the range expected during test, it was concluded that the gage coupling was not a significant error source for block impact loads. Because the dowel strain gages were effectively isolated from the block, it was assumed that the dowel gages would not respond to a block collision force input.

6.5.7. Two-Component Load Cell Verification

Dynamic load verification tests were performed on fuel element and reflector block load cells measuring two components of dowel force as illustrated in Figs. 6-32 and 6-33. By mounting a Kistler load washer on the loading pendulum (Fig. 6-32), an accurate measurement of the transient input load was made. Comparison of this load with that of the dowel load cells for the impact conditions of Tables 6-7 and 6-8 constituted the verification testing and provided a check for defective hardware (load cells or circuitry) and for load cell installation errors. These errors, cited by the load cell manufacturer,^{*} were postulated assuming improper preloading or application of an overturning moment.

Results of the tests are summarized graphically in Figs. 6-34 through 6-37, and complete data are contained in Ref. 40. These figures show that the manufacturer's calibration constant of 0.00833 V/lb was not actually achieved for the dowel load cells.

During impact by the loading pendulum, more voltage response was measured for the fuel element dowel load cell than for the load cells on the pendulum. It was believed that the discrepancy is due to nonuniform preloading of the dowel load cell and/or the overturning moment applied by the transfer plate rather than the misalignment problem noted by the test lab in Ref. 40. The reason for this conclusion was that there were no apparent misalignment problems in similar testing described in Section

^{*}This concern is discussed again in Section 6.5.9 as it applies to block force load cell verification.

Fig. 6-32. Test setup for two-component load cell verification, fuel element

Fig. 6-33. Test setup for two-component load cell verification, reflector block

TABLE 6-7
FUEL ELEMENT DOWEL LOAD CELL DYNAMIC LOADING

Peak Input Load (lb)	Pulse Duration (ms)
10	1.0
20	10.0
50	1.0
50	10.0
125	0.5
125	5.0

TABLE 6-8
REFLECTOR BLOCK DOWEL LOAD CELL DYNAMIC LOADING

Peak Input Load (lb)	Pulse Duration (ms)
20	20
100	50
100	2

Fig. 6-34. Fuel element X-axis dowel load cell dynamic load verification

Fig. 6-35. Fuel element Y-axis dowel load cell dynamic load verification

Fig. 6-36. Reflector block X-axis dowel load cell dynamic load verification

Fig. 6-37. Reflector block Y-axis dowel load cell dynamic load verification

6.5.6, and there was doubt that a small misalignment, if present, could cause this much discrepancy. Furthermore, the data of Ref. 40 show more discrepancy and crosstalk at shorter impact durations, suggesting a resonance effect, possibly in the load cell and preloading structures. It was also concluded that the pendulum load cell was functioning properly, since it was not subject to overturning moments, and that it had functioned accurately in the other calibration tests (Sections 6.5.6 and 6.5.9).

The calibration results in Figs. 6-34 and 6-35 indicate that more conservative results were obtained using the precalibrated value for the load cell; however, the position taken here was that dynamic calibration of the actual instrument under controlled conditions represents the best estimate of instrument response.

Overall correlation of the input and dowel load cells was slightly better for the reflector block, as shown in Figs. 6-36 and 6-37, although more crosstalk was obtained for Y-axis loading and, in general, less response was obtained for the dowel load cell.

No firm explanation was available for the fundamental difference in behavior between the fuel element and reflector block dowel load cells, but it could be a matter of the specific nonuniformity in the preloading. Perhaps interchanging load cells between fuel element and reflector blocks and retesting would have provided some basis for an explanation.

6.5.8. Block Force Strain Gage Calibration

Strain gages were installed in two fuel elements to measure block collision forces. In fuel element 004-10, a gage was attached near each end of the block; in fuel element 001-6, only one strain gage was mounted near the lower end of the block.

The purpose of the single gage was to provide collision force data which, in comparison to that from an adjacent block instrumented with load

cells, could be used to correct the calibration factor of the remaining block strain gages for loading on all block faces during core lumping.

6.5.8.1. Fuel Element With Two Strain Gages. Fully restrained and free surface impact calibration was performed as illustrated in Figs. 6-38 and 6-39 for loads up to 600 lb in 50 lb increments. The impact duration was in the range of 0.0003 s to 0.001 s for each restraint case. This range did not include the longer duration achieved during core boundary impact because calibration of similar strain gage instruments in the 1/5-scale, full-array tests indicated that larger impact durations (for the same restraint case) had little or no effect on the gage calibration constant.

A four-channel oscilloscope was used to display the response of each block strain gage and pendulum (input) load cell. Photographs of the response during an impact constituted a calibration point by comparing the upper and lower gage records with the upper and lower pendulum load cell records.

The final calibration data are given in Ref. 40 and plotted in Figs. 6-40 and 6-31 for the compression and free impact cases, respectively.

When the compression calibration was begun, large data scatter was reported. After reviewing the data, it was observed that the dispersion was associated with impacts misaligned with respect to pitch angle, showing up as a noticeable time lag between the lower and upper load cells and strain gages.

At this time, it was decided to admit data only from flat, or nearly flat, impacts in order to establish a reference calibration. For the restrained configuration, this was particularly appropriate because this orientation corresponds to a lumped core where interelement gaps are closed. The criterion for a flat hit was that the time lag between the peak response of the upper and lower pendulum load cells during an impact be within 10% of the pulse width, as shown in Fig. 6-41. The structural

Fig. 6-38. Block strain gage calibration method, compression

Fig. 6-39. Block strain gage calibration method, free impact

Fig. 6-40. Block force strain gage calibration data, FE 004-10, compression

Fig. 6-41. Flat hit criterion for block strain gage calibration

soundness of the calibration rig permitted fine adjustment of the pendulum orientation at impact and consistent results were obtained. By holding a sheet of paper between the pendulum and block and observing the graphite markings after impact, it was determined that virtually no misalignment occurred due to torsional rotation of the pendulum.

The compression calibration factor was determined by a single least squares fit to all the data points from both gages because this curve had a smaller standard deviation (13%) with respect to any data point than a separate least squares fit of the top and bottom gage data, and was therefore statistically better. One calibration curve applied to both gages also simplified data reduction.

Free swing calibration of the two-strain-gage block was more difficult because the impact orientation could not be finely controlled with respect to pitch or torsional rotation. This made it impossible to impose the flat hit criterion used for compression calibration. Therefore, larger scatter of data resulted as shown in Fig. 6-31. Since similar block impact occurs in testing, the scatter represents a measure of the error for the free impact loads as treated in Section 10. On the basis of these tests, however, it was concluded that the large data scatter disqualified the instrument design for future use in core seismic testing.

6.5.8.2. Calibration of Fuel Element with One Strain Gage

6.5.8.2.1. Gage Calibration. The strain gage in the lower end of the dowel bar element, FE001-6, was calibrated for fully restrained and free impact loadings. This gage was particularly difficult to calibrate primarily because of its eccentric mass center, which tended to rotate the block during impact, and the additional strain wave reflection surfaces in the block near the dowel load cell preloading hardware. It was believed that both factors contributed to the large data scatter originally encountered in calibration for each restraint case.

After reviewing the data, it was decided to calibrate the gage using only those impacts where the lower end of the block received initial pendulum loading. Additional testing with this procedure removed much of the scatter shown in Fig. 6-42. However, large scatter and gage insensitivity to the input load was observed for load levels exceeding about 375 lb. Test loads obtained beyond this level should be disregarded.

As in the case of the calibration data for the block containing two strain gages, a straight line least squares fit was made with the result that a single curve fit to all the data was a better statistical approximation than separately fitting the compression and free impact data.

6.5.8.2.2. Dowel Bar Cross Coupling. During strain gage calibration of block FE001-6, the dowel load cell output in line with the pendulum load was displayed. For collision loads having a duration greater than 0.5 ms, the dowel loads (resulting from the preload plate inertia) were less than 6 lb. For impact durations less than 0.5 ms, the dowel load reached a value of 12 lb, which was about 25% of the expected test load range. This high frequency response of the dowel load cell tends to confirm the resonance noted during dowel load cell dynamic verification.

6.5.9. Block Force Load Cell Dynamic Verification

The final phase of instrument calibration was to verify that the block load cell instrumentation accurately measured dynamic collision forces. Two separate tests were performed on the two-load-cell block, FE006-6, and the five-load-cell block, FE005-7 (Fig. 6-30).

The initial tests were set up for flat hits on the pendulum with a pulse of approximately 150 lb for 1 ms. A four-channel oscilloscope was used to display the results.

For the two-load-cell block, the response of each block and pendulum load cell was displayed and photographed. The criterion for verification was that, at the time of peak response, the sum of the block load cells

Fig. 6-42. Dowel bar block strain gage calibration

(output) be within 5% of the sum of the pendulum load cells (input). The tests were repeated until a very accurate flat hit was obtained, having no time lag between peak response of the two pendulum load cells. No time lag was expected nor was it found to occur between the output and input load cells, indicating negligible effect of the preload plate inertia.

For the five-load-cell block, the two pendulum load-cell signals were summed into one channel of the oscilloscope, and the remaining three channels were allocated to the block load cells by summing the top pair, center, and bottom pair of load cells, respectively. The previous criterion of agreement to within 5% was again imposed.

The results of the flat hit tests for the two blocks are given in Table 6-9. Good correlation was obtained since the total output from the two-load-cell block differed from the input load by only 3% to 15%, while for the five-load-cell block the difference was in the range of 3% to 6%. The larger deviations are believed due to lack of achieving a flat hit.

A second verification test was performed as shown in Fig. 6-43. The loading pendulum was modified to carry a single Kistler load cell behind a spherically shaped preload plate. This ensured uniform preload, as prescribed, and an impact force directed along the load cell centerline, which was positioned 0.1 in. below the edge of the fuel element preload plate. Using the same impact duration, the tests were conducted to verify the response of the load cell design for loading similar to that which occurs during edge or corner loads. This was a concern in development of the load cell applications inasmuch as the manufacturer took the position that, unless concentric loads were applied to the cells, an indefinite error may result. Similar statements were made regarding the two-component load cells in Section 6.5.6.

As a result of this information, individual load washers were tested in a separate study to verify their accuracy under eccentric loads similar to what would probably occur in core testing. The test consisted of comparing the output of two load cells during the same impact, one loaded

TABLE 6-9
BLOCK LOAD CELL DYNAMIC VERIFICATION

A. FE 006-4 (2 Load Cells)

Impact Type	Pendulum Load Cells (Input)			Block Load Cells		
	Top (lb)	Bottom (lb)	Σ (lb)	Top (lb)	Bottom (lb)	Σ (lb)
Flat	147	188	335	144	182	326
Flat	162	156	318	144	150	294
Flat	156	146	302	126	132	258
Flat	156	156	312	132	144	276
Point ^(a)	144		144	146	-23	123
Point ^(a)	144		144	156	-19	137
Point ^(a)	144		144	156	-19	137

B. FE 005-7 (5 Load Cells)

Impact Type	Input (lb)	Output (lb)		
		Σ Top LC	Center LC	Σ Bottom LC
Flat	145	36	90	24
Flat	144	42	84	27
		Top Left ^(b) LC	Center ^(b) LC	Top Right ^(b) LC
Point ^(a)	151	84	-11	
Point ^(a)	152	72	-11	84
				72

(a) Point impact in center of block face 0.1 inch below top edge.

(b) Bottom load cell load approximately 0.

Fig. 6-43. Load cell block edge loading verification

concentrically while the other was loaded eccentrically. The method is illustrated in Fig. 6-44. The results, not documented here, showed essentially no difference in response. A reference test was also performed as shown to establish the relative performance of the two units under identical concentric loading.

Results of the offset pendulum tests of Fig. 6-43 are also given in Table 6-9. Again, good correlation between input and output was achieved lending high confidence in the use of these instruments regardless of the orientation of the impinging load. Overall, the data show a 6% one-sigma standard deviation between input and output for the two-load-cell block and a deviation of about 2% for the five-load-cell block.

As a final point of interest, negative load cell reactions were properly registered for the eccentric load cases as shown in the table. These loads were necessary to balance the moment of the input edge load. Using the load cell locations and preload plate dimensions shown in the sketch below, the data in run number 3 of Table 6-9 predicted the contact point of the input load to be 0.27 in. from the edge, as opposed to 0.1 in.

$$\Delta = \left(0.82 - \frac{19.2 \times 4.12}{144} \right) = 0.27 \text{ in. (versus 0.10 in.)}$$

This calculation demonstrates that in applications where continuous output is obtained from the load cells, this instrument may be used to calculate the impact point with good accuracy; however, added complications for interpreting impact point or block orientation at impact arise with the use of signal peak holders in the data acquisition system as previously discussed in Section 6.4.

Fig. 6-44. Load cell testing for eccentric load response

7. TEST PLAN AND RIG EXCITATION

The core model was tested using a series of sine sweeps, sine dwells, and displacement time histories. Tests for core damping were also performed by measuring the free vibration decay of the core from resonance. In these tests, an automatic shutdown circuit was employed to stop the rig oscillation within a very short time interval to avoid the problems encountered with manual rig shutdown as used in the previous full-array test program. Another estimate of core damping was subsequently made by constructing a plot of the phase angle of the core with respect to the rig displacement during a sine sweep.

Before beginning the dowel force test program, the NRC published new seismic response spectra for use in the seismic design of all seismic category 1 components (Ref. 1). These requirements were satisfied by requiring that the spectra of the displacement time history input waveforms envelop the regulatory design spectra.

The complete test plan, showing rig excitation, input intensity, and instrument location, is given in Table 7-1. Details of the rig motion are given in the following sections.

7.1. SINE SWEEP EXCITATION

Following the course of previous full-array tests, sine sweeps were defined in the range of 1.6 to 10 to 1.6 Hz (sweep-up and sweep-down), which was sufficient to cover all core resonance conditions. Since the effect of g-level was measured in earlier tests, this parameter was held constant at 0.5 g.

TABLE 7-1
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.

7.2. SINE DWELL EXCITATION

The purpose of the sine dwell tests was to measure the overall core decay motion from a particular resonance condition. The dwell frequencies coincided with the core resonances, which were previously measured and specified in Table 7-1.

Because the core response was nonlinear, described in its simplest mode as vibration of a lumped mass between bilinear springs located across a gap, the maximum (resonant) response can be obtained only by sweeping up to the dwell at the resonant frequency. Instead of performing the sweeps at constant g -level, as specified in Ref. 10, the test laboratory performed constant amplitude sweeps, which were later accepted on the basis that the correct resonant frequencies were in fact achieved.

The specified sweep, dwell, and shutdown sequence is shown in Fig. 7-1. After resonance was established for approximately five cycles, the shutdown sequence was initiated manually, triggering the rig shutdown device to stop the rig when the shaker arm reached the bottom of its stroke. The data obtained from the test was made up of four boundary LVDT records describing the transient core decay motion.

A second function of the shutdown device was to provide protection for the core model, particularly the new instrumentation, by performing an automatic shutdown if the rig acceleration inadvertently exceeded 50% of the nominal specified value. Shutdown was always executed at the bottom of the shaker arm stroke.

Imposed on the shutdown device circuit design was the requirement that the rig decay be fast enough so that no distortion of the core decay motion occurred. This problem invalidated the previous full-array core damping tests, using a manual shutdown technique. By requiring that the rig decay motion (taking place when the shaker arm bottomed out) completely cease

Fig. 7-1. Sine dwell test rig motion

within one-tenth of the smallest dwell period tested (test No. 7), the transient time of the shutdown was specified in Ref. 10 to be within

$$\Delta t = \frac{1}{10} \times \frac{1}{5.1} \text{ Hz} \approx 0.020 \text{ s} \quad .$$

7.3. DISPLACEMENT TIME HISTORY EXCITATION

Synthesized displacement time history motions for the prestressed concrete reactor vessel (PCRv) satisfying the criteria of Ref. 1 were used as input to the test rig. Four of these input traces were safe shutdown earthquakes (SSE), representing four soil hardness conditions, and one operating base earthquake (OBE) for the soft soil. A sixth trace representing the El Centro earthquake was used to correlate results with previous full-array test results. All time history rig inputs are identified in Table 7-2 and plotted in Figs. 7-2 through 7-7.

Several calculational steps were made before obtaining the final time history input traces. The basic input was taken from the PCRv response in Ref. 43, which in turn was based on the synthesized ground motions in Ref. 44. These traces were then scaled down to 1/5 scale.

Since the horizontal PCRv response was not available at the elevation of the core midheight, a study was made to calculate motion at this elevation using motion at adjacent elevations. The results, documented in Ref. 45, were used to calculate the test input in full scale.

The requirement for input motion at the core center-of-gravity elevation conforms to an accepted NRC guideline stating that the seismic input used for analysis of seismic category 1 structures that are supported at more than one elevation be taken at the center of mass of the section of structure spanning the support elevations.

The traces in the figures are normalized to 1 g peak ground acceleration. These time histories were transmitted to the test lab in digital form for insertion onto magnetic tape.

TABLE 7-2
DOWEL FORCE TEST TIME HISTORY INPUT IDENTIFICATION

Shock No.	Type	Soil	Soil Modulus (psi)
1	Synthesized, SSE ^(a)	Rock	10×10^6
2	Synthesized, SSE	Firm	9×10^4
3	Synthesized, SSE	Soft	2.5×10^4
4	Synthesized, OBE ^(b)	Soft	2.5×10^4
5	Synthesized, SSE	Very soft	3.6×10^3
6	El Centro, SSE	Soft	2.5×10^4

(a) Incorporates 5% PCRV structural damping.

(b) Incorporates 2% PCRV structural damping.

Fig. 7-2. Horizontal displacement input excitation, earthquake No. 1, 1.0 g peak ground acceleration

Fig. 7-3. Horizontal displacement input excitation, earthquake No. 2, 1.0 g peak ground acceleration

Fig. 7-4. Horizontal displacement input excitation, earthquake No. 3, 1.0 g peak ground acceleration

Fig. 7-5. Horizontal displacement input excitation, earthquake No. 4, 1.0 g peak ground acceleration

Fig. 7-6. Horizontal displacement input excitation, earthquake No. 5, 1.0 g peak ground acceleration

Fig. 7-7. Horizontal displacement input excitation, earthquake No. 6, 1.0 g peak ground acceleration

Several calculations were necessary to adjust the displacement input to the limits of the shaker, while retaining the maximum possible g-level. Since the containment building/PCRV model is linear (Ref. 44), PCRV displacements scale proportionally with ground g-level. The results of these calculations are given in Table 7-3. In cases where the amplitude of the scaled trace exceeded the shaker amplitude limits of 2.0 in., but where the total shaker travel of 4.0 in. was not exceeded, the displacement trace was offset in order to remain within the shaker limits at every point.

After g-level scaling, the six time histories were reproduced on tape, tip-to-tail, for each of the four g-levels given in Table 7-3. These four series of input traces were used to excite the rig. For example, the input for test number 9 contains the following input data:

<u>Shock No.</u>	<u>Ground g-level</u>
1	0.20
2	0.176
3	0.20
4	0.20
5	0.176
6	0.50

Since most of the shocks have a ground g-level of 0.20, this value is referenced in the table.

TABLE 7-3
ONE-FIFTH-SCALE DOWEL FORCE TEST SHAKER INPUT AMPLITUDES

	1-g Amplitude (in.)	1-g Double Ampl. (in.)	Ground g-Level	Shaker Amplitude (in.)	Shaker Double Ampl. (in.)	Amplitude Offset (in.)
No. 1, synthesized, SSE, rock	-9.0	15.0	0.200	-1.80	3.00	--
	-9.0	15.0	0.176	-1.58	2.64	--
	-9.0	15.0	0.150	-1.35	2.25	--
	-9.0	15.0	0.100	-0.90	1.50	0.10
No. 2, synthesized, SSE, firm	-9.2	15.3	0.20	-1.84	3.06	--
	-9.2	15.3	0.176	-1.620	2.693	--
	-9.2	15.3	0.15	-1.38	2.29	--
	-9.2	15.3	0.10	-0.92	1.53	--
No. 3, synthesized, SSE, soft	+9.3	14.8	0.25	+2.225	3.70	0.385
	+9.3	14.8	0.20	1.86	2.96	0.308
	+9.3	14.8	0.150	1.395	2.22	0.231
	+9.3	14.8	0.10	0.930	1.48	0.154
No. 4, synthesized, OBE, soft	-9.3	15.7	0.25	-2.325	3.925	0.365
	-9.3	15.7	0.20	-1.86	3.14	0.292
	-9.3	15.7	0.15	-1.395	2.355	0.219
	-9.3	15.7	0.10	-0.93	1.57	0.146

TABLE 7-3 (Continued)

	1-g Amplitude (in.)	1-g Double Ampl. (in.)	Ground g-Level (in.)	Shaker Amplitude (in.)	Shaker Double Ampl. (in.)	Amplitude Offset (in.)
No. 5, synthesized, SSE, very soft	-9.3	18.3	0.20	-1.86	3.66	--
	-9.3	18.3	0.176	-1.637	3.22	--
	-9.3	18.3	0.15	-1.395	2.74	--
	-9.3	18.3	0.10	-0.930	1.83	--
No. 6, El Centro, SSE, soft	+0.76	1.44	0.62	1.885	3.57	--
	+0.76	1.44	0.50	1.52	2.88	--
	+0.76	1.44	0.375	1.14	2.16	--
	+0.76	1.44	0.25	0.76	1.44	--

8. DATA REDUCTION

This section describes the data reduction process from receipt of the raw data tapes from the test lab to output of the final data contained in Ref. 30.

An identification and summary description of the dowel force data reduction routines is given in Table 8-1, while a more detailed code description is presented in succeeding sections. Code input instructions and program listings are contained in Ref. 46. Card decks corresponding to the listings are filed with the dowel force test data computer output.

8.1. TEST LAB DATA TAPES

Five nine-track magnetic tapes containing the raw test data in digital counts were received from the test lab. The data were recorded by a Varian 620/1-100 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, data, 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 contained instrument tare records and dc insert calibration data. The remaining logical records contained 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.

8.2. GENERAL ATOMIC DATA TAPES

The nine-track data tapes transmitted by the test lab were converted to General Atomic seven-track magnetic tapes ("tape 10s") using routines

* A multiplexer pass is equivalent to 0.005 s of test time.

TABLE 8-1
COMPUTER PROGRAM SUMMARY DESCRIPTION

Program	Description
1. DATAT	Converts digital data on 9-track magnetic tape to engineering units on 7-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 displacements.
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 ^(a)
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 seconds of a sine sweep, at 0.5 decade per minute.
16. VIEWR	Provides printout and 4020 plots of time history, rocking angle, and orientation angle for two instrumented core blocks.

TABLE 8-1 (Continued)

Program	Description
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.

(a) Datagraphics SC4020 plots

DATAT and NEWTEN, described in Sections 8.4.1 and 8.4.2, and the calibration factors also submitted by the test lab. The tape 10s were compatible with all data reduction routines and contain 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 tape 9s were condensed into one physical record on the tape 10s 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 employs the logical record numbers specified in the test log sheets (for the tape 9s) in order to process blocks of data (on the tape 10s) associated with a particular test.

8.3. TEST DATA PACKAGE

In addition to the nine-track raw data tapes and oscillograph data, a test package was submitted by the test lab containing all documentation necessary to locate the data for a given test and convert the raw data, in counts, to engineering units. The content of the data package is listed below:

1. Test log sheets
2. Digital tape log sheets
3. Notice of deviations
4. Instrumentation table
5. System calibration summary
6. DC insert calibrations

7. Header records, pre- and post-test (tare) records, and data examination records
8. Data examination summary sheet

8.4. DATA REDUCTION PROGRAMS

The following computer programs and subroutines were used to reduce the dowel force test data.

8.4.1. DATAT

Program DATAT performs two basic operations. Using the nine-track capability of the UNIVAC 1110 computer, the 16-bit, 1994 word blocks of data on the test lab data tape are broken down and reassembled into 7776 16-bit word records on GA seven-track tape. This task, performed with subroutines CONST and MATRIX, replaces the Univac 9300 operation on C&CSD code UTL011, which was performed separately prior to acquisition of the Univac 1110 at GA.

Secondly, the overall calibration factors discussed in Section 3 are applied via subroutine VOLT, converting the raw data in counts to engineering units. These factors are loaded into the array CALIB(80). For each transducer having a nonlinear calibration curve, the volt versus unit data must be input to the code in tabular form. These data override the constant transducer sensitivity used to derive the constant calibration factor in the CALIB array for the instrument. The constant value in this case was most probably the initial slope of the nonlinear calibration curve.

8.4.2. NEWTEN

Following the conversion of raw dowel force test data to engineering units, statistical analyses were performed which resulted in RMS fits to some of the calibration test data in the form $L = mV + b$, where variable

V is in transducer volts and L is in engineering units. Program NEWTEN converts the tape 10 data back to volts only on the transducers of interest, accounting for the signal conditioner (SC) gain, and then reconverts the data to engineering units (EU) with the RMS calibration line. The sequence is:

$$V + [\text{Tape 10 data (EU)}] \times [\text{CALIB (V/EU)}] \times [\text{SG gain}] \quad .$$

New Tape 10 data:

$$L = mV + b \quad .$$

A bilinear option was added to NEWTEN which substituted a linear segment for the RMS line near the origin for the purpose of obtaining zero output in the data when the amplifier output was zero. Otherwise, the b-term above might be interpreted as drift. A similar option was included for more accurately defining the eddy current probe calibration data near the origin. Erroneous values of probe response in this region, although having negligible effect on rocking angle, caused large excursions in orientation angle and uplift.

8.4.3. PEAKS

Program PEAKS defines the peak instrument response within specified time intervals. The output consists of the maximum, minimum, and the time from the first record when each occurred.

Since the function is duplicated in more versatile routines in the data reduction package, it is proposed to use PEAKS to scan all tape 9s prior to conversion by DATAT for the purpose of detecting saturated or open instruments not so identified by the test lab.

8.4.4. Subroutine SPEED

As a subroutine of program HANDY, SPEED calculates block velocity by differentiating LVDT displacement data. Use of the subroutine was suspended due to large inaccuracies in the output occurring from noise in the digital data. This problem can be eliminated by applying a smoothing technique to the data before differentiation.

8.4.5. Subroutine PLOTT

As a subroutine of programs DATAP and DATADF, PLOTT generates a plot on the UNIVAC line printer of instrument response versus time for up to 11 channels.

8.4.6. Subroutine ANGLES

As a subroutine of programs DATAR, HANDYR, and VIEWR, subroutine ANGLES calculates the rocking angle, rocking axis orientation, and vertical separation for two vertically adjacent fuel blocks.

The code is currently set up for three eddy current probes located in a 1/5-scale-model fuel block as shown in Fig. 8-1, and three probes similarly located in the face of a permanent side reflector block. Using the formulation below, the code could be modified to accept data from a two-probe configuration such as used in the single column and basic rocking tests; however, in this case the orientation angle calculation must be bypassed.

Having the planar location of the three probes (A, B, C) and the vertical probe displacements relative to the top of the bottom block (Z_1 , Z_2 , Z_3), the rocking angle θ and orientation angle β are calculated using vector algebra. Referring to Fig. 8-2, the following equations apply:

PROBE LOCATIONS IN AXIS SYSTEM:

$X_a = -0.453 \text{ IN.}$	$Y_a = +0.784 \text{ IN.}$
$X_b = -0.453 \text{ IN.}$	$Y_b = -0.784 \text{ IN.}$
$X_c = +0.905 \text{ IN.}$	$Y_c = 0 \text{ IN.}$

D.F.T. PROBES

ECP	7308
ECP	7309
ECP	7307

Fig. 8-1. Fuel block eddy current probe locations

8-9

Fig. 8-2. Rocking and orientation angles

$$\theta = \arccos (n_z) \quad ,$$

$$\beta = \arccos \frac{n_x}{\sqrt{n_x^2 + n_y^2}}$$

where

$$n_x = \frac{N_x}{N}, \quad n_y = \frac{N_y}{N}, \quad n_z = \frac{N_z}{N} \quad ,$$

$$\overline{N} = \overline{AC} \times \overline{BC} \quad ,$$

$$\overline{AC} = \overline{ac} + (z_3 - z_1)\hat{k} \quad ,$$

$$\overline{BC} = \overline{bc} + (z_3 - z_2)\hat{k} \quad ,$$

$$\overline{ac} = \overline{c} - \overline{a} \quad ,$$

$$\overline{bc} = \overline{c} - \overline{b} \quad ,$$

$$\hat{k} = \text{unit vector in the } +Z \text{ direction.}$$

Orientation angle is referenced to the Y-axis because this was expected to be the rocking axis during X-axis rig excitation.

Block uplift is determined in the program by use of the rocking angle, orientation angle, and one eddy current probe location. In Fig. 8-3A, the distance to the contact point in a rockup is established as

$$\ell = 1.622 \cos \gamma \text{ (in.)} \quad ,$$

where

$$\gamma = 30 - \text{abs}(\beta) \text{ (deg)} \quad .$$

Fig. 8-3. Block uplift calculation

Figure 8-3B illustrates the separation distance calculated by the equation

$$\Delta = H - H_2 = H_3$$

where

$$H = H_3 + Z_3 \quad ,$$

$$H_3 = \ell_2 \tan \theta \quad ,$$

$$H_2 = \ell \tan \theta \quad .$$

Throughout the program, logic was used to differentiate between plus and minus rocking and apply the proper sign of θ in the calculations and output.

8.4.7. DATAP

Program DATAP was designed to display the recorded data for examination. Numerical lists of data and page plots via subroutine PLOTT are output.

DATAP may accept up to 10 channels of data per run; however, only instruments sampled once per multiplexer pass are accommodated and storage limitations restrict the total amount of data that can be output. The program input instructions present two equations, one of which is empirical, for determining the number of records of data that can be output as a function of the number of channels output, without exceeding the Univac 65,000-word storage capacity.

8.4.8. DATADF

Program DATADF is a modification of DATAP for specific output of the net X-axis and Y-axis dowel force on fuel block 004-10, which is formed by

the sum of forces measured separately on three dowels. These data were also recorded at four points per multiplexer pass. The core centerline displacement, which was derived from four specific boundary LVDTs (see PHASE), may also be output for comparison.

8.4.9. DATAR

Program DATAR, a modification of DATAP, utilizes subroutine ANGLES to calculate and print the rocking angle, orientation angle, and vertical separation for an instrumented fuel block. The page plotting option was eliminated.

8.4.10. PHASE

Program PHASE was run on sine sweep data to calculate the phase angle of an instrument with respect to the rig input displacement. Its most successful use was to calculate the phase angle of the core centerline displacement whose frequency response plot was used to predict core damping.

8.4.11. HANDY

Program HANDY prints and provides 4020 plots of the maximum and/or minimum instrument response occurring within an interval of time (as in a time history) or frequency (as in a sine sweep). HANDY reduces all individual data channels and includes special features for (1) peak averaging over a frequency or time interval, (2) providing velocity output via subroutine SPEED, (3) summing forces on three individually monitored dowels for the net X and Y dowel force, and (5) forming the sum of channels 41 plus 42, and 65 plus 66 for the total collision force on fuel blocks 006-4 and 004-10, respectively. HANDY also provides a step-by-step printout of the response for special analysis of the data.

8.4.12. HANDYR

Program HANDYR is a modification of HANDY which, via subroutine ANGLES, provides frequency response plots and printout of the maximum and/or minimum rocking angle, orientation angle, and vertical separation of up to two instrumented fuel elements per run. A step-by-step printout option of the above response quantities is currently included in the program.

8.4.13. VIEW

Program view was used to obtain printouts and 4020 plots of the instrument response for time history excitation. Four versions currently exist.

8.4.13.1. VIEW4. This original version prints and plots the response of instruments sampled up to four times per multiplexer pass. Special features include (1) an option for obtaining the net X or Y dowel force (on block 004-10) as a sum of forces on three dowels, and (2) automatic formation of the sum of channels 41 plus 42, and 65 plus 66 for the total collision force on blocks 006-4 and 004-10, respectively.

8.4.13.2. VIEW1. This version of VIEW uses the same input format as version 1 and contains the summing technique for collision forces. The utility of handling channels sampled more than once was eliminated in order to allow the reduction of up to eight channels per run.

8.4.13.3. VIEWD. This version of VIEW was constructed to obtain printouts and 4020 plots of the rig displacement and frequency channel during a sine sweep. Any two channels sampled once per pass may be output. The program handles approximately 47 s of sweep data starting at 2 Hz, at a rate of 0.5 decade per minute. The listing should be scanned to remove the smoothing and attenuation operations on the rig displacement.

8.4.13.4. VIEWR. Program VIEWR is a modification of program VIEW, which provides printouts and 4020 plots of rocking angle and orientation angle

via subroutine ANGLES for up to two instrumented blocks per run. Only time history data should be input to the program as in the case of the other versions of VIEW since storage capacity limits the program to only about 100 logical records of data.

8.4.14. PEAKAB AND PEAKF

Programs PEAKAB and PEAKF are two versions of a search routine that identifies the peaks in the seismic response of an instrument. The programs apply to data having plus or minus variations of magnitude larger than the channel noise variations.

For program PEAKAB, parameters ALFA and BETA shown in Fig. 8-4 are input as a test for peaks in the response. The program requires the tail-off from a peak to reach a value less than ALFA times the peak value in order for the peak to be registered. Successive peaks must rise above parameter BETA times the preceding trough of the response in order to be registered.

The approximate channel drift level should be known prior to running the program so that parameter PNOISM may be input. This parameter is assigned a positive value somewhat larger than the drift above which no values are counted in the algorithm that calculates drift in the program. Thus, the chance of inadvertently using a peak response value in the drift calculation is eliminated. The logic flow diagram for PEAKAB is shown in Fig. 8-5.

Program PEAKF is a modification of PEAKAB where parameters ALFA and BETA are replaced by the single parameter FLIMIT for defining valid load cycles in the response, as illustrated in Fig. 8-6. PEAKF also has the capability to define peaks for up to eight instruments in one run.

FLIMIT has special meaning for collision forces where it was chosen to correspond to the endurance limit for a corner compression loading of a

Fig. 8-4. PEAKAB - peak identification criteria

Fig. 8-6. PEAKF - peak identification criteria

prototype fuel element, scaled to 1/5 scale. Using a tentative value of 3500 lb for the prototype, the value of FLIMIT becomes:

$$FLIMIT = \frac{1}{125} \times 3500 = 28.0 \text{ lb} \quad .$$

8.5. TAPE INDEXING

In order to reduce data from more than one shock in a time history test, or from more than one test on the same tape, the following tape rewind cards are entered at the end of a data set. These are followed by the next set of data cards.

▽ REWIND 10, NAME

▽ MOVE 10, X X = Number of files

▽ XQT

9. TEST RESULTS

9.1. INTRODUCTION

The dowel force test results presented in this section have been arranged into the following categories:

1. Evaluation of core damping from the dwell and decay tests, and sine sweep tests.
2. Presentation of the core vibration characteristics by analysis of the instrument frequency response at 0.5 g.
3. Presentation of the core time history response to GA synthesized earthquakes at several g-levels up to 0.25 g (ground).
4. Comparisons of core response with data from previous full-array tests, correlation of data from different transducers recorded simultaneously, and comparison of data recorded at the 45° position (core position number 4) with that from core locations in line with the hydraulic shaker.

9.2. DATA REDUCTION PLAN

The many records of data from the 26 tests in the program were reduced to selected samples, which were sufficient to meet the test objectives. Table 9-1 identifies the data tape numbers associated with each test in the program. This information and the tape record numbers in Table 9-2* can be

* Taken from the test log sheets in Ref. 41.

TABLE 9-1
DOWEL FORCE TEST DATA TAPE IDENTIFICATION

Wyle Lab Reel No.	Old Tape 10(a)	Test	New Tape 10	Test	Comments
Reel 1 No. 148	5339	1R 2R	3148 4194	1R 2R	Obsolete
W151 No. 151	5823	3-4 5-6 ^(b) 7	4428 4442 4403	3-4 5-6 7-8	Obsolete Test 5 data absent Obsolete
	4571	8R			
	4997	9	4619	8R-9	
	0040	10	4708	10-11	
	7485	11			
Newone No. 153	3854	12	4667	12	
	4249	13			
	6569	14	4866	13-14	
	4064	15-16	5196	15-16	
Reel 17 No. 155	5457	17	4643	17	
	7340	18-19	5079	18-19	
	4576	20			
	4611	21	5250	22	
Reel 22 No. 157	3272	22	5073	22	
	5711	23			
	2520	24	5189	23-24	
	7177	25			
	4058	26	5233	25-26	

(a) Checked to contain correct "nominal" calibration factors.

(b) Test 5 absent from Tape 5823, January 27, 1977.

TABLE 9-2
DOWEL FORCE TEST RECORD NUMBERS

Test	Shock					
	1	2	3	4	5	6
1R	SINS	FILE 2, UP: 192-815, DOWN: 834-1443				
2R	SIND		3/191-387			
3	SIND		3/3-660			
4	SIND		4/3-228			
5	SIND		5/3-565			
6	SIND		6/3-698			
7	SIND		7/3-529			
8	8/3-95	8/96-186	8/187-291	8/292-400	8/401-499	8/500-594
8R	9/3-96	9/97-195	9/196-294	9/295-391	9/392-488	9/489-584
9	10/3-89	10/90-176	10/177-278	10/279-376	10/377-478	10/479-580
10	11/3-90	11/91-190	11/191-288	11/289-383	11/384-493	11/494-574
11	12/3-86	12/87-169	12/170-273	12/274-367	12/368-466	12/467-553
12	SINS	FILE 3, UP: 33-667, DOWN: 679-1297				
13	4/3-97	4/98-184	4/185-284	4/285-385	4/386-479	4/480-570
14	5/55-147	5/148-237	5/238-337	5/290-389	5/436-530	5/
15	6/3-90	6/91-190	6/191-281	6/282-373	6/374-479	6/
16	7/3-85	7/86-166	7/167-269	7/270-361	7/362-455	7/
17	SINS	FILE 3, UP: 3-609, DOWN: 626-1234				
18	4/3-82	4/83-162	4/163-255	4/256-348	4/349-436	4/437-552
19	5/3-83	5/84-162	5/163-257	5/258-345	5/346-425	5/426-542
20	6/3-82	6/83-174	6/175-265	6/266-351	6/352-454	6/455-577
21	7/3-82	7/83-156	7/157-254	7/255-338	7/339-431	7/432-557
22	SINS	FILE 3, UP: 33-641, DOWN: 661-1288				
23	4/3-87	4/88-181	4/182-282	4/283-379	4/380-476	4/477-609
24	5/3-85	5/86-175	5/176-273	5/274-373	5/374-473	5/474-605
25	6/3-90	6/91-197	6/198-299	6/300-391	6/392-497	6/498-632
26	7/3-88	7/89-178	7/179-280	7/281-372	7/373-477	7/478-617

used to obtain any specific transducer record that may become of interest in the future.

Response distributions are given with respect to both core elevation and radial location. However, the block collision forces and dowel forces are not compared as a function of core elevation because the mass of each model core block containing an instrument assembly was different, and this resulted in a wide variation in the range of recorded loads. In addition, the effects of soil condition and ground g-level on the core time history response were investigated.

9.3. CORE DAMPING

The assumption underlying the core damping measurements was that the entire core represented a viscously damped, single-degree-of-freedom system. This dynamic model was justified from visual observations and data recorded in previous tests, which showed the existence of a tightly packed, or lumped, core configuration over a wide range of sinusoidal and time history excitation. This core mode was also associated with peak boundary forces, core displacement and velocities, and peak in-core forces.

Two methods were utilized to evaluate the damping associated with the lumped core motion. In the first case, the equations for an ideal viscously damped, single-degree-of-freedom system were fit to the free transient decay motion of the core centerline, using dwell and decay tests number 3, 5, 6, and 7.

The second method was to formulate and plot the phase lag of the core centerline with respect to the rig for a sine sweep input, and compare the result with the well known single-degree-of-freedom response. The role of the response phase angle for the nonlinear behavior of the test model is discussed in Section 9.3.2.3.

9.3.1. Calculation of the Core Centerline Motion

The core centerline motion relative to the test rig was used to represent the core as a single-degree-of-freedom system. This motion was expressed in terms of the gaps measured by four boundary LVDTs, using the assumption of tightly packed core elements. The following equations are based on the model in Fig. 9-1.

$$X(t) = \frac{D - (\Delta X_R + \Delta X_L)}{2} + \Delta X_R \quad .$$

Shifting the rig reference point to the center results in

$$X_X(t) = X(t) - \frac{D}{2} = \frac{\Delta X_R - \Delta X_L}{2} \quad .$$

Also

$$\Delta X_R = \Delta R_R + \Delta C_R + R \quad ,$$

$$\Delta X_L = \Delta R_L + \Delta C_L + R \quad .$$

Therefore

$$X_C(t) = (\Delta R_R + \Delta C_R) - (\Delta R_L + \Delta C_L) \quad . \quad (9-1)$$

In terms of the channel numbers listed in Ref. 29, Eq. 9-1 becomes

$$X_C(t) = \frac{(\text{ch } 24 + \text{ch } 7) - (\text{ch } 23 + \text{ch } 21)}{2} \quad (9-2)$$

Figure 9-1 illustrates that the 0.2 in. soft spring deflection of the spring pack, prior to the hard stop contact, is not accounted for in the calculation for $X_C(t)$. It was believed that this might result in some underestimation of the viscous damping factor because the initial peak in

Fig. 9-1. Lumped core model for damping calculations

the decay curve $X(t)$ would be smaller by this amount as the core impacted the boundary, while the succeeding peak or peaks would be unaffected if the core did not again reach the boundary. This source of error was also reported for the lumping calculations of Ref. 4 and resulted in an error of +16%.

9.3.2. Damped Transient Method

9.3.2.1. Equations for the Free Transient Decay. Equations for the transient decay model were taken from Ref. 47. The object was to calculate the damping ratio ν and three other parameters characterizing the ideal damped model, using four data points on the measured core decay transient. In this way the calculated ideal model could be plotted in comparison to the measured core decay transient. Figure 9-2 illustrates a typical decay transient and identifies the measured data input to the model. The four output parameters of the ideal model are given below.

$$\nu = \frac{-\ln\left(\frac{x_4}{x_3}\right)}{\sqrt{\pi^2 + \left[\ln\left(\frac{x_4}{x_3}\right)\right]^2}} \quad (\text{viscous damping}) \quad (9-3)$$

$$p = \frac{\pi}{(t_4 - t_3) \sqrt{1 - \nu^2}} \quad (\text{undamped natural frequency, radius/s}) \quad (9-4)$$

$$\phi = pt_2 \sqrt{1 - \nu^2} - \frac{\pi}{2} \quad (\text{phase angle, radians}) \quad (9-5)$$

$$V_o = X_o p \left(\sqrt{1 - \nu^2} \tan \phi - \nu \right) \quad (\text{initial velocity, in./s}) \quad (9-6)$$

9.3.2.2. Results of the Damped Transient Method. The core transient decay curves and fitted viscous single-degree-of-freedom models are shown in Figs. 9-3 through 9-6 for tests 3, 5, 6, and 7. The results indicate similarity between the data and viscous model, yielding an average viscous damping coefficient of 41%, with very small deviation. The dwell frequencies for these tests were determined in the previous full-array tests.

Fig. 9-2. Core decay transient and damping model input parameters

Fig. 9-3. Core decay and damping model, 3.5 hertz dwell, 0.3 g

Fig. 9-4. Core decay and damping model, 2.4 hertz, 0.5 g

Fig. 9-5. Core decay and damping model, 4.1 hertz, 0.5 g

Fig. 9-6. Core decay and damping model, 5.1 hertz, 0.5 g

Tests 2 and 4 were not used because the core decay was impossible to fit, apparently because of inadequate core lumping as a result of a low input excitation frequency and amplitude.

As shown by the numerical data in the figures, a centering correction was applied in the calculations. This was equivalent to centering the decay oscillation of the core, which for the first three cases was nominally offset by 0.05 in. as given by the dowel displacement data.

Although the correction was small and probably due to core asymmetry or failure to zero all LVDTs, it was significant for the damping calculations, being about equal to the transient core displacement at the end of the first cycle of the decay (X_4). Numerically, this modified the damping estimates from 60%, 27%, and 42%, respectively, to a more consistent 39%, 39%, and 46%. However, the average damping calculated in the three tests remained essentially the same.

For the data recorded in test number 7 (Fig. 9-6), the small displacements recorded during the dwell (0.027 in. maximum) indicated that the core oscillated without impacting the boundary spring packs. Observations of the core motion at this frequency led to the conclusion that the core mass was not tightly lumped as in the case of tests 2 and 4. However, since the dwell frequency of 5.1 hertz was equal to the core support floor resonant frequency, the calculated damping ratio of 50.6% was considered to represent that of the core support floor.

9.3.2.3. Phase Angle of the Response. The phase angle between the core centerline displacement and test rig displacement is used to establish a criterion for resonance in the damping tests and in the frequency response tests described in the next section.

The 90° phase lag condition can be shown analytically to exist at resonance for a sinusoidally excited linear model. A similar condition is observed for the nonlinear core model as obtained from the dwell tests.

Verification of the 90° phase lag at resonance follows from Section 6-11 of Ref. 47, assuming that the core, in its lumped mode during resonance, is adequately described by the viscously damped Duffing model. This assumption was made because:

1. The spring characteristics of the test models, consisting of a small soft spring located across a gap followed by a very hard spring (the hard stop), were similar to the cubic spring force equation in the Duffing model.
2. The core motion demonstrated a high degree of core mass lumping, approximating single mass behavior over a wide frequency range, particularly in the resonance region.
3. The frequency response behavior of the core during sweep-up and sweep-down excitation showed the unique nonlinear characteristics of the Duffing model.

The remaining task was to show that the Duffing model itself exhibits the 90° phase lag of the response with respect to the input displacement at resonance. This is illustrated in Fig. 9-7, which is from Ref. 51. Plots of the solution to the viscous Duffing equation,

$$\left[1 + \frac{3K^2 X^2}{4} - \frac{\omega^2}{p^2} \right]^2 + \frac{4v^2 \omega^2}{p^2} = \frac{F^2}{R^2 X^2} \quad ,$$

are at constant input force and are shown to peak on the $S = 0$ resonance line. Parametric curves of the same equation, given by

$$\tan \Psi = \frac{\frac{2v\omega}{R}}{1 + \frac{3K^2 X^2}{4} - \frac{\omega^2}{p^2}} \quad ,$$

Fig. 9-7. Response of viscous Duffing equation (Ref. 51)

with the phase angle constrained to be 90° (denominator equal to 0), are shown to intersect the particular solutions only at the resonance point. Therefore, the 90° phase lag condition for the response can be interpreted as a criterion for core resonance.

9.3.3. Sine Sweep Test Method

Computer program PHASE, described in Section 8.4.10, was utilized to calculate the phase of the core centerline motion with respect to the rig. The result is shown in Fig. 9-8 for test 1R. Superimposed on the data is the plot of a linear SDOF system phase angle response at 20% (viscous) damping.

The results indicate that for the core in forced motion, the viscous damping coefficient of the lumped core mode was equal to about 18%. This is in contrast to a value of 40% calculated from the transient decay tests in Section 9.3.2.2. The lower damping value was believed due to a lower number of interelement collisions taking place in the lumped core.

9.4. RESULTS FOR SINUSOIDAL EXCITATION

Sinusoidal tests were performed to evaluate the core dynamic characteristics. Comparisons of data from the same instruments in different locations were also desirable for periodic excitation as opposed to simulated earthquake rig inputs.

9.4.1. Fuel Element Rocking Angles

Fuel element and permanent side reflector block rocking angles were obtained during sine sweep excitation at the three instrument positions shown in Fig. 6-6. These angles are presented as a function of core elevation and radius. Although variations in instrumented block mass were known to significantly influence the magnitude of dowel forces and collision forces measured for a given core motion, eliminating a meaningful

Fig. 9-8. Phase angle frequency response of the core second mode

comparison of the forces taken at different elevations in the model, it was assumed that block displacements were not affected by local changes in core block mass, and therefore all rocking angles were compared on an equal basis. Furthermore, only the relative size of the angles is important here since the 0.5 g sinusoidal rig excitation had no relationship to the NRC design earthquakes; hence, conclusions that can be drawn regarding core disarray from the sine sweep data are inappropriate.

The frequency response of the rocking angle instrumentation at three core levels at the core center (blocks 001-5, 001-7, and 004-11 of Fig. 6-2) are shown in Figs. 9-9 through 9-11. These figures indicate presence of column deflections in the lower core regions while the core is in its second mode resonance at 4.1 Hz, so the lumping is predominant in the upper half of the core.

During the sweep up to resonance, the rocking angles in the upper core region tend to decrease, with smaller angles prevailing at the higher elevations. This behavior is in agreement with observations of the lumped core motion during sine testing, where rocking in the top layer was not apparent.

An additional observation from the data was that for frequencies just above the second mode resonance, larger rocking angles occurred in the upper core regions.

The plots in Figs. 9-9 through 9-11 illustrate a systematic rocking angle error for each block of about $+0.25^\circ$. The source of this offset was considered as drift in each of three eddy current probes located at one block interface, plus a small initial gap below each probe. Each curve was therefore adjusted (lowered) by this amount before recording the results because the orientation angle^{*} of the rocking axis associated with the offset was near zero. If the orientation angle had been near 90° , indicating hypothetical rocking angle perpendicular to the excitation axis,

* Section 8.46

Fig. 9-9. Rocking angle at bottom of block 007-5, test 1R

Fig. 9-10. Rocking angle at bottom of block 001-7, test 1R

Fig. 9-11. Rocking angle at bottom of block 004-11, test 1R

the effect of the offset would vanish as soon as any appreciable rocking displacement took place in line with the excitation.

A sample of the time history rocking angle and orientation angle response during a sine sweep is shown in Fig. 9-12. Large orientation angles are indicated only for very small rocking angles; they were attributed to relative error (systematic and random) in the eddy current probes while near the zero point. Near-parallel rocking with the excitation axis was always indicated by a small value of orientation angle whenever appreciable rocking angles were calculated from the probe data, as expected.

Fuel element uplift calculations were made from the eddy current probe measurements during the sinusoidal tests. Analysis of the data using program DATAR (Section 8.4.9) showed that larger values of uplift, on the order of 0.02 in., were calculated while the blocks were at rest and therefore attributed to drift and random errors in the probes at the null position. Nonzero values of uplift during a rocking event, on the order of 1 to 3 mils, were considered to be at least influenced by random variations as well as calibration errors in the probe. Hence, all uplift values were concluded to be insignificant and were not considered further in the report.

The remaining fuel element rocking angle frequency response data are summarized in Figs. 9-13 and 9-14. The data in the figures show that the rocking angle at each elevation tends to increase from the center toward the core periphery. The negative sign on the ordinate of Fig. 9-14 designates the larger negative angles calculated from the probe data.

9.4.2. Permanent Side Reflector Block Rocking Angles

The instrumented side reflector block pair in column number 596 was lowered one step in elevation whenever the in-core instruments were moved radially outward. At core position number 4, the instrumented reflector

Fig. 9-12. Block 007-5 rocking and orientation angle sine sweep response, test 1R

Fig. 9-13. Fuel element rocking angle variation with core radius, sinusoidal excitation at 4.0 hertz

Fig. 9-14. Fuel element rocking angle asymmetry as a function of core radius

blocks were located in positions PSR-584-5 and PSR-584-6. Rocking angles calculated from the probe measurements at 4.0 Hz are plotted with respect to core elevation in Fig. 9-15.

The rocking angle distribution shown in the figure is unlike that of the fuel elements in that the largest response was at the midheight elevation. Overall, the reflector block rocking angles were smaller than those determined for the fuel elements for sinusoidal rig motion. Symmetrical rocking did not occur in the column and greater positive angles were measured at the top elevation in contrast to the fuel elements, where larger negative angles were found to prevail at all instrument locations (Ref. 30).

Since the direction of the prevailing rocking angle was assumed to depend on the column deflection mode and block elevation within the column, no further conclusions were attempted for these results. A possible deflected configuration of the reflector column is indicated in the figure.

9.4.3. Core Boundary Forces

Lateral spring packs at positions 001-5 and 019-5 (Fig. 6-1) were instrumented with strain gages to record boundary forces. The frequency responses of these instruments for both sweep-up and sweep-down are shown in Figs. 9-16 and 9-17.

The results show that peak boundary forces were controlled by the lumped core mode at 4.1 Hz. However, the response of spring pack 19-5 shows a lesser peak at about 2.2 Hz, which was attributed to a column deflection resonance discovered in previous full-array tests at 2.4 Hz, for a 0.5 g excitation.

The sweep-down response was also plotted in the figures to verify the nonlinear behavior of the core vibration. As illustrated, the limit

Fig. 9-15. Permanent side reflector rocking angles, SINS excitation, 4.0 hertz, 0.5 g

Fig. 9-16. Dowel force test 1R, LC 0015 response to 0.5 g sweep

Fig. 9-17. Dowel force test 1R, LC 0195 response to 0.5 g sweep

frequency for lumping in the down sweep was slightly lower than in the up sweep, defining an unstable region. From then on the down-sweep response was essentially identical to the up-sweep response, lending confidence that the variations in the response are real frequency characteristics and not random variations, or variations due to error in the data acquisition system. Boundary load cell frequency response curves for the remaining sine sweep tests are contained in Ref. 30.

9.4.4. Fuel Element Dowel Forces

The radial distribution of X-axis fuel element dowel forces is plotted in Figs. 9-18 and 9-19. In the first figure, dowel loads in pounds are compared directly for the strain gaged dowels on blocks 004-10, 007-4, and the core support floor block. Since the loads recorded by the substantially heavier dowel load cell fuel block, number 001-6, were greater than the others by approximately one order of magnitude, only the normalized force is shown for this block. Normalized distributions at all core elevations are plotted in Fig. 9-19.

A post-test examination of fuel element 001-6 revealed that one terminal of the dowel load cell made contact with the adjacent block. Hence the data from this instrument is considered to have an indeterminate error. The examination was triggered by exceptionally poor correlation of the data with the analytical results. Plots of the response of this instrument were retained for illustration.

The figures illustrate that maximum dowel loads occur at the core periphery for all instrument elevations and gradually decrease toward the core center. The single exception to this trend occurs for block 004-10 where the midradius peak dowel load is 35% lower than at the core center.

An unexpected result shown in Fig. 9-18 was that, barring one exception for block 001-6 at the midradius location, the peak dowel load was not received during the lumped resonance at 4.1 Hz, but rather in the range of

Fig. 9-18. X-axis dowel force radial distribution, sinusoidal excitation

Fig. 9-19. Normalized dowel force radial distribution, sinusoidal excitation, X direction

2.75 to 3.75 Hz, with a large proportion of peaks occurring in the 2.7 to 3.3 Hz range. This result is in contrast to the boundary loads of Section 9.4.3 showing a single distinct peak at the lumped core resonance. The cause of this behavior was attributed to the superposition of core column vibration upon the predominantly lumped core motion.

With similarity to the rocking angle response, the curves in Figs. 9-20 through 9-22 illustrate that the fuel block dowel force frequency response varies depending on block location in the column. These curves represent the response at the three-quarter, one-half, and one-quarter elevations in the core, at the midradius location, and are typical for each instrumented block. The noticeable difference in the shape of the response is that the midheight instrument, block 001-6, exhibits a strong peak and subsequent decay at 4.1 Hz, indicating that the core second mode resonance is responsible for the midheight peak dowel forces, while block 997-4 at the lower elevation obtains distinctly higher loads at lower frequencies. In contrast, block 004-10, at the upper elevation, receives a peak loading at lower frequencies (but not necessarily those of block 997-4), and the 4.1 Hz resonance is not pronounced.

A second characteristic of these curves is that the lumped floor mode resonance is clearly identified at 4.7 Hz (as opposed to 5.1 Hz determined in full-array testing), and the relative influence of the mode is largest in the lower core elevations as expected. The remaining dowel force frequency response curves are contained in Ref. 30.

Figure 9-23 shows the ratio of the peak X-axis dowel force to the peak Y-axis dowel force achieved during a sine sweep at each core position. The forces making up the ratios were not necessarily acting simultaneously or in the same frequency interval. The results show that peak dowel forces perpendicular to the excitation are generally about 40% of those in line with the rig excitation. The exception is block 004-10 at the core mid-radius position where X-axis and Y-axis forces become nearly equal. This behavior is investigated in more detail in Section 9.7 by examining the response of a single dowel on an individual time step basis.

Fig. 9-20. Rectified frequency response for final block 004-10, dowel force, test 12

Fig. 9-21. Dowel force frequency response, block 001-6, test 12

Fig. 9-22. Dowel force frequency response, block 007-4, test 12

Fig. 9-23. Radial distribution of the X to Y dowel force ratio, sinusoidal excitation, 0.5 g

9.4.5. Reflector Block Dowel Forces

Peak values of the dowel force frequency response in permanent side reflector column number 596 are shown in Fig. 9-24. The results show a distinct increase in both X-axis and Y-axis loads with elevation in the column.

An unexpected result was the relatively large cross-axis dowel forces, particularly at the midheight elevation where it exceeds the X-axis dowel load by a factor of two. The X-axis and Y-axis dowel load response curves for this point (test 12) and for test 1R are plotted for comparison in Figs. 9-25 and 9-26.

Examination of the reflector block dowel force response with respect to time over a short frequency interval of test 12 revealed the presence of a large Y-axis dowel force lagging the X-axis dowel force once every vibration period. This behavior was attributed to block forces exerted in line with the excitation followed by circumferential block forces in the reflector columns. Any particular misalignment of the blocks at the midheight location due to dimensional tolerances could also have contributed to the larger Y-axis dowel forces.

9.4.6. Fuel Element Collision Forces

9.4.6.1. Collision Force Radial Distribution. Fuel element collision forces were measured at three elevations in the core during sinusoidal rig excitation and are summarized in Fig. 9-27. The forces shown represent the peak response achieved in the sweep from 1.6 to 10 Hz. All values were normalized with respect to the force measured at the center position because the different mass associated with each instrumented block affected the measured collision forces. Hence, conclusions made from force distributions with respect to core elevation were not meaningful.* However, collision force distributions along a core radius were considered valid for each force-instrumented block in the core.

*The recorded data were considered valid for analytical code correlation when the proper block masses were introduced into the analysis.

Fig. 9-24. Permanent side reflector 596 dowel force distribution with elevation, sinusoidal excitation, 0.50 g

Fig. 9-25. Reflector block 596 X-axis and Y-axis dowel force frequency response, test 1R

Fig. 9-26. Reflector block 596 X-axis and Y-axis dowel force frequency response, test 1R

Fig. 9-27. Normalized block force radial distribution, sinusoidal excitation, 0.5 g

The results indicate that, with the exception of fuel block 006-4 located at the lower core elevation, fuel element collision forces remain approximately constant from the core center to the periphery, on a diameter parallel to the axis of excitation.

An explanation for the smooth and marked increase in collision load with core radial location for block 006-4 in comparison to the relatively constant distributions of the remaining blocks can be postulated by considering core block lumping within one cycle of rig oscillation. Under the assumption of a fully lumped core during any full cycle of the sweep, maximum fuel block loads would be anticipated at the core periphery and minimum loads at the core center since the full core inertia acts at the periphery once per cycle, while at the core center one-half of the core inertia acts on the blocks twice per vibration cycle. Such behavior was exhibited by fuel block 006-4.

However, if there was a small separation between the columns at the beginning of core impact with the boundary, the collision force at that point was due to less than the full core inertia. This behavior would explain the constant distribution of the collision forces shown in Fig. 9-27.

The lumping results for the full-array model determined in Ref. 6 and reproduced here in Figs. 9-28 through 9-30 suggest the dynamics described above. Less than peak lumping occurs per cycle as the excitation frequency deviates from the resonant frequency of 4.1 Hz. However, even at resonance there was a minimum of 85% lumping, and this value existed at boundary impact as illustrated by the superimposed hard stop load pulse in Fig. 9-30. The single factor which exists to shed uncertainty on postulated behavior, however, is that no reason can be found to explain why the core lumping should be greater at elevation 4 in the core.

9.4.6.2. Representation of Collision Forces on Instrumented Fuel Blocks Having Multiple Transducers. Fuel blocks instrumented for collision forces

Fig. 9-28. Core lumping diagram - core midheight, 0.5 g, 1.6 hertz

Fig. 9-29. Core lumping diagram - core midheight, 0.5 g, 3.0 hertz

94-6

Fig. 9-30. Core lumping diagram - core midheight, 0.5 g, 4.1 hertz

contained more than one strain gage or load cell, with the exception of block 001-6. Since the analytical codes correlating the test data calculate a single collision force per fuel block, the net, or total, block collision force was formulated from the test data.

Only fuel element number 005-7 was equipped with the proper circuitry for acquisition of the total block collision force under all impact conditions. In essence, each of the five block load cells was connected in a series-parallel network so that the simultaneous sum of the forces on the load cells was recorded on a separate channel, in addition to the unaltered individual load cell forces recorded on five separate channels.

For the remaining two blocks containing two collision force transducers with no such summing circuits (blocks 004-10 and 006-4), the total block force was represented by the sum of the individual transducer records, peak held over a multiplexer pass. This was considered the best estimate available during either sinusoidal or time history excitation, but particularly during the former and in the low frequency part of the latter, where the core tends to lump together resulting in flat hits among the blocks.

The fuel block collision force frequency response was completed with derivation of the total force on block 005-7 for sine sweep test 1R. This test was run prior to installing the load cell summing circuit. The total collision load on the block was determined by plotting the simultaneous sum versus the sum of the individual load cells for sine sweep tests 12 and 17, as shown in Figs. 9-31 and 9-32. The ratios of the peak loads of the two curves in each figure were averaged to obtain the factor of 1.5 by which the separate load cell sum for test 1R was lowered, as shown in Fig. 9-33.

It was concluded that the load cell calibration factors for blocks 005-7 and 006-4 were erroneously high by a factor of 3 for test 1R, and the recorded loads for these blocks were therefore lowered accordingly. The

Fig. 9-31. Block 005-7-comparison of load cell response, test 12

Fig. 9-32. Block 005-7-comparison of load cell response, test 17

Fig. 9-33. Block 005-7 load cell response, test 1R

conclusion was based on:

1. The loads on block 005-7 being suspiciously large in test 1R.
2. The loads on this block and block 006-4 during the 0.5 g sine dwell at 4.1 Hz of test number 6 being approximately one-third of those in test 1R in the 4.1 Hz region.
3. A post write-in by the test laboratory increasing the calibration factors of the transducers under question by a factor of three.
4. The experience that the initial few tests in a program were likely to be less well documented than the remainder.

The rest of the fuel element collision force frequency response curves are given in Ref. 30.

9.4.6.3. Correlation of Block Strain Gage Data. An objective of the test was an in-core calibration of the block force strain gages by correlation of the loads from adjacent blocks 005-7 and 001-6 during sine sweep testing. The end product of the correlation was a factor by which the strain gage load data would be adjusted to compensate for the in-core compression loading on all block faces, since dynamic calibration of the strain gaged blocks considered only flat, or nearly flat, hits on a single face.

The excessively high loads predicted by these blocks in previous full-array tests suggested that simultaneous loading of all block faces produced internal strain waves responsible for the high load predictions. Sine sweep testing was considered appropriate for this data correlation because the observable core lumping induced a flat impact orientation among the elements, similar to that achieved in calibration, and a more compressive element loading in general. Loads recorded during the low frequency position of the time history inputs were also considered applicable.

Using Fig. 9-27, the loads predicted by strain gaged block 001-6 are different than those predicted by block 005-7 by +59%, +25%, and -8%, respectively, proceeding from the core center to the boundary. Considering the larger rocking angles at the core periphery for block 007-5, as shown in Fig. 9-13, the last correlation point was deleted and the first two averaged. The conclusion reached was that the strain gaged block predicts collision loads high by a factor of about 45% relative to (load cell) block 005-7.

Once the analytical codes are utilized to compute the increased collision force on block 007-5 due to its higher mass, this and the above factor of 45% can be combined to ratio down the strain gaged block forces giving values applicable to a typical core block.

Although these loads would be applicable for code correlation, it is emphasized that they are rough estimates as the load cell versus strain gage data correlation was somewhat dubious since the frequency distributions of collision forces on block 007-5 and block 001-6 do not show the same trends in Fig. 9-13.

9.5. RESULTS OF TIME HISTORY EXCITATION

9.5.1. Introduction

This section presents core response data obtained with the time history excitation described in Section 7. Each shock was input to the rig at each of the in-core instrument locations illustrated in Fig. 6-2.

Because analysis of the oscillograph data revealed that the digital rig displacements were generally too low by a factor of about 1.25, the actual input g-levels were determined from the oscillograph records (Section 10.4.1). Plots of the digital rig displacements in Ref. 30 were used to determine the relative location of the peak instrument response within

the time history. In addition, these plots were used to locate the time of the artificially imposed lead-in and tail-off transients for shocks 3 and 4 since these transients were inadvertently severe and often resulted in a peak instrument response that was not admitted as valid data.

During the test phase of the program it was discovered that shock number 6, El Centro, safe shutdown earthquake (SSE), soft soil, was input at twice the correct frequency. This problem was corrected with the result that data from only tests 18 through 21 and 23 through 26 were valid for this shock. Finally, as discussed in Section 10.4.1, test number 26 was run at too low a g-level.

The peak time history response of the in-core and boundary transducers is presented in summary in Tables 9-3 through 9-6. Only that part of the test data specifically useful for code correlation was reduced from the tapes. Additional data can be accessed with any of the data reduction programs using the tape and record numbers in Tables 9-1 and 9-2. The remaining time history data not specifically discussed in succeeding paragraphs, including tabulated peak response data and associated random noise errors, are contained in Ref. 30.

Note that dowel forces from block 001-6 are in error per Section 9.4.4.

9.5.2. Treatment of Drift in Peak-Held Instruments

Systematic error (drift) was generally subtracted from the data before it was logged. However, it was not obvious for the peak-held block impact force instrumentation (recording only compression loads) whether to add or subtract the drift since only the absolute value of the peak response within a multiplexer pass was recorded. As a result, the peak-held response constructed in Fig. 9-34A might have been derived from either analog possibility shown in Fig. 9-34B, leading to the initial conclusion that the overall data error should include both plus and minus the drift value.

TABLE 9-3

DOWEL FORCE TEST SUMMARY TIME HISTORY PEAK RESPONSE, 0.10 g (GROUND) (REFERENCE)

Instrument	Core Center					Midradius					Core Boundary				
	1	2	3	4	5(a)	1	2	3	4	5(a)	1	2	3	4	5(a)
Eddy current probes 4-11 (deg)															
Eddy current probes 1-7				+0.39					+0.34					+0.35	
Eddy current probes 7-5				+0.32					+0.33					+0.31	
Eddy current probes 596															
5 load cells (block) 5-7 (1b)		0		0			0		9.0			0		10.5	
2 load cells (block) 6-4		0		0			0		0					3.6	
2 strain gages (block) 4-10				42.2					81.1					69	
1 strain gage (block) 1-6															
Strain gage (dowel)-X net 4-10				8.0					5.89					2.06	
Strain gage (dowel)-Y net 4-10				1.27					-3.0					1.58	
Strain gage (dowel)-X net 7-4				0					0					1.21	
Strain gage (dowel)-Y net 1-4															
Strain gage (dowel)-X net CSB				1.18										6.0	
Load cell (dowel)-X net 1-6				0					34.6					6.7	
Load cell (dowel)-Y 1-6				0					2.8					0	
Load cell (dowel)-X net 596				55.6					18.3					28.5	
Load cell (dowel)-Y net 596				47.7					12.2					4.9	
Spring pack 1-5		0		0					0			0		0	
Spring pack 19-5		0		0					0			0		0	

(a) Shocks 1, 2, 3, 4, 5

TABLE 9-4
SUMMARY TIME HISTORY RESPONSE, 0.15 g (GROUND) (REFERENCE)

Instrument	Core Center					Midradius					Core Boundary				
	1	2	3	4	5(a)	1	2	3	4	5(a)	1	2	3	4	5(a)
Eddy current probes 4-11 (deg)															
Eddy current probes 1-7				-0.72					-0.91					-0.55	
Eddy current probes 7-5				+0.27					+0.33					+0.42	
Eddy current probes 596															
5 load cells (block) 5-7 (1b)		0		0		6.9	0		0			21.7		25.8	
2 load cells (block) 6-4		0		0		0	0		0					9.1	
2 strain gages (block) 4-10				317					57.6					83.1	
1 strain gage (block) 1-6									17.1						
Strain gage (dowel)-X net 4-10				4.2					7.8					5.3	
Strain gage (dowel)-Y net 4-10				-2.95					-5.65					-5.6	
Strain gage (dowel)-X net 7-4				0					0					1.3	
Strain gage (dowel)-Y net 7-4				0.4					0						
Strain gage (dowel)-X net CSB				4.5										3.7	
Load cell (dowel)-X net 1-6				1.4					22.5					10.2	
Load cell (dowel)-Y 1-6				0					0					6.1	
Load cell (dowel)-X 596				114					16.6					54.8	
Load cell (dowel)-Y net 596				265					7.5					0	
Spring pack 1-5				0					0			0		0	
Spring pack 19-5															

(a) Shocks 1, 2, 3, 4, 5

TABLE 9-5
SUMMARY TIME HISTORY RESPONSE, 0.20 g (GROUND) (REFERENCE)

Instrument	Core Center					Midradius					Core Boundary				
	1	2	3	4	5 ^(a)	1	2	3	4	5 ^(a)	1	2	3	4	5 ^(a)
Eddy current probes 4-11 (deg)															
Eddy current probes 1-7				1.21					1.68					1.64	
Eddy current probes 7-5				0.29					0.38					0.38	
Eddy current probes 596															
5 load cells (block) 5-7 (1b)		0	24.3	36			0		57.6			14		56.3	
2 load cells (block) 6-4				0			0		0					37	
2 strain gages (block) 4-10			138	197					164					162	
1 strain gage (block) 1-6									96.3						
Strain gage (dowel)-X net 4-10				-8.25					6.1					-18.1	
Strain gage (dowel)-Y net 4-10				235					-7.0					-13.2	
Strain gage (dowel)-X net 7-4			0.61	0					0.76					3.63	
Strain gage (dowel)-Y net 7-4				0					0					1.52	
Strain gage (dowel)-X net CSB				6.9										9.8	
Load cell (dowel)-X net 1-6			28.2	49.2					64.2					50.4	
Load cell (dowel)-Y 1-6			0	6.1					12.5					14.1	
Load cell (dowel)-X net 596			143	131					35				52	58.6	
Load cell (dowel)-Y net 596			186	193					19.5				7.2	8	
Spring pack 1-5		0		0					0			0		0	
Spring pack 19-5				0					0					0	

(a) Shocks 1, 2, 3, 4, 5

TABLE 9-6
SUMMARY TIME HISTORY RESPONSE, 0.25 g (GROUND) (REFERENCE)

Instrument	Core Center					Midradius					Core Boundary				
	1	2	3	4	5(a)	1	2	3	4	5(a)	1	2	3	4	5(a)
Eddy current probes 4-11 (deg)	0.54	0.60	0.52	0.90	0.50										
Eddy current probes 1-7	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	1.70	-1.66
Eddy current probes 7-5	0.34	0.25	0.78	1.10	0.34	+0.35	+0.39	-0.76	0.69	+0.32	+0.30	+0.34	+0.42	0.52	0.33
Eddy current probes 596	0.25	0.42	0.34	0.66	0.39										
5 load cells (block) 5-7 (1b)	3.3	0	114	143	19.5	0	0	125	91.2	10.2	17.4	54	180	182	11
2 load cells (block) 6-4	0	0	4.6	12.6	18.5	0	0	3.6	6.3	0	3.6	30.3	62	146	1.5
2 strain gages (block) 4-10	27	46.3	205	320	53	26	29.8	261.3	268	36.4	65.8	101.8	372	457	72
1 strain gage (block) 1-6	13	0	104	184	51	0	32.1	196.5	248	24.2	75.3	29	184	106	67
Strain gage (dowel)-X net 4-10	16	10	6.6	17	14	-8.5	-21.6	7.7	6.4	-13.4	3	-2.9	9.8	-28	2.9
Strain gage (dowel)-Y net 4-10	4	2	6	5.4	4				-5.6					20	
Strain gage (dowel)-X net 7-4	0	0	2.36	8.2	1.0	0	0	1.82	2.33	0	1.9	3.65	5.45	8.4	2.2
Strain gage (dowel)-Y net 7-4	0	0	2.07	3.2	0										
Strain gage (dowel)-X net CSB	2.25	2.4	4.55	4.5	3.0						6.25	5.35	10.8	9.9	3.9
Load cell (dowel)-X net 1-6	10.8	4.5	72.4	73.8	18.0	34	23.7	149.5	160.5	28	18.5	5.70	124	129	33.8
Load cell (dowel)-Y 1-6	0	0	6.6	47.3	0	0	0	21	26.2	0	0	0	76.5	57	0
Load Cell (dowel)-X net 596	68	110.5	159	181	23			101.4	93				55	95	
Load cell (dowel)-Y net 596	63	177	157	383	9.8			78.7	84				15	25.4	
Spring pack 1-5	0	0	2351	2505	0				2781					2781	
Spring pack 19-5	0	0	1179	1474	0				1518					1287	

(a) Shocks 1, 2, 3, 4, 5

Fig. 9-34. Digital peak-held response record and possible associated analog records

After the bulk of the time history data was obtained, a study was made that led to a method for treating drift in the peak-held instruments. By observing that the drift was approximately the same for all time history tests for a particular instrument, it was assumed that the drift in a particular instrument was of the same sign for all tests. In this event, if the drift were negative, it was reasonable to expect that troughs in the response would occur in at least some of the data taken throughout the program, during the time when the response dropped below the drift level while changing sign, as shown in Fig. 9-34B.

Since no such troughs were observed in the data, it was concluded that the indicated drift was of the same sign as the peak response, and therefore the drift was subtracted from the data before it was logged.

Since the peak-held dowel force transducers were subjected to loads in opposite directions, as illustrated by the dowel strain gage response of Fig. 9-35 (not peak-held), troughs in the response should have occurred regardless of the sign on the drift. However, the only troughs observed in the dowel force data were several records of the instrumentation on fuel block 007-4 (Fig. 9-36) indicating small dowel loads in the negative axis direction.

Two other explanations for the absence of troughs in the data should be considered. In the first case, the calibration curve for several strain gages and load cells in the test was made up of a straight line RMS fit of the form $Y = MV + b$. If the transducer drift was in fact nulled ($V=0$), the constant term b would still appear as drift in the data. This result was eliminated in program NEWTEN (Section 8.4.2), however, by introducing a short segment to the calibration curves intersecting the origin.

Finally, troughs in the response would be absent if the observed drift in the data were introduced during digitization. Since this was the only theory that explained the absence of troughs in the recorded dowel forces, which was expected to have some negative values similar to the nonpeak-held

Fig. 9-35. Block 004-10 net Y-axis force, test 11, shock 4, record 284 to 367

Fig. 9-36. Block 007-4 X-axis dowel force, test 19, shock 4, record 258 to 345

response in Fig. 9-35, it was adopted with the result that the drift was subtracted from the peak-held dowel force data as well.

9.5.3. Time History Response as a Function of Core Radius

The time history responses of fuel element rocking angles, dowel forces, and collision forces are given in this section as a function of core radial location on the axis of excitation. The response measured at core position number 4, 45° to the excitation, is compared with the on-axis data in Section 9.7.

To avoid excessive data reduction, only the response for a 0.25 g (ground) input was plotted. Instrument response was plotted for each shock and its associated soil modulus in the test program. Comparison of the data for shocks 3 and 4 was made with the data from sinusoidal tests since these shocks generally resulted in peak instrument response and therefore contained lower frequencies nearer to those for which the sinusoidal data were plotted.

9.5.3.1. Fuel Element Rocking Angles. The rocking angle responses of fuel blocks 001-7 and 007-5 are plotted versus core radius in Figs. 9-37 and 9-38, respectively. The rocking angles measured on fuel block 004-11 and in the permanent side reflector column were not plotted since these angles were approximately 50% as large for the same excitation, as indicated in Table 9-6.

The results in the figures indicate little variation of rocking angle with core radius. The relative magnitude of the time history response differs from that of the frequency response shown in Fig. 9-13, where the magnitude of the angle generally increases toward the core periphery. The lower rocking angle response of block 004-11, noted in Table 9-6, agrees with that shown for the sinusoidal excitation, presumably because of the greater lumping occurring at elevation 11 in the core.

Fig. 9-37. Rocking angle time history response versus core radius for block 001-7, 0.25 g (ground)

Fig. 9-38. Rocking angle time history response versus core radius for block 007-5, 0.25 g (ground)

9.5.3.2. Fuel Element Dowel Forces. Core element dowel force radial distributions are shown in Figs. 9-39 through 9-43 for instrumentation at four core elevations. Except for block 004-10, shocks 3 and 4 produced the largest dowel force response.

The core support block dowel force shown in Fig. 9-39 was larger at the periphery than at the center. A midradius point was not recorded for this instrument. The trend shown is similar to that in Fig. 9-19 for sinusoidal excitation.

For illustration, the response of the core support block dowel force instrumentation to shock 2 at the core periphery is shown in Fig. 6-40. The plateau in the curve was interpreted as a static force resulting from a packed fuel block configuration around the dowel. The peak loads in the response were interpreted as either peak-held loads in the opposite direction or transient dowel loads not associated with a packed core block configuration.

The dowel force on block 007-4 shown in Fig. 6-41 is similar to the sine sweep distribution except that the midradius loads are somewhat lower in a relative sense. The difference between these distributions could be attributed to the transient motion of the core, which was absent in a sine sweep.

The radial distribution of the dowel forces on block 001-6 at the core midheight was of a trend opposite to that measured in a sine sweep. For each time history input shown in Fig. 9-42, the dowel force maximized at the midradius location rather than at the core periphery. No specific reason is offered at this time for the distribution since the collision forces measured in the same vicinity of the core did not exhibit this trend.

The time history dowel force radial distribution for block 004-10 in Fig. 9-43 shows no specific trend among the five shocks input in the rig.

Fig. 9-39. Core support block X-axis dowel force versus core radius, time history excitation, 0.25 g (ground)

Fig. 9-40. X-axis core support floor/dowel force, shock 2, test 21, 0.25 g (ground)

Fig. 9-41. Block 007-4 X-axis dowel force versus core radius, time history excitation, 0.25 g (ground)

Fig. 9-42. Block 001-6 dowel force time history response versus core radius, 0.25 g (ground)

Fig. 9-43. Block 004-10 X-axis dowel force versus core radius, time history excitation, 0.25 g (ground)

Close inspection of the numerical data indicated that the loading transients on the dowels were faster than expected so that the peak loads were not recorded within a sampling time of 0.00125 s. It was concluded that all dowel force instrumentation should be peak held in future seismic tests.

9.5.3.3. Reflector Block Dowel Forces. The distribution of reflector block dowel loads with core elevation is shown in Fig. 9-44 for shocks 3 and 4 at 0.25 g (ground). The distributions are quite similar to that for the sinusoidal input of Fig. 9-24, indicating that the dowel load increases by a factor of about 3.5 in going from the bottom to the top of the reflector column.

The figure also shows the overall similarity of the X-axis and Y-axis loads, and illustrates that intermittently large Y-axis loads occurred. A similar result was shown by the sine sweep data where the Y-axis dowel force was approximately 1.8 times the X-axis force at the core midheight for a portion of the sweep.

9.5.3.4. Fuel Element Collision Forces. The fuel element collision force radial distributions are shown in Figs. 9-45 through 9-48 for all shocks at 0.25 g (ground). At each elevation, shocks 3 and 4 distinctly produced the greatest response.

Only block 005-7 was equipped with a special summing circuit to record the peak-held, instantaneous collision force in addition to the individual response of the load cells. For block 004-10, containing two strain gages and block 006-4, containing two load cells, the responses of the individual transducers were added in the data reduction to represent the total block load. However, as discussed in Section 9.6 covering impact orientation analysis, the sum of the individual transducers is generally much greater than the actual peak load for an edge or corner impact.

In virtually all of the data examined, the response of the lower strain gage on block 004-10 and the upper load cell on block 006-4 was 6 to

Fig. 9-44. Permanent side reflector block dowel force versus core elevation, time history excitation, 0.25 g (ground)

Fig. 9-45. Block 006-4 collision force versus core radius, time history excitation, 0.25 g (ground)

Fig. 9-46. Block 005-7 collision force time history response versus core radius, 0.25 g (ground)

Fig. 9-47. Block 004-10 strain gage block force versus core radius, time history excitation, 0.25 g (ground)

Fig. 9-48. Block 001-6 strain gage block force versus core radius, time history excitation, 0.25 g (ground)

10 times that of the remaining transducer on each block. For block 004-10, this distribution means that the recorded loads were from 11/10 to 7/6 larger than the actual collision loads if, in fact, edge or corner hits with rebounding occurred. However, there are two other possibilities that suggest scrutiny of the data from this instrument:

1. The strain gage block was calibrated for flat hits because edge hits produced large data scatter. Hence, edge hits on this block during test probably contain a high random error.
2. The displacement LVDTs and eddy current probes indicated high core lumping at level 10 in the core so that a majority of flat impacts was expected. If the overall impact orientation was, in fact, modified by size and alignment errors in the dowel and sockets, an important determination is the range of loads and number of load cycles that result from the dimensional tolerance range in the array of blocks. Estimates for the effect of geometry on dowel, block, and spring pack force are derived in Section 10.

Block 006-4 had two load cells with a preload plate, and the observed load distribution, calculated in Fig. 9-49, indicates that the individual transducer sum can be up to 40% greater than the actual impact load, if it was indeed a perfect edge or corner hit. Hence, a summing circuit should be provided on all fuel block force instruments for better accuracy of the total impact load as well as a means of determining impact orientation as discussed in Section 9.6.

The radial distribution of the time history collision forces was similar to that for sinusoidal excitation except that the increase in the time history loads near the core periphery was more dramatic. In each case, the greatest relative increase in load with radial location was at level 4, except a relatively greater response was achieved at the midradius point for sinusoidal excitation. The load interpreted from the single

$$|R_2| + |R_1| = 1.4 P.$$

Fig. 9-49. Load cell preload plate reaction to an edge impact

strain gage in the element at level 6 decreased toward the core periphery in the sine tests, while in the time history tests the curves from shocks 3 and 4 were concave downward.

Comparison of the loads measured by the strain gage at level 6 and the adjacent five-load-cell block is illustrated in Fig. 9-50. The trends of the curves are inconsistent to the extent that determination of a correction factor even roughly accurate for the loads interpreted by the block strain gages was not considered possible. Considering the comparison of load cell and strain gage data made for the sine sweep tests, the only conclusion was that the strain gage block forces were high in the range of 0% to 100%; therefore, the strain gage block force data from blocks 001-6 and 004-10 were not considered reliable.

9.5.4. Time History Response as a Function of Input g-Level

Time history displacements were input to the model at each of the four acceleration levels listed in Table 7-2. The in-core instrument response as a function of g-level is plotted in Figs. 9-51 through 9-60 for three in-core instrument locations. The variation of reflector block dowel forces with g-level was also plotted for three instrument elevations.

In all cases except the core support block dowel load, the instrument response increased nonlinearly with respect to g-level. This behavior was expected based on previous 1/5-scale, full-array test results. An explanation for the flat response of the core support block dowel force in Fig. 9-53 is the apparent restricted movement of the mating fuel block which resulted in a static limit load on the dowel illustrated in Fig. 9-40.

Another characteristic in the instrument response to g-level was that in most cases the greatest variation occurred near the core periphery. For the top reflector block Y-axis dowel force shown in Fig. 9-57, the knee in the curve depicts the intermittent large loads also shown in Figs. 9-24 and 9-44. Based on one test for each instrument location, it is difficult to

Fig. 9-50. Comparison of collision forces on block 005-7 (load cell) and block 001-6 (strain gage) versus core radius for time history excitation, 0.25 g (ground)

Fig. 9-51. Block 001-7 rocking angle versus time history g-level, three core locations, shock 4

Fig. 9-52. Block 007-5 rocking angle versus time history g-level, three core locations, shock 4

Fig. 9-53. Core support block dowel force versus time history g-level, two core locations, shock 4

Fig. 9-54. Block 007-4 X-axis dowel force versus time history g-level, three core locations, shock 4

Fig. 9-55. Block 001-6, X-axis dowel force versus time history g-level, three core locations, shock 4

Fig. 9-56. Permanent side reflector block X-axis dowel force versus time history g-level, three core elevations, shock 4

Fig. 9-57. Permanent side reflector block Y-axis dowel force versus time history g-level, three core elevations, shock 4

Fig. 9-58. Block 006-4 collision force versus time history g-level, three core locations, shock 4

Fig. 9-59. Block 005-7 collision force versus time history g-level, three core locations, shock 4

Fig. 9-60. Block 004-10 X-axis dowel force versus time history g-level, three core locations, shock 4

conclude whether these loads actually result from a frequency and mode shape change in the blocks due to a change in g-level, or whether the variations in the curve are random due to geometry or initial condition errors, or other error sources.

9.6. COLLISION FORCE ORIENTATION OF THE FIVE-LOAD-CELL BLOCK

9.6.1. Introduction

An analysis was developed to determine the orientation of collision forces on the five-load-cell block, FE 005-7, and tabulate the number of impacts for the duration of a single earthquake input. Impacts were classified as either flat, sided-flat, edge, or corner. These data provide valuable information for further code correlation and development of a technique for fuel element fatigue analysis.

9.6.2. Technique

The technique developed to determine the orientation of a collision event involved comparison of the five individual load cell measurements with the (peak-held) instantaneous total impact force, at the peak of the load pulse. Program PKLOAD was designed to print the individual load cell measurements opposite the total load for all load peaks greater than a prescribed value.

Due to the specific channel allocation, the impact orientation could not be interpreted for some element collisions. This was caused by a time lag of 1.02 ms between the individual load cell measurements on channels 43 through 47, and measurement of the instantaneous total via channel 64. Since the channels discharge when they are passed by the multiplexer, a peak occurring in this interval was recorded as a sum on channel 64, but was not represented on channels 43 through 47 until the following multiplexer pass. If, in the meantime, one or more additional collisions occurred, the data from the first collision would be distorted or lost altogether. For this reason, in future core seismic tests, the individual load

cell channels and the summation channel should be specified to be adjacent to each other in the data acquisition system.

9.6.2.1. Flat and Sided-Flat Impacts. The center load cell was the key to distinguishing flat and nonflat impacts. Since the blocks were stiff elements, edge and corner hits and their rebound loads left the center load cell essentially unloaded. This behavior was noted in most of the test data and in the calibration data. Since the corner transducers on the block were much smaller in size than those on the two-load-cell block, they were located nearer to the preload plate boundary. A static analysis similar to that depicted in Fig. 9-49 predicted the measured edge loads to be 14% larger than the actual load. The center load was analyzed to be only about 12.5% of the corner load for a corner impact. The recorded forces were not adjusted to reflect these percentages.

Using this calculation, the criteria for a flat hit on the block was written as:

1. $C \geq 0.25 (COR1_{\max} + COR2_{\max})/2,$
2. $T \leq (\Sigma 5 \text{ Load Cells}) \leq 1.15 T$

where $COR1_{\max}$ and $COR2_{\max}$ are the peak loads on two adjacent corner load cells, C is the load on the center load cell, and T is the total instantaneous load recorded on channel 64.

The second criterion was met in a true flat hit when all load cells and the sum peaked together. The 15% margin was allowed to account for small nonuniformities in the collision settling process.

There was at least one collision event where the center load cell and two corner load cells were relatively large and their sum closely approximated the total (T) while the two remaining load cell measurements were relatively small. This impact was identified as a sided-flat hit, which

can occur when two blocks impact flat-to-flat with components of rotation and translation before impact, as shown in Fig. 9-61.

9.6.2.2. Edge Impacts. An edge impact on the block was identified by a relatively small center load cell response and the sum of two adjacent load cells, plus the center load cell, being greater or equal to the total response from channel 64, within a 20% margin; i.e.,

$$1. \quad C \leq 0.25 * (COR1_{\max} + COR2_{\max})/2$$

$$2. \quad \text{Total} \leq (COR1_{\max} + COR2_{\max} \left\{ \pm \right\} C) \leq 1.20 * T$$

The second criterion allows the edge load to be up to 20% greater than the total on channel 64 to account for nonuniformities in the edge load transient or settling process. Since load verification of the five-load-cell block showed that the center load cell received a small negative reaction force during an edge hit, this term must be included in the summation for the total force.

Two other edge load configurations were impacts near, but not exactly on, the edge of the preload plate. If the impact occurred directly over two corner load cells, the center load cell would receive a negligible reaction force. If the exact point of loading in the impact occurred inside of the corner load cells, the center load cell would receive a positive reaction force. The plus-minus term in the second criterion accounts for the three possibilities. Since the five-load-cell block was located in a staggered control rod column as shown in Fig. 6-2, it was reasoned that the impact orientation of the block was more varied than if the block were located in a nonstaggered column where the interfaces were aligned.

9.6.2.3. Corner Impacts and Multiple Impacts Within One Sampling Period. Comparison of the five separate load cell measurements with the total allowed identification of corner impacts, including secondary impacts

Fig. 9-61. Fuel element sided-flat impact configuration

(rebounds) within one sampling period. A typical case would be a top edge hit of 100 lb and a bottom edge hit of 60 lb, as illustrated by the example load distribution shown below.

<u>Individual Load Cells</u>					<u>Total</u>
TR	TL	C	BR	BL	T
50	50	5	30	30	100

The data show the absence of a flat hit since the center load cell response is too low and the total is similar to the sum of only the top two load cells. The chronological order of the impacts cannot be determined, and more than two rebound impacts cannot be ascertained.

It was not conclusive whether the rebound in this case was an edge load of 60 lb or two separate corner loads of 30 lb each. A rule adopted for interpreting rebounding edge versus corner loads was that if the loads on two adjacent corner load cells were within 20% of each other, it was registered as an edge hit, otherwise two separate corner hits were registered. The top edge impact in this case is conclusive since the sum of the top two load cells is equal to the total.

If the collision had been made up of four individual corner loads, the total would not have been larger than 50 lb. Likewise, if the impact had been a right or left edge hit, the total had to be less than or equal to 80 lb. Using the adopted rule for rebounds, separate corner loads of 30 and 60 lb, respectively, would then have been registered for the remaining two load cell measurements. All identified impacts greater than a prespecified value were counted, as outlined in the next section.

9.6.2.4. Impact Orientation and Number of Load Cycles. The results of the impact orientation and load cycle measurements on the fuel block considered above are summarized in Tables 9-7 through 9-10. The computer output of program PEAKF, from which these tables were constructed, is given in Ref.

TABLE 9-7
IMPACT ORIENTATION AND COLLISION FORCE^(a)
FREQUENCY DISTRIBUTION, 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	43.4-52.6	1	128.9
Top left corner	1	53.5				
Bottom right corner	1	49.4	1	28	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 pounds.

(b) Center and one corner hit simultaneously.

TABLE 9-8
IMPACT ORIENTATION AND COLLISION FORCE^(a)
FREQUENCY DISTRIBUTION, FIVE-LOAD-
CELL BLOCK, SHOCK 3, 0.25 g (GROUND)

Occupation	Core Center		Core Mid-Radius		Core Periphery	
	No. of Events	Load Range (lb)	No. of Events	Load Range (lb)	No. of Events	Load Range (lb)
Top right corner	1	56.7	4	33.8-83.6	1	113.7
Top left corner	1	32.0				
Bottom right corner	1	28.9	1	44.3	1	61.2
Bottom left corner					1	42.2
Top side	2	88.5-112.8				
Bottom side			3	36.7-51.7		
Right side	1	83.5	1	125.7		
Left side						
Flat	2 ^(b)	41.0-50.4			4 ^(c)	48.3-180.6
					3 ^(b)	51.7-113.7
Total hits/ peak load	8	112.8	9	125.7	10	180.6

(a) Minimum recorded load (FLIMIT) = 28 pounds.

(b) Right-side flat hits.

(c) Center plus one corner hit simultaneously.

TABLE 9-9
IMPACT ORIENTATION AND COLLISION FORCE^(a)
FREQUENCY DISTRIBUTION, FIVE-LOAD-
CELL BLOCK, SHOCK 3, 0.20 g (GROUND)

Orientation	Core Center		Core Mid-Radius		Core Periphery	
	No. of Events	Load Range (lb)	No. of Events	Load Range (lb)	No. of Events	Load Range (lb)
Top right corner	1	37.9	1	64.5	1	45.6
Top left corner						
Bottom right corner						
Bottom left corner						
Top side						
Bottom side						
Right side						
Left side						
Flat					3 ^(b)	41.6-55.3
Total hits/peak load	1	37.9	1	64.5	4	55.3

(a) Minimum recorded load (FLIMIT) = 28.5 pounds.

(b) Hits were typically a large center with either top right or bottom right corner, as if this or adjacent block were bowed out near center and right side.

TABLE 9-10
IMPACT ORIENTATION AND COLLISION FORCE^(a)
FREQUENCY DISTRIBUTION, FIVE-LOAD-
CELL BLOCK, SHOCK 3, 0.20 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			2	29.3-46.5		
Top left corner						
Bottom right corner			1	37.7	1	32.8
Bottom left corner						
Top side						
Bottom side						
Right side						
Left side						
Flat					1 ^(a)	54.3
Total hits/ peak load	--	--	3	46.5	2	54.3

(a) Minimum recorded load (FLIMIT) = 20.5 pounds.

(b) Hit was large center with top right corner as if this or adjacent block were bowed.

30. Additional data showing the application of program PEAKF to responses other than collision forces are presented in Ref. 30.

Results are presented only for shocks 3 and 4 corresponding to the reference 0.20 and 0.25 g-levels since these were the only combinations producing at least several events of collision loads greater than the 28.5 lb criterion (parameter FLIMIT of program PEAKF) discussed in Section 8. The data show that for equal g-level, shocks 3 and 4 produce about the same total number and distribution of loads, with shock 3 (SSE) producing somewhat smaller loads overall.

Further analysis of the data in the tables shows that flat hits and side hits occur in about equal numbers, which is about half the number of corner hits over the shock. However, a significant percentage of the flat hits was singled out by the criterion of a large center load cell response, but they were probably not true flat hits since only the center plus one corner load cell responded. It seems quite probable that this could have been a point or line hit by the adjacent block in the staggered control rod column. The conclusion reached here was that, for the shocks investigated, true flat hits made up perhaps as low as 5% to 10% of the total number.

9.7. SPECIAL COMPARISONS

In this section, various response quantities measured in the last program are compared. The comparisons of special interest include:

1. Dowel force versus rocking angle at the same location.
2. Dowel force versus collision force at the same location.
3. X-axis versus Y-axis dowel force response for the same dowel.
4. Individual dowel forces versus the total dowel force across the block.

5. X-axis dowel force versus the modulus of the X-axis and Y-axis component loads for the same dowel.
6. The rocking angle, dowel force, and collision force response at the 45° core position versus those measured near the boundary on the line of excitation.

Comparisons of boundary forces with those recorded in the 1/5-scale, full-array test with the same input waveform (El Centro, soft soil, SSE) are presented in Section 10.4.1 with a discussion of core geometry errors. Similar comparisons of fuel element collision forces were not made since the 1/5-scale test data were presented only at the center core position (Ref. 6), while in the dowel force test, the El Centro waveform, shock number 6, was not input properly until the in-core instruments were located near the core boundary.

9.7.1. Fuel Element Dowel Force and Block Force Versus Rocking Angle

A topic of particular interest for strength verification of the dowels during seismic loading was the frequency of occurrence of simultaneous peaks in the response of dowel force and rocking angle at the fuel element interface. The basis of this concern was that more severe stresses may be imposed in the dowels when loaded by the mating block in a rocked-up configuration; i.e., the load may concentrate on one dowel rather than two or three dowels sharing it when the blocks are fully mated. Although the actual dowel stress depends on the size of the rocking angle and dowel-end configuration, Figs. 9-62 through 9-64 illustrate the relative magnitudes of the response.

The data in Figs. 9-62 and 9-63, plotted for fuel blocks 004-10/11 and 001-6/7, respectively, include the total number of rocking events recorded over the duration of shock number 4. In each figure, approximately 25% of the points were isolated (by the dashed circles) and identified as simultaneous, peak dowel force, and rocking angle events. It is emphasized

Fig. 9-62. Rocking angle versus block and dowel force, test 11, shock 4, 0.25 g (ground), blocks 004-10 and 004-11

Fig. 9-63. Rocking angle versus block and dowel force, test 11, shock 4, 0.25 g (ground) blocks 001-6 and 005-7

Fig. 9-64. Typical dowel force and rocking angle events for fuel elements 001-6/7, test 11, shock 4, 0.25 g (ground)

that the force scales on the abscissa cannot be compared since the fuel blocks under consideration were of different mass, as previously discussed in Section 9.4.

The data in the figures also illustrate that no correlation exists between rocking angle and fuel block collision force (independent of dowel force). Finally, typical dowel force and rocking angle events are shown in Fig. 9-64.

9.7.2. Dowel Force Versus Block Collision Forces

An objective of the dowel force test was the measurement of simultaneous dowel and block forces, since these loads determine the resultant fuel block and dowel stresses.

The significant dowel force events measured at two instrument locations for test 11, shock 4, are plotted versus the collision load on the same block in Figs. 9-65 and 9-66. The dashed envelope in each figure was drawn to isolate the points corresponding to simultaneous dowel force and collision force greater than 33% of the peak response on each axis. Superposition of the loads can be distinguished to within only one sampling period of 5 ms.

Figure 9-65 illustrates that for the instrumented blocks at the core midheight elevation, relatively large simultaneous dowel and block forces occurred in 8 out of 22 events. This is in contrast to the data recorded at the three-quarter elevation (Fig. 9-66) where only one such event was observed. The reason postulated for the difference in behavior was the greater rocking motion at the midheight, which resulted in more collisions and greater dowel forces per collision than at the higher elevation, where the core was shown to be more tightly lumped.

9.7.3. Dowel Load Sharing at an Interface

The dowel forces recorded on fuel element 004-10 were investigated to determine the distribution of X-axis and Y-axis forces among the three

Fig. 9-65. Block and dowel forces for 22 events, test 4, shock 4, 0.25 g (ground), fuel elements 005-7 and 001-6

Fig. 9-66. Block and dowel forces for 31 events, test 11, shock 4, 0.25 g (ground), fuel element 004-10

individual dowels. This effort was required because the analytical codes are capable of calculating only the total, or net, dowel loads across a fuel block interface. Furthermore, the analytical codes calculate only forces in line with the core excitation (X-axis), and the individual dowel pin moduli cannot be predicted from analysis. Presently, the assumption is made that only two dowels share the total load and the individual dowel pin is designed for one-half the total (predicted) load. It was hoped that this investigation would verify the current design practices.

Block 004-10 contained dowel pins instrumented with X-axis and Y-axis strain gages, which were individually monitored during the test at 1.25 ms with no peak holders. Since the dowel force pulse widths were often within two or three sampling intervals, it is probable that the true load peaks were often missed. However, as the conclusions reached in regard to load sharing were based on many load cycles, they are assumed to be generally true.

9.7.3.1. Sinusoidal Excitation at the Center Core Position. Dowel forces on block 004-10 recorded at the center core position (Position 1) were compared for the sinusoidal sweep input shown in Fig. 9-67. The frequency range during this time was approximately 2.85 Hz to 3.1 Hz as shown in Fig. 9-68.

Referring to Fig. 6-24 for dowel pin identification, the load distribution among the dowels was interpreted from the data in Figs. 9-69 through 9-79.

Comparison of the net loads^{*} with the individual dowel X and Y component loads in Figs. 9-71 through 9-73 resulted in the following observations.

1. In sharing the net X-axis dowel force as shown in Table 9-11, the maximum individual dowel pin load for the four events listed was

*The two largest positive and negative response peaks were chosen for comparison of the individual dowel loads.

Fig. 9-67. Rig displacement, test 1R, records 372-400

Fig. 9-68. Frequency, test 1R, records 372-400

Fig. 9-69. Net X-axis dowel force, test 1R, records 372-400

Fig. 9-70. Net Y-axis dowel force, test 1R, records 372-400

Fig. 9-71. Dowel force individual, test 1R, records 372-400, pin 1, X-axis

Fig. 9-72. Dowel load individual, test 1R, records 372-400, pin 2, X-axis

Fig. 9-73. Dowel force individual, test 1R, records 372-400, pin 3,
X-axis

Fig. 9-74. Dowel force individual, test 1R, records 372-400, pin 1,
Y-axis

Fig. 9-75. Dowel force individual, test 1R, records 372-400, pin 2, Y-axis

Fig. 9-76. Dowel force individual, test 1R, records 372-400, pin 3,
Y-axis

Fig. 9-77. Modulus of dowel force, test 1R records 372-400, pin 1

Fig. 9-78. Modulus of dowel force, test 1R, records 372-400, pin 2

Fig. 9-79. Modulus of dowel force, test 1R, records 372-400, pin 3

TABLE 9-11
DOWEL PIN LOAD DISTRIBUTION FOR SINUSOIDAL EXCITATION

Net Load Peak (lb)		X-Component Loads			Y-Component Loads		
X-Axis	Y-Axis	Pin 1	Pin 2	Pin 3	Pin 1	Pin 2	Pin 3
+18.3		7.2 lb 39%	4.0 lb 22%	7.1 lb 39%			
+16.5		3.8 lb 23%	4.7 lb 28%	8.0 lb 48%			
-22.3		-8.1 lb 36%	-8.5 lb 38%	-5.7 lb 26%			
-17.0		-8.6 lb 50%	-6.0 lb 35%	-2.5 lb 15%			
	10.3				7.2 lb 70%	1.8 lb 17%	1.3 lb 13%
	8.1				5.5 lb 68%	1.8 lb 22%	0.8 lb 10%
	-13.0				-6.5 lb 50%	-4.5 lb 35%	-2.0 lb 15%
	-11.3				-5.3 lb 47%	-1.7 lb 15%	-4.3 lb 38%

50% of the total, and the minimum X-axis dowel pin load was 15% of the total.

2. The average distribution for the four X-axis loading events shown was 37%, 31%, and 32% for dowel pins 1, 2, and 3, respectively, or relatively equal load sharing on an average basis.
3. For Y-axis loading during X-axis excitation, dowel pin number 1 carried between 47% and 70% of the net Y-axis load. On an average over the four loading events, the load percentages were 59, 22, and 19 for dowel pins 1, 2, and 3, respectively. The bias for pin 1 could have been due to dowel-socket clearance or location biases, or the manner of cross-axis loading.

The individual dowel pin load moduli, formed from X and Y component loads, are shown in Figs. 9-77 through 9-79. Dowel load comparisons were made from these moduli and (1) the peak X-axis force on each dowel pin, and (2) the net X-axis dowel force across the block face.

Table 9-12 lists the peak individual dowel pin X-axis loads and the peak individual pin moduli that occurred during the period of excitation, though not necessarily at the same time. Only for pin number 1, which took a greater proportion of the net X-axis load as explained above, was the modulus significantly larger than the X-component load (by 24%). Furthermore, for a peak net X-axis load of 22.3 lb, the maximum single dowel pin force modulus was 10.9 lb or 49% of this peak total. This was considered an interesting result considering the aforementioned assumption of allocating 50% of the peak net load to each of three dowels for design purposes. The final conclusion was that the peak X and Y dowel loads on a single pin do not act simultaneously based on the generally small differences between the peak component loads and peak moduli; on the basis of this small data sample, the current dowel design criterion is valid.

TABLE 9-12
SINGLE DOWEL COMPONENT LOADS AND MODULI
SINUSOIDAL EXCITATION

Dowel Pin	Peak X Load (lb)	Peak Y Load (lb)	Peak Modulus (lb)	Modulus/Peak X Load
1	8.8	9.1	10.9	1.24
2	8.5	6.5	8.6	1.01
3	8.0	6.5	8.2	1.03

9.7.3.2. Time History Excitation. The distribution of dowel forces and comparison of the individual dowel moduli to the net X-axis dowel load were obtained for fuel element 004-10 for shock 4 with the block located at both the center core and peripheral core positions. The input waveform at each location is shown in Figs. 9-80 and 9-81, and the dowel force response data at the center core position appears in Figs 9-82 through 9-92. Similar data were recorded at the peripheral core position.

The dowel force data summarized in Tables 9-13 and 9-14 illustrate distributions somewhat different than those obtained for sinusoidal excitation; i.e., dowel pin number 1 now takes the smallest share of the net X-axis load, on an average basis.* The conclusion reached was that loads of varying frequency may result in a change of force distribution among the dowels.

Table 9-15 illustrates that the individual dowel pin moduli exceed the peak individual component loads by only a small margin, as found for sinusoidal sweep excitation. Since relatively large X and Y dowel pin loads occurred during the time history with no associated increase in moduli, the conclusion was reached that peak X and Y loads did not occur simultaneously.

The data in the preceding table also suggest that the adopted technique of allocating 50% of the peak total X-axis load to each individual dowel on a fuel element for strength analysis was sufficient (based on the above sampling) since for shock 4, test 11, this results in a load of $17.45/2 = 8.73$ lb, while the peak dowel pin modulus load recorded during the shock on any one dowel was only 7.8 lb. For test 21, the half-peak net X-axis load and single pin modulus were 14.0 and 11.4 lb, respectively.

9.7.3.3. Load Cycles of the Dowel Pin Moduli. The last topic of interest in regard to individual versus net dowel loads is the number of modulus

* The three largest load pulses in the total X-axis and Y-axis dowel force responses were used for these comparisons.

Fig. 9-80. Center core position test rig displacement, test 11, shock 4, records 274-367

Fig. 9-81. Test rig displacement, test 21, shock 4, records 255-338

Fig. 9-82. Total X-axis dowel force, test 11, shock 4, records 274-367

Fig. 9-83. Total Y-axis dowel force, test 11, shock 4, records 274-367

Fig. 9-84. Pin 1 dowel force individual, test 11, shock 4, records 274-367, X-axis

Fig. 9-85. Pin 2 dowel force individual, test 11, shock 4, records 274-367, X-axis

Fig. 9-86. Pin 3 dowel force individual, test 11, shock 4, records 274-367, X direction

Fig. 9-87. Pin 1 individual, channel 16, test 11, shock 4, records 274-367, Y-axis

Fig. 9-88. Pin 2 individual, channel 18, test 11, shock 4, records 274-367, Y-axis

Fig. 9-89. Pin 3 individual, channel 20, test 11, shock 4, records 274-367, Y-axis

Fig. 9-90. Pin 1 dowel force modulus, test 11, shock 4, records 274-367

Fig. 9-91. Pin 2 dowel force modulus, test 11, shock 4, records 224-367

Fig. 9-92. Pin 3 dowel force modulus, test 11, shock 4, records 274-367

TABLE 9-13
DOWEL PIN LOAD DISTRIBUTION FOR TIME HISTORY
EXCITATION, CENTER CORE POSITION, SHOCK 4, 0.25 g (GROUND)

Net Load Peak (lb) (a)		X-Component Loads			Y-Component Loads		
X-Axis	Y-Axis	Pin 1	Pin 2	Pin 3	Pin 1	Pin 2	Pin 3
17.45		4.53 lb 27%	7.5 lb 44%	4.90 lb 28%			
12.25		3.30 lb 27%	6.0 lb 49%	3.20 lb 26%			
9.45		-0.5 lb 5%	3.3 lb 35%	7.0 lb 70%			
	-5.49				-0.42 lb 7%	-2.60 lb 47%	-2.50 lb 45%
	-5.11				-0.29 lb 6%	-2.90 lb 56%	-2.00 lb 39%
	+3.81				+0.31 lb 8%	+3.43 lb 90%	+0.24 lb 6%

(a) Only the largest three load pulses in the net X-axis and Y-axis responses were considered.

TABLE 9-14
DOWEL PIN LOAD DISTRIBUTION FOR TIME HISTORY
EXCITATION, PERIPHERAL CORE POSITION, SHOCK 4, 0.25 g (GROUND)

Net Load Peak (lb)		X-Component Loads			Y-Component Loads		
X-Axis	Y-Axis	Pin 1	Pin 2	Pin 3	Pin 1	Pin 2	Pin 3
-27.9		-10.4 lb 37%	-5.9 lb 21%	-11.41 lb 42%			
-24.9		-8.1 lb 33%	-10.2 lb 41%	-6.8 lb 27%			
+13.7		1.7 lb 12%	7.4 lb 42%	7.9 lb 46%			
-15.4					-3.5 lb 23%	-3.9 lb 25%	-8.0 lb 52%
-14.1					-0.56 lb 4%	-7.1 lb 48%	-7.1 lb 48%
-10.9					-5.9 lb 54%	-2.0 lb 18%	-3.0 lb 28%

(a) Only the largest three load pulses in the net X-axis and Y-axis responses were considered.

TABLE 9-15
SINGLE DOWEL COMPONENT LOADS AND MODULI, TIME HISTORY
EXCITATION AT 0.25 g (GROUND), SHOCK 4

Dowel Pin	Absolute Peak X Load (lb)	Absolute Peak Y Load (lb)	Peak Modulus (lb)	Modulus/Peak X
(a) Test 11 Core Center				
1	4.5	0.42	4.8	1.07
2	7.5	3.4	7.8	1.04
3	7.0	2.5	7.8	1.11
(b) Test 21 Core Periphery				
1	10.4	5.9	11.4	1.10
2	10.2	7.1	10.3	1.01
3	11.4	8.0	11.4	1.00

load cycles occurring on a single dowel pin as compared to the number of load cycles of the net X-axis load, which would be predicted by analysis. Even though the peak moduli were shown to exceed the peak X and Y component loads by only a small margin, the data indicate that the fatigue loading of the individual dowels may be actually more severe than predicted by analysis since the unidirectional analytical codes do not account for Y-axis dowel pin forces.

Table 9-16 gives the dowel load frequency distributions on fuel element 004-10 for shock 4 of test 11 [center core position, 0.25 g (ground)]. The data illustrate that, while not changing the overall number of load cycles, the admittance of Y-axis forces in the individual dowel pin moduli caused only a slight shift of the distribution to higher force levels.

The table also shows the frequency distribution of the net X-axis dowel force and the distribution obtained by halving these loads, which would apply to a single dowel using the adopted technique described in the previous section. Since the latter distribution contains several relatively large loads and about the same total number of events as the single pin modulus distributions, it would appear that its use would result in a similar fatigue stress prediction. Similar dowel force frequency distributions for test 21, shock 4 are shown in Table 9-17.

9.7.4. Off-Axis In-Core Response

This section of the report discusses the comparison of the in-core response at instrument position 4 (Fig. 6-2) with the response on the core plane parallel to the line of rig excitation.

9.7.4.1. Frequency Response Characteristics

9.7.4.1.1. Fuel Element and Reflector Block Rocking Angles. The fuel element and permanent side reflector block rocking angle frequency responses at core positions 3 and 4 are shown in Figs. 9-93 through 9-100.

TABLE 9-16
DOWEL FORCE FREQUENCY DISTRIBUTIONS TEST 11, SHOCK 4, 0.25 g (GROUND)

Load Range (lb)	Modulus Events			Peak X-Axis Events			Net X-Axis Events	Half Net X-Axis Events
	Pin 1	Pin 2	Pin 3	Pin 1	Pin 2	Pin 3		
1-2	12	17	10	9	20	10	20	15
2-3	3	2	6	7	1	1	11	7
3-4	2	3	4	2	2	2	4	0
4-5	4	2	2	2	0	1	5	1
5-6	0	0	0	0	0	0	2	2
6-7	0	1	0	0	1	0	0	0
7-8	0	2	1	0	2	1	0	0
8-9	0	0	0	0	0	0	0	1
9-10	0	0	0	0	0	0	1	0
12	0	0	0	0	0	0	2	0
17.5	0	0	0	0	0	0	1	0
Total Events	21	27	23	20	27	15	46	26

9-143

TABLE 9-17
DOWEL FORCE FREQUENCY DISTRIBUTIONS TEST 21, SHOCK 4, 0.25 g (GROUND)

Load Range (lb)	Modulus Events			Peak X-Axis Events			Net X-Axis Events	Half Net X-Axis Events
	Pin 1	Pin 2	Pin 3	Pin 1	Pin 2	Pin 3		
1-2	13	5	10	13	6	13	5	13
2-3	9	3	8	5	0	6	10	4
3-4	1	1	2	2	2	3	3	5
4-5	5	1	1	1	1	2	1	3
5-6	1	3	1	0	1	1	3	0
6-7	0	2	0	0	0	2	3	0
7-8	0	1	3	0	4	1	2	2
8-9	0	0	0	1	0	1	0	0
9-10	1	0	2	1	0	0	3	0
10-15	1	2	1	0	2	1	2	2
15-20	0	0	0	0	0	0	0	0
20-25	0	0	0	0	0	0	0	0
25-30	0	0	0	0	0	0	2	0
Total Events	31	18	28	23	16	30	34	29

9-144

Fig. 9-93. Frequency response of rocking angle at the bottom of block 007-5, core position 4, test 22

Fig. 9-94. Frequency response of rocking angle at the bottom of block 007-5, core position 3, test 17

Fig. 9-95. Frequency response of rocking angle at the bottom of block 001-7, test 22

Fig. 9-96. Frequency response of rocking angle at the bottom of block 001-7, test 17

Fig. 9-97. Frequency response of rocking angle at the bottom of block 004-11, test 22

Fig. 9-98. Frequency response of rocking angle at the bottom of block 004-11, test 17

Fig. 9-99. Frequency response of rocking angle at block PSR-596, test 22

Fig. 9-100. Frequency response of rocking angle at block PSR-596, test 1R

These figures show that the fuel elements on the periphery, 45° to the line of excitation, respond in rocking similar to those on the axis of excitation, both in magnitude and shape of the resonance curve.

The only significant difference in response occurs for the permanent side reflector block where the response at position 4 does not exhibit the characteristic step increase at the 4.1 Hz core resonance, although the magnitude at 4 Hz is only about one-third that on the core center for the same frequency, as shown previously in Fig. 9-14. For the permanent side reflector block, position 4 corresponds to column 584, 90° to the excitation at level 5-6, and this was compared to test 1R where the blocks were at the same level but on the excitation axis, column 596.

Fuel element and reflector rocking angles and orientation angles were also plotted versus time for a short segment of the sine sweep at core positions 3 and 4. The objective was to compare the block orientation angle behavior at position 4 since visual observation of the plenum blocks during a sine sweep test illustrated a swirling, or circular, motion of the fuel elements in the 45° regions.

These figures, included in Ref. 30, did not confirm such motion for the instrumented blocks. However, for the permanent side reflector block at position 4, the orientation angle was largely near 90° and the rocking angle response was symmetrical, which was the expected response at this location.

9.7.4.1.2. Fuel Element and Reflector Block Dowel Forces. An outstanding feature of the dowel force frequency response curves at position 4 was the sharp resonance point in the range of 4.3 to 4.5 Hz, which begins just as the remaining core falls out of the 4.1 Hz resonance. This peak was absent in the response at the other core locations. As shown in Figs. 9-101 through 9-106, the effect was more dramatic at lower core elevations and occurs more consistently in the X direction than in the Y direction. These curves suggest that there might be a local mode of vibration at this

Fig. 9-101. Frequency response of X-dowel force on block 007-4, test 22, position 4

Fig. 9-102. Frequency response of Y-dowel force on block 007-4, test 22, position 4

Fig. 9-103. Frequency response of X-dowel force on block 001-6, test 22, position 4

Fig. 9-104. Frequency response of Y-dowel force on block 001-6, test 22, position 4

Fig. 9-105. Frequency response of X-axis dowel force net on block 004-10, test 22, position 4

Fig. 9-106. Frequency response of Y-axis dowel force net on block 004-10, test 22, position 4

location that did not appear on instruments recorded along the line of excitation. However, the peak dowel load measured at position 4 ranged from 45% to 68% of the peak at location 3, lending support that analytical codes modeling the core center strip will predict the maximum dowel loads. The X-axis dowel load frequency response at position 3 for comparison is shown in Figs. 9-107 through 9-109.

The X-axis and Y-axis permanent side reflector block dowel force frequency response at location 4, column 584, is shown in Figs. 9-110 and 9-111. The dowel force frequency response for the block when in column 596 (position 1) is shown in Figs. 9-112 and 9-113.

Comparison of the data at the two locations reveals that the shapes of the response curves for reflector elements do not differ as much as in the case of the fuel element dowel forces. Furthermore, the peak reflector block X-axis dowel force at position 4 was only 39% of that measured at position 1, and the ratio of the peak Y-axis to X-axis forces at position 4 was only 67% versus 84% at position 1. Due to its location 90° to the excitation, it was anticipated that large reflector block Y-axis dowel forces would not occur at position 4.

9.7.4.1.3. Fuel Element Collision Forces. Examination of the data in Figs. 9-114 through 9-116 reveals a less consistent frequency response at core position 4 than was obtained for the same instruments located at core position 3, shown in Figs. 9-117 through 9-119. In the latter case, the shape of the response was fairly constant with respect to core elevation, having a maximum response in the range of 3.2 to 3.6 Hz and exhibiting the characteristic falloff after reaching the 4.1 Hz resonance.

The response at position 4 was similar to position 3 with respect to shape; however, the magnitude of the peak varies from 62% to 107% of the peak measured at position 3. This was the first case where a load response at position 4 exceeded that at position 3, on a diameter in line with the

Fig. 9-107. Frequency response of X-axis dowel force on block 007-4, test 17, position 3

Fig. 9-108. Frequency response of X-axis dowel force on block 001-6, test 17, position 3

Fig. 9-109. Frequency response of X-axis dowel force on block 004-10, test 17, position 3

Fig. 9-110. Frequency response of X-axis dowel force on block PSR-596-5, test 22, position 4

Fig. 9-111. Frequency response of Y-axis dowel force on block PSR 596-5, test 22, position 4

Fig. 9-112. Frequency response of X-axis dowel force on block PSR-596-5, test 1R, position 1

Fig. 9-113. Frequency response of Y-axis dowel force on block PSR-596-5, test 1R, position 1

Fig. 9-114. Frequency response of block 006-4, sum of two load cells, test 22, position 4

Fig. 9-115. Frequency response of block 005-7, sum of five block load cells, test 22, position 4

Fig. 9-116. Frequency response of block 004-10, sum of two strain gages, test 22, position 4

Fig. 9-117. Frequency response of block 006-4, sum of two load cells, test 17, position 3

Fig. 9-118. Frequency response of block 005-7, sum of five block force load cells, test 17, position 3

Fig. 9-119. Frequency response of block 004-10, sum of two strain gages, test 17, position 3

excitation. No conclusion was formed based on this larger load since the collision force data measured on block 004-10 was considered to contain large scatter.

The collision force measured at level 4 of core position 4 showed a prominent peak at about 4.3 Hz, similar to the dowel force response.

9.7.4.2. Time History Response Characteristics. Fuel element rocking angles, dowel forces, and block forces recorded at core position 4 for the five-column instrument assembly were compared to those recorded on the line of excitation at position 3. The comparisons were made for shock 4 of tests 20 and 25, Figs. 9-120 and 9-121, respectively, which were run at a nominal 0.20 ground g-level since test 26 was discovered to be in error with respect to its planned level of 0.25 g (ground).

The reflector block dowel forces from test 25 were compared with those from test 10 since the instrumented reflector blocks from these tests were at the same core elevation, although on radial lines, approximately 90° apart.

9.7.4.2.1. Fuel Element Rocking Angles. Rocking angles and orientation angles for fuel elements 007-5 and 001-7 are shown in Figs. 9-122 through 9-129. The data in the figures illustrate very similar rocking behavior at the two core locations in terms of both the number of events and magnitude. As in the case of sinusoidal excitation, the circular motion of the blocks observed at the 45° position was not indicated by the orientation angle response; in fact, it generally varies less than at position 3, which indicates the blocks rocked in line with the excitation axis.

9.7.4.2.2. Fuel Element and Reflector Block Dowel Forces. Dowel forces recorded on fuel elements 007-4, 001-6, and 004-10 and the permanent

Fig. 9-120. Fixture displacement, test 20, shock 4, records 266-351, 0.20 g (ground) reference

Fig. 9-121. Rig displacement, test 25, shock 4, records 300-391, 0.20 g (ground) reference

Fig. 9-122. Rocking angle of block 007-5, test 20, shock 4, records 266-351

Fig. 9-123. Orientation angle of block 007-5, test 20, shock 4, records 266-351

Fig. 9-124. Block 007-5 rocking angle, test 25, shock 4, records 300-391

Fig. 9-125. Block 007-5 orientation angle, test 25, shock 4, records 300-391

Fig. 9-126. Rocking angle of block 001-7, test 20, shock 4, records 266-351

Fig. 9-127. Orientation angle of block 001-7, test 20, shock 4, records 266-351

Fig. 9-128. Block 001-7 rocking angle, test 25, shock 4, records 300-391

Fig. 9-129. Block 001-7 orientation angle, test 25, shock 4, records 300-391

side reflector blocks are shown in Figs. 9-130 through 9-142. The data in the figures exhibited the following notable characteristics:

1. For block 007-4, the peak X-axis dowel force for position 4 was only 29% of that for position 3. The time duration of the load pulses at position 4 was much less than that at position 3, indicating free impacting as opposed to compression loading of the blocks.
2. For block 001-6, the number of loading events was approximately equal at positions 3 and 4, although the peak X-axis load was 20% larger at position 4. The position 4 peak Y-axis loads for this block were about equal to those measured at position 3, and only 22% of the peak X-axis load at position 4.
3. For block 004-10, the peak X-axis loads measured at positions 3 and 4 were about equal; however, the peak Y-axis load at position 4 was only 24% of that at position 3, and only 18% of the position 4 peak X-axis load.
4. For the permanent side reflector block, the peak X-axis load at position 4 (column 584) was only 39% of the peak X-axis load measured at position 1. The Y-axis dowel force at position 4 was negligible.

Based on the above dowel force response characteristics, which are summarized in Table 9-18, the following interpretations were made.

1. For the permanent side reflector blocks, the dowel forces in line with the excitation were much larger on the core diameter in line with the excitation where they reacted to the full core momentum. Larger circumferential dowel loads (Y-axis loads) at positions 1, 2, and 3 were present, while the Y-axis loads at position 4, normal to the line of excitation, were negligible.

Fig. 9-130. Block 007-4 total X-dowel force, test 20, shock 4, records 266-351

Fig. 9-131. Block 007-4 net X-dowel force, test 25, shock 4, records 300-391

Fig. 9-132. X-axis dowel force for block 001-6, test 20, shock 4, records 266-351

Fig. 9-133. Block 001-6 X-dowel force, test 25, shock 4, records 300-391

Fig. 9-134. Block 00-6 Y-dowel force, test 20, shock 4, records 266-351

Fig. 9-135. Block 001-6 Y-dowel force, test 25, shock 4, records 300-391

Fig. 9-136. X-axis total dowel force, test 20, shock 4, records 266-351, block 004-10

Fig. 9-137. X-axis total dowel force, test 25, shock 4, records 300-391, block 004-10

Fig. 9-138. Y-axis total dowel force, test 20, shock 4, records 266-351, block 004-10

Fig. 9-139. Y-axis total dowel force, test 25, shock 4, records 300-391, block 004-10

Fig. 9-140. PSR-596 X-dowel force, test 25, shock 4, records 300-391

Fig. 9-141. PSR-596 Y-axis dowel force, test 10, shock 4, records 289-383

Fig. 9-142. PSR-596 Y-dowel force, test 25, shock 4, records 300-391

TABLE 9-18
SUMMARY COMPARISON OF THE FUEL ELEMENT AND REFLECTOR
BLOCK PEAK DOWEL FORCES AT INSTRUMENTED CORE POSITIONS
3 AND 4, SHOCK 4, 0.20 g (GROUND) (REFERENCE)

Block	Position 3 (1b)		Position 4 (1b)	
	X-Axis	Y-Axis	X-Axis	Y-Axis
FE 007-4	2.34		0.68	
FE 001-6	50.4	14.2	60.3	13.3
FE 004-10	-18.1	-13.17	17.4	-3.13
PSR 596	143	194	56.2	13.7

2. Since the Y-axis dowel forces on block 004-10 at position 4 were relatively small compared to the X-axis loads, the individual dowel moduli were not calculated. It was anticipated that due to the inclined boundary of the rig adjacent to the 45° points (position 4), and the circular motion observed in this region during testing, the Y-axis forces and/or the dowel force moduli might be relatively large. However, the data showed otherwise.
3. The result believed most significant was the larger dowel force at position 4 recorded on block 001-6. Thus, it was concluded that the dowel loads on the fuel blocks located out in the 45° regions may be equal to or greater than the dowel loads occurring on the main core diameter.
 - a. Since no repeated tests were performed in the program, the mean peak dowel load and data spread at the two positions are unknown, and this data may minimize or even reverse the difference in the recorded loads at the two positions. An estimate of the two-sigma random data spread was calculated to be 21.5% based on the methods of Section 10, which is larger than the 20% difference shown in Table 9-17.
 - b. It is possible that the peak dowel force always occurs at another location on the main core diameter and is larger than that at the 45° region. Based on a single test run at each instrumented core position, this was actually the result, as shown previously in Fig. 9-55, where the midradius dowel load for this block at the same g-level was 64 lb.

9.7.4.2.3. Fuel Element Collision Forces. Collision forces on fuel elements 006-4 and 005-7 were recorded at core position 4 and were compared to those at position 3, using shock 4 at 0.20 g (ground) (reference). The results in Table 9-19, which were summarized from Figs. 9-143 through 9-146, show a wide variation in the response at position 4 in that no

TABLE 9-19
SUMMARY COMPARISON OF FUEL ELEMENT COLLISION FORCES AT
INSTRUMENTED CORE POSITIONS 3 AND 4, SHOCK 4,
0.20 g (GROUND) (REFERENCE)

Block	Position 3 (1b)	Position 4 (1b)
FE 006-4	36	0
FE 005-7	56	75

Fig. 9-143. Block 006-4 total block force, test 20, shock 4, records 266-351

Fig. 9-144. Block 006-4 total block force, test 25, shock 4, records 300-391

Fig. 9-145. Five load cell block collision force, test 20, shock 4

Fig. 9-146. Block 005-7 total block force, test 25, shock 4, records 300-391

impacts occurred for block 006-4 while the load at block 005-7 was 34% larger than the peak recorded at position 3.

This percentage difference is in excess of the two-sigma random data spread estimated by the component error model in Table 10-8. However, the trend of the curves in Fig. 9-59 indicates that the variation of the collision force in the vicinity of 0.185 g may really be more radical than that calculated from the slope of the curves, with the final result that a small deviation of input g-level would cause a larger deviation in the response magnitude than the value given in Table 10-8.

10. ERROR ANALYSIS

10.1. INTRODUCTION

In order to qualify the dowel force test results, an analysis was performed to estimate the overall precision and accuracy of the recorded data.

Since the tests were not originally planned to support a large error analysis effort, a number of assumptions are stated in regard to component errors in the test which were, in general, individually estimated and then combined to form the total error. However, for a limited number of instruments, straightforward statistical analyses were applied to repeated data taken under nearly identical conditions.

Throughout this section, Ref. 48 is cited almost exclusively for its error analysis methods since these were directly applicable to the testing and data handling processes performed in the dowel force test. Details of the methods and theory actually used to analyze the data are explained in Section 10.4.

10.2. ANALYSIS OBJECTIVES

The objectives of the data error analyses were to:

1. Obtain an estimate of the accuracy and precision of the test data.
2. Identify all error sources in the testing and determine their relative influence on the total error. The objectives of this

task were to -

- a. Set up a framework from which the data error in future core seismic tests may be estimated before the tests are actually run.
- b. Provide recommendations for writing error control requirements into future core seismic test specifications in order to minimize the final data errors.

10.3. ERROR IDENTIFICATION

Identification of the error sources in the test data was necessary since combination of these errors for an estimate of the total represented the only method applicable to the in-core instrument data. If repeated tests had been made with the instruments at fixed in-core locations, the precision of the final recorded data could be determined by a single straightforward calculation, as in the case of the fixed boundary transducers. Accuracy, or systematic errors in the total error, was considered separate from random error.

Comparison of the digitized test data with the results of the test laboratory's error analysis report (Ref. 49) indicated that additional error sources were present in the test data. Further investigation led to the following conclusions:

1. The digitized data contained both random and systematic error.
2. The test rig input motion contained the same kind of errors and its effect on instrument variation must be determined.
3. The dowel load cell of fuel element 001-6 provided data with an indeterminate error since it contacted the adjacent block during impact.

An error flow diagram for the dowel force test was subsequently constructed, as shown in Fig. 10-1. All errors are identified below. Numbers in parentheses match those in the figure.

10.3.1. Transducer Circuit Error

The errors in the transducer circuits downstream of the calibration circuit (10) in Fig. 10-1 are superimposed on the data in the manner described in Section 10.4. Referring to Fig. 10-1, these errors originate from summing circuit amplifiers, peak holders, and computer digitization. Applicable error values in this category, taken from Ref. 49, are summarized in Table 10-1. Figs. 10-2 through 10-6 show circuits for the five transducer types used in the test.

10.3.2. Calibration Error

Referring to Fig. 10-1, it was observed that instrument calibration was conducted from the sensor input (load, displacement, etc.) to the analog signal downstream of the bridge amplifier (and signal conditioning filter, if any). As noted in Ref. 49, the actual leads from transducer to computer were included. Thus, any systematic errors in the transducer or amplifier circuits were accounted for by the resulting calibration curves and did not enter in the analysis as additional errors. This point was somewhat indicated in Ref. 49 in the description of the "end-to-end" calibration technique.

Similar treatment holds for random error in the transducer and calibration circuit components since these contribute to the random error in the calibration data, as calculated by the methods of Section 10.4.

Comparison of the total random error present in the calibration data and that in the components making up the calibration circuits indicates a large additional error source. This source was identified in Section 6.5 as the variation in point of application of the input, a factor to which

Fig. 10-1. Flow chart for error identification

TABLE 10-1
TWO-SIGMA TRANSDUCER CIRCUIT RANDOM ERRORS

Source	Instrument	% Error (Parent) (a)
Computer	All	0.050
Peak holder	Force transducers	1.00
Summing circuit	Dowel strain gages	1.00

(a) Applies to parent population.

Fig. 10-2. Linear displacement transducer block diagram

Fig. 10-3. Pitch angle instrumentation

Fig. 10-4. Strain gaged dowel instrumentation

Fig. 10-5. Block force load cell instrumentation

10-10

Fig. 10-6. Dowel bar and reflector block instrumentation

the transducers are sensitive to some degree, and which may be controlled only within limits, depending on the type of transducer being calibrated.

For example, dowel strain gages were relatively insensitive to a change in dowel load over the small portion of the dowel protruding from the block because they were located nominally 2 in. away from the end where little relative variation in bending strain results. Furthermore, it was a simple matter to impose the dynamic calibration load at the same point on the protruding end.

In contrast, dynamic calibration of a block strain gage resulted in much greater scatter because the resultant pendulum load could lie at any point on the block face depending on the impact orientation of the pendulum. This was quite difficult to control within the limits necessary for even less-than-acceptable data scatter (Section 6.5).

Calibration data errors formulated in Section 10.4 are listed in Table 10-2. Table 10-3 gives a summary of the error sources within the calibration data.

10.3.3. Extraneous Error

Figure 10-1 indicates an extraneous error source that is somewhat ambiguous in nature because its origin is not entirely known. For example, the dc shift seen on portions of the data probably originates in the bridge amplifier, but it could also be added due to temperature changes in the other components. Sixty-cycle noise may enter at one or more of the electrical circuits. Observed on some displacement data was a 4.5 Hz beat frequency of unknown origin. These errors were generally handled test by test, compensating the systematic components where observed, and entering the random components at a single location. Typical random noise levels for the time history response data are given in Ref. 30.

TABLE 10-2
TWO-SIGMA INSTRUMENT CALIBRATION AND GEOMETRIC RANDOM ERRORS

Instrument	Calibration Error ^(a) (%)		Geometric Error (%)	
	$2\hat{S}$	N ^(b)	$2\hat{S}$	N
Eddy current probes ^(c)	15	5	2	>25
Dowel strain gages	17	14	10	6
Two-component load cell, FE	$\hat{S}_X = 21$	10	10	6
	$\hat{S}_Y = 15$	6	10	6
Two-component load cell, RB	$\hat{S}_X = 21$	6	10	6
	$\hat{S}_Y = 6$	--	10	6
FE2 block strain gage				
Restrained	26	>25	8	5
Free	110	>25	8	5
FE1 block strain gage	90	22	8	5
FE2 block load cells	12	7	8	5
FE5 block load cells	4	4	8	5

(a) See Section 10.4 for methods

(b) Number of data points

(c) Average for three probes

TABLE 10-3
CALIBRATION DATA ERROR COMPONENTS

Name	Random	Systematic
1. Amplifier error, manufacturer's quote	X	X
2. Dowel strain gage bonding material hysteresis ^(a)	X	X
3. Charge amplifier low frequency fall-off ^(a)	X	X
4. Eddy current probe on inclined surface		X
5. Load cell nonuniform preload		X
6. Load cell eccentric load effect	X	

^(a) Systematic for a transient load of given duration, but treated as random for a number of loads having random duration.

10.3.4. Geometry and Initial Condition Error

10.3.4.1. Geometry Error. Response magnitudes of the transducers were dependent on the geometry of the neighboring core elements. This behavior was first observed in previous full-array tests where spring pack forces were measured as a function of the stop insertion distance.

Geometry parameters include, but are not limited to, core block dimensional tolerances, location and size tolerances of the dowels and dowel sockets, and boundary spring pack size and adjustment tolerances. Core response quantities most sensitive to variations in these parameters were the fuel block loads and boundary hard stop loads requiring only very small surface displacements to produce large variations.

Assessment of the effect of this random error can be accomplished only by controlled parameter tests or a large amount of repetitious testing to determine the natural spread of the data. For the spring pack loads and fuel element collision loads, the data in Fig. 10-7 (from Ref. 6) were used to estimate the effect of varying geometry, based on the slope of the curve and the expected block misalignments.

The dowel-to-socket gap test results (Fig. 10-8) and column analysis results (Fig. 10-9), taken from Ref. 48, were to make an estimate for dowel force error in similar fashion, being the only data available. The estimates are summarized in Table 10-2.

Use of these data in predicting the overall test data error is discussed in Section 10.3.5. Based on the amount of data in the figures, a value of N equal to 5 was assigned for block loads and N equal to 6 for dowel forces, for use in correcting the data to the parent population.

Recognition of geometry variations in the core block and support system raised two questions fundamental to the accomplishment of the dowel force test objectives. The first was whether particular geometry

Fig. 10-7. Variation in boundary force as a function of stop position, one-fifth-scale, full-array test

Fig. 10-8. Dowel force sensitivity to socket gap size

Fig. 10-9. Maximum dowel shear force as a function of gap, single column shake test

arrangements existed giving significantly larger loads than those that were measured. The second question was how to determine the ultimate result of these critical geometries.

It was concluded that there was no sure answer to the first question since only little parametric study has been completed. The second question was answered by reverting to the basic strategy of test versus analysis in the core seismic program, plus one statistical argument. That is, the purpose of testing was to supply representative data for code correlation, and subsequently the analytical codes will be used for parametric studies investigating extreme conditions (one of which is geometry), yielding a far more efficient process than detailed parametric testing.

To answer how representative the test data is involves a scaling law analysis, which is outside the scope of this report; however, the theory in Refs. 48 and 50 can be used to account for the effect of geometry variation on the results.

In essence, the argument states that as long as variations in the data are random, having removed the systematic error, the mean value and dispersion calculated for even a small sample of data can be used to estimate the mean value and dispersion of the hypothetical parent population, which represents an infinite number of tests (with all geometry variations represented).

Specifically:

1. The mean value of the test sample is the most probable value of the response and itself is the best estimate of the parent mean value. The estimate is valid even for several data points because the sample mean converges exponentially to the parent mean as the number of tests increases, assuming random error.

2. The standard deviation of the sample (Section 10.4) is corrected to the parent distribution by multiplying by the factor

$$\sqrt{\frac{n}{n-1}} ,$$

where n is the number of tests in the sample.

The statistical argument in item 1 qualifies the test results as being representative for code correlation. Thus, the mean value of the boundary instrument response measured in three tests was taken as a satisfactory estimate of the parent mean value; for the in-core instruments, where no repeated tests were made, the measured response was most probably representative of the mean, and least probably an extreme value with respect to all possible variations in geometry.

The calculation given in item 2 specifies the spread of the data corrected to the infinite population of tests. This precision about the mean can be applied to the test results where at least two tests were performed.

In conclusion, the closeness of the sample dispersion of test data to the parent dispersion, after multiplication by the factor $n-1$, is not actually known. The reference quotes it as being "close, even for small samples." Since this correction increases the value of the dispersion, it will be assumed here that the estimate is accurate, as least until:

1. Future test results alter present estimates of mean values and dispersion for the instruments.
2. Calculations of core response with postulated extreme geometry arrangements, made using previously correlated codes, alter the present estimates.

10.3.4.2. Initial Condition Error. Core initial condition error is discussed here separately although it is actually a geometry error. The main concern was variation in transducer response as a function of the variation in the initial fuel element gap configuration within the core. Although the test results in Section 9 gave no indication of such variations, it was anticipated that variations were possible in tests where the peak in the excitation occurred very early in the shock. During dowel force testing, several seconds of low excitation preceded the peak input, in allowing the core to assume a regular lumped configuration, owing to its high damping (Section 9.3.2). Critical initial geometry configurations could be treated in analytical parametric studies as discussed in the previous section.

10.3.5. Rig Control Errors

Since core response is a function of the seismic rig input, it was necessary to determine the accuracy and precision of the rig motion relative to the inputs originally specified. No requirements on rig input error were stated in the test specification and hence no single overall error can be referenced.

Figure 10-10 shows the rig control and displacement measuring scheme. It shows that the true motion executed by the rig may vary from the GA specified reference input due to tape processing and rig control errors, (1) and (2) in the figure. This motion will also be unknown to the extent of the rig displacement LVDT transducer error by which it was measured, (3) and (8). The relative error between the Visicorder data and digital data, (6), depends on the analog-to-digital error and the Visicorder calibration error.

Rig control error must be calculated separately for sine sweeps and dwells and time history tests because each involves a different control scheme. As illustrated in Figs. 10-1 and 10-10, time history tests are initiated by a taped input signal to the control unit, while in the former case a sweep generator was used to oscillate the rig at a prescribed

Fig. 10-10. Dowel force test rig control system

g-level and sweep rate. Digital readout of the frequency is taken at the sweep generator, which is upstream of the control unit. Items (4), (5), and (7) in Fig. 10-1 were located to identify possible frequency variation between the rig and sweep generator output.

The rig control error is computed in Section 10.4, and the magnitude of the variation between the GA specified rig motion and the digital rig displacement data (9) is shown.

10.4. ERROR CALCULATIONS AND RESULTS

Several different techniques were employed to determine the accuracy and precision of the test data. All calculations follow the theory in Ref. 48.

10.4.1. Rig Motion Error

10.4.1.1. Rig Displacement Data. The accuracy and precision of the rig motion was determined for all tests that were categorized into groups having the same reference g-level. These were

1. Sine sweeps at 0.50 g
2. Sine dwells at 0.15 g
3. Sine dwells at 0.30 g
4. Sine dwells at 0.50 g
5. Time history tests at 0.10 g
6. Time history tests at 0.15 g
7. Time history tests at 0.20 g
8. Time history tests at 0.25 g

Initial investigation of the digital data indicated that the rig g-level was 25% down from the reference levels; however, the Visicorder data revealed that the reference levels were actually executed to good accuracy and precision.

For sinusoidal tests, g-levels were calculated from the Visicorder data using the formula

$$g_R = \frac{1}{386} \left(\frac{2R\pi^2}{T^2} \right) ,$$

where R = rig double amplitude, inches,
T = rig period, seconds.

For the time history tests, ground g-level was proportional to peak amplitude and was determined by comparison to the GA reference shocks.

The Visicorder data were accepted as verification of the actual rig motion because:

1. The Visicorder was calibrated using true rig static displacements prior to each test series run after a change in in-core instrument location, as shown in Fig. 10-11.
2. The signal to the Visicorder was taken just upstream of the computer as shown in Figs. 10-1 and 10-2, and hence the calibration compensates for inaccuracies in the transducer circuit.

The exact reason for the 24% discrepancy in the digital data was not resolved with the test lab; however, it was believed to be related to the signal conditioning filter (Fig. 10-2) gain of 0.746 since the data were consistently low by approximately this factor.

10.4.1.2. Rig Displacement Error. The Visicorder data were used to calculate the mean rig displacement and variation about the mean on an envelope basis for the eight test groups identified above. These data were incorporated into the overall instrument response error as described in the

Fig. 10-11. Visicorder calibration, all tests

following sections. Dispersion of the data was expressed here, and in all cases, as the fractional standard deviation

$$\hat{S}_R = \frac{\left[\sum_{n=1}^N \frac{(R_n - \bar{R})^2}{N} \right]^{1/2}}{\bar{R}}, \quad (10-1)$$

where

R_n = nth double amplitude measurement,

$\bar{R}$ = mean double amplitude in each group = $\sum_{n=1}^N \frac{R_n}{N}$,

N = number of tests in each group.

Rig displacement characteristics for test group number 8 are shown in Table 10-4. The result was a mean motion down by a total of 4.4% when including the Visicorder calibration data in Fig. 10-11, interpolating on an assumed linear curve. The data also show that test number 26 was run far off the reference g-level, which was interpreted here as a blunder and hence disregarded.

The mean value and fractional standard deviation for the other test groups are shown in Table 10-5.

10.4.1.3. Sine Sweep and Dwell Frequency Error. The accuracy and precision of the frequency measurement shown in Fig. 10-1 was investigated since this was critical to determining frequency response characteristics in the core. Accuracy of the dc proportional-to-frequency channel was checked by comparison of the rig displacement data period to the specified period during the last few cycles in the sine dwell of test number 6. Random error in the measurement was checked by observation of the signal over a portion of a sine sweep.

TABLE 10-4
RIG MOTION FOR TIME HISTORY TESTS, 0.25 g (GROUND) VISICORDER DATA VERSUS REFERENCE INPUT

Shock (a)	G (ground) (b)	R _{ref} (in.)	R _{visicorder} (in.) (c)				(d) R _{vis} (in.)	$\left[\frac{\sum (R_{ref} - R_{vis})^2}{N=3} \right]^{1/2}$	(R _{ref} - R _{vis})
			Test 11	Test 16	Test 21	Test 26			
5	0.20	3.66	3.53	3.49	3.53	2.89	3.52	0.023	+0.14
4	0.25	3.92	3.76	3.74	3.78	3.09	3.76	0.020	0.16
3	0.25	3.70	3.58	3.51	3.56	2.90	3.55	0.036	0.15
2	0.20	3.06	2.88	2.83	2.87	2.40	2.86	0.026	0.20
1	0.20	3.00	2.78	2.76	2.78	2.32	2.77	0.012	0.23

Average over 5 shocks: $\hat{R}^{(e)} = \frac{(R_{ref} - R_{vis})}{R_{ref}} \times 100 = 5.2\% \text{ (down)}$
 $-0.8\% \text{ Vis. Cal. at } R = 3.25 \text{ in.}$
 $4.4\% \text{ (down)}$

Average over 5 shocks: $\hat{S}_R^{(e)} = \left[\frac{\sum (R_{ref} - R_{vis})^2}{N=3} \right]^{1/2} \times 100 = \pm 0.65\%$
 R_{ref}

- (a) Shock 6 in error for these tests.
 (b) Refer to Table 7-3.
 (c) Measured by hand to approx. $\pm 0.02 \text{ in. (double amplitude)}$.
 (d) Does not include Test 26; improper g-level execution.
 (e) Result applicable to g-level, proportional to shock amplitude.

TABLE 10-5
DOWEL FORCE TEST RIG MOTION CHARACTERISTICS

Test	G-Level ^(a)	Mean Deviation ^(b) (%)	Standard Deviation ^(c) (%)
1. SINS	0.50 rig	+2 (0.51)	2.9
2. SIND	0.15 rig	-2	--
3. SIND	0.60 rig	0	--
4. SIND	0.50 rig	+0.8	5
5. TH	0.10 ground	0	1
6. TH	0.15 ground	-4.0	1.87
7. TH	0.20 ground	-7.4	1.38
8. TH	0.25 ground	-4.4	0.65

(a) SIND test No. 3 run at 0.6 g rather than 0.3 reference. TH test No. 26 run at approximately 0.20 g (ground) rather than 0.25 g (ground) reference and hence data not included in 8.

(b) Percentage shift from reference input.

(c) Fractional standard deviation of Visicorder data with respect to the mean in each test group.

Results of the observations led to the conclusion that the total error in the frequency coordinate was sufficiently small, having only a -1.17% difference in the dwell (4.05 Hz versus 4.10 Hz, as measured) and a total spread (3 σ) due to random noise of approximately 1% from the mean line as shown in Fig. 10-12.

10.4.2. Calibration Curves and Error Calculation

Section 6.5 presents several references to statistical calculations using the calibration data for obtaining curve fits and spread of data. These calculations are discussed in this section for the appropriate instruments.

10.4.2.1. Selection of Instruments for Random Error Calculation. The dispersion of random calibration error was essentially restricted to instruments receiving dynamic calibration. Although random behavior was present for static calibration, the error was extremely small, as recorded. Furthermore, static dowel strain gage data were not used for reduction of results, and the rig LVDT signal was statistically analyzed from the Visicorder traces of actual tests, as described in the previous section.

The eddy current probe calibration data were analyzed statistically with the result given in Table 10-2. Strictly speaking, the data spread was attributed to a systematic error, which theoretically could be corrected for data reduction by first determining the displacement mode (uplift, or plus or minus rocking), and then using the appropriate calibration curve. In neglecting this process, it was assumed that the rocking events were random in direction (as in the time history tests) and the error associated with the difference in calibration curves for each mode was an uncorrectable random error given in Table 10-2.

10.4.2.2. Curve Fits to Calibration Data. With the exception of the eddy current probes, curve fits to the data were RMS fits as these minimize the data scatter as described in Ref. 52. Since the calibration data showed

Fig. 10-12. Digital frequency random variation

a linear trend (with exception of the eddy current probes), straight line fits were used with no further correlation analysis.

Equations for the calibration lines are given in the figures of Section 6.5. In all cases, the curves miss the origin, indicating a transducer voltage with no input, which is an impossibility. The curves were adjusted to intersect with the origin in program NEWTEN (Section 8.4.2) in order to eliminate mistaking the offset as instrument drift. This modification affects only response values near the origin, which are of the least interest; that is, larger values of data in a given test are of more interest for code correlation than the very small values.

The above argument could be extended to propose weighting the larger calibration points when constructing the curve fits, as described in Ref. 48. However, all data points were given equal weight for reducing the test data.

10.4.2.3. Calibration Data Dispersion. Random dispersion of the calibration points was expressed as the fractional standard deviation with respect to the RMS line, which was calculated by the formula:

$$\hat{S} = \frac{\left(\frac{\sum_{n=1}^N [V_n - (A + BL)_n]^2}{N} \right)^{1/2}}{(A + BL)_m},$$

where V_n = nth transducer voltage measurement,

L = calibration input load,

N = number of calibration data points,

A = ordinate intercept of RMS line,

B = slope of RMS line,

$(A+BL)_n$ = transducer voltage given by RMS line
at nth data point location,

$(A+BL)_m$ = mean voltage given by RMS line
over the range of data.

An alternative expression would be to sum the quantity

$$\left(\frac{V_n - (A + BL)_n}{(A + BL)_n} \right)^2$$

to form the fractional standard deviation; however, this method overweights the deviations of small input loads for the block strain gage instruments because of the relatively large scatter in this region. In the case of dowel strain gages, where the data scatter decreased with input load, both methods gave about the same results. Fractional standard deviations of the in-core instruments are given in Table 10-2.

10.4.3. Boundary Instrument Error

Analysis of the random error in the boundary spring packs and displacement transducers was initially completed by applying the formula for fractional standard deviation to the final digitized data:

$$\hat{S}_u = \frac{\left[\frac{\sum_{n=1}^N (U_n - U_m)^2}{N} \right]^{1/2}}{\bar{U}}, \quad (10-2)$$

where the quantities are defined by comparison with Eq. 10-1. $\bar{U}$, which is the representative mean in the distribution of values (i.e., versus frequency), is equal to the mean, U_m , for single data point calculations (e.g., one boundary hit per time history).

For the boundary forces, comparisons were made to previous 1/5-scale, full-array test data to check for data consistency from one test series to another. Previous calculations were made on several sine sweep and time history tests, as well as for several hits during the same sine dwell. Displacement data from boundary LVDTs were differentiated for velocity before calculating precision, and these data were first smoothed by averaging every second data point to remove a 4.5 Hz beat frequency of unknown origin.

10.4.4. Spring Pack Force Comparison with Previous Full-Array Test Data

Data from spring pack 019-5 were recorded in the dowel force test and full-array test for sine sweeps of the same nominal g-level and sweep rate. The results, plotted for comparison in Fig. 10-13, show a wide discrepancy with respect to amplitude but a close agreement in resonance location (about 4.1 Hz).

The dowel force test curve in the figure was a calculated mean from three sine sweep tests. Although the discrepancy in the data was unexpectedly large, this amount could exist due to a 30 mil difference in spring pack adjustment, as shown in Fig. 10-7, since the instrument was removed for recalibration prior to testing. Differences in the actual dimensions of adjacent reflector blocks that were interchanged prior to testing could have added to the discrepancy; however, this geometry effect was believed to be very small because only little variation in spring pack force about the mean was observed for several tests where adjacent reflector blocks were interchanged, as noted in Section 10.4.6.

The wide variation between the curves in Fig. 10-14 was not unexpected for spring packs at different locations, even though they lie in the same region.

Fig. 10-13. Comparison of boundary loads, with previous full-array test data, spring pack 019-5, sine sweep, 0.5 g

Fig. 10-14. Comparison of boundary loads for dowel force test vs. full-array test, El Centro, soft soil, SSE

10.4.5. Boundary Spring Pack Precision in a Sine Dwell

Boundary load precision during a sine dwell test was computed for spring pack 001-5 to check for the expected low error associated with only transducer, transducer circuit, and random noise, since all other effects were constant over this small portion of the dwell. Data and computed results are shown in Table 10-6. Although the low one-sigma value of 3.14% was computed, this error was large compared to both the random channel noise and transducer circuit error. The postulated source of the error was data scatter for dynamic loading, which was not accounted for in the static calibration described in Ref. 40.

10.4.6. Precision of Boundary Loads for Sine Sweep Tests

The precision of loads on spring packs 019-5 and 001-5 was calculated for three separate sine sweep tests conducted for each change in in-core instrumentation. The results encompass all random error sources, including the rig motion and geometric effects of reflector block tolerances, since the reflector blocks adjacent to spring pack 019-5 were changed prior to each sweep in order to change the vertical position of pitch angle instrumentation in one reflector block in column number 596.

The fractional standard deviation with respect to the mean was calculated using Eq. 10-2 and applied to at least 12 points distributed over the spring pack transducer frequency response curves. The results of the calculations were:

$$\hat{SLC1-5} = 8.1\% \quad N = 36 \quad ,$$

$$\hat{SLC19-5} = 4.1\% \quad N = 36 \quad .$$

The mean frequency response curve for spring pack 001-5 is shown in Fig. 10-15.

TABLE 10-6
SPRING PACK 001-5 SINE DWELL RESPONSE AND ERROR RESULTS

A. Last 12 Hits Before Shutdown
(1b)

1.	3031.5
2.	3140.8
3.	3088.1
4.	2957.3
5.	2953.4
6.	3019.7
7.	3002.1
8.	2937.8
9.	3148.6
10.	2922.1
11.	2859.7
12.	3131.0

B. Results of Error Analysis

$$S_{SP1-5} = 94.75 \text{ lb}$$

$$\bar{U}_{SP1-5} = 3016.0 \text{ lb}$$

$$\hat{S}_{SP1-5} = 3.14\%$$

Fig. 10-15. Boundary force frequency response, dowel force test

10.4.7. Precision of Boundary Loads for Time History Tests

The precision of spring pack forces was calculated for three tests using the same nominal time history input. Fractional standard deviations were calculated using Eq. 10-2 since only one load pulse was recorded during the excitation. The results were:

$$\begin{aligned}\hat{SLC1-5} &= 5\% , \\ \hat{SLC19-5} &= 4.7\% .\end{aligned}$$

10.4.8. Precision of Boundary Velocities for Sine Sweep Tests

The precision of the core boundary velocity at four locations was calculated for four sine sweep tests in the same manner as the boundary forces described in Section 10.4.6.

Prior to this calculation, a 100 Hz waveform with a 4.5 Hz beat frequency was observed to be imposed on the LVDT data, including the rig LVDT. Since this waveform had no relation to the input motion, and was not present in the Visicorder data, it was concluded to be an extraneous signal and was essentially eliminated prior to differentiation for velocity by averaging every second displacement data point.

Typical velocity frequency response curves for each LVDT considered are shown in Figs. 10-16 through 10-19. Channels 7 and 21 record relative displacements between opposite permanent side reflector blocks and adjacent replaceable reflector blocks, while channels 5 and 6 record displacements between adjacent core support blocks in the center and edge regions of the floor.

Figures 10-16 and 10-17 depict the velocity differentiated from channel 7 for two repetitive runs. The spike in the data of Fig. 10-17 at 4.25 Hz was not considered as a valid deviation in comparison to the data

Fig. 10-16. Dowel force test 1R, average velocity, channel 7

Fig. 10-17. Dowel force test 22, average velocity, channel 7

Fig. 10-18. Dowel force test 12, average velocity, channel 2

Fig. 10-19. Dowel force test 1R, average velocity, channel 6

of Fig. 10-16 because it was an unstable region corresponding to the core second mode resonance.

The random errors in the transducer displacements for separate sine sweep tests are given below. The value of N was subsequently used to correct the results to the parent population as discussed previously in Section 10.3.4.1.

$$\begin{aligned}\hat{S}_{vel} \text{ Ch 7} &= 5.2\% \quad N = 4, \\ \hat{S}_{vel} \text{ Ch 21} &= 5.7\% \quad N = 4, \\ \hat{S}_{vel} \text{ Ch 6} &= 8.2\% \quad N = 3.\end{aligned}$$

10.5. CALCULATION OF THE IN-CORE RESPONSE RANDOM ERRORS

10.5.1. Error Calculation

The random error bound of the in-core response is calculated by combining the component errors in Table 10-7 using Eq. 10-3, which is derived in Ref. 30.

$$\begin{aligned}\frac{\hat{S}_{UR}}{\bar{U}_R} &= \left\{ \hat{S}_{G_c}^2 + \hat{S}_{N_R}^2 + \left[\frac{\bar{g}}{\bar{U}_R} \frac{\partial U_M}{\partial g} (f, g) \right]^2 \hat{S}_g^2 \right. \\ &\quad \left. + \left[\frac{\bar{f}}{\bar{U}_R} \frac{\partial U_M}{\partial f} (f, g) \right]^2 \hat{S}_f^2 + \hat{S}_{G_P}^2 + \hat{S}_{G_S}^2 + \hat{S}_{G_V}^2 + \hat{S}_{G_G}^2 \right\}^{1/2}\end{aligned}\tag{10-3}$$

where

S_{UR} = standard deviation (one-sigma) of the response,

TABLE 10-7
NOMINAL PARAMETERS AND COMPONENT ERRORS

Parameter	Instrumentation									
	DF4-10	DF7-4	DF1-6 ^(a)	DF596	DF-CSB	SG4-10	SG1-6	LC6-4	LC5-7	ECP (All) ^(b)
$U_R^{(c)}$	17 lb	7.0 lb	74 lb	100 lb	8 lb	300 lb	(d) lb	35 lb	143 lb	0.03 in.
g	0.24	0.24	0.24	0.24	0.24	0.24	(d)	0.24	0.24	0.24
f	--	--	--	--	--	--	(d)	--	--	--
$\% \left(\frac{\partial U_M}{\partial g} \right) \left(\frac{g}{U_R} \right) \hat{s}_g$	3.5	4.7	1.5	2.1	1.4	1.6	(d)	6.4	3.3	1.5
$\% \hat{s}_{G_c}/N$	0.025/ ∞	0.025/ ∞	0.025/ ∞	0.025/ ∞	0.025/ ∞	0.025/ ∞	0.025/ ∞	0.025/ ∞	0.025/ ∞	0.025/ ∞
$\% \hat{s}_{N_R}/N$	0.41/100	0.5/100	0.14/100	0.5/100	0.3/100	0.5/100	(d)	2.6/100	0.28/100	1.7/100
$\% \hat{s}_g/N$	1.0/3	1.0/3	1.0/3	1.0/3	1.0/3	1.0/3	(d)	1.0/3	1.0/3	1.0/3
$\% \hat{s}_f/N$	0	0	0	0	0	0	(d)	0	0	0
$\% \hat{s}_{G_P}/N$	0.50/ ∞	0.50/ ∞	0.50/ ∞	0.50/ ∞	0.50/ ∞	0.50/ ∞	0.50/ ∞	0.50/ ∞	0.50/ ∞	0
$\% \hat{s}_{G_S}/N$	0	0.50/ ∞	0	0	0	0	0	0	0	0
$\% \hat{s}_{G_R}/N$	8.5/14	8.5/14	9.0/8	10.0/6	8.5/14	13/25 ^(f) 55/25	45/22	6/7	2/4	7.7/5
$\% \hat{s}_{G_G}/N$	5.0/6	5.0/6	5.0/6	5.0/6	5.0/6	4.0/5	4.0/5	4.0/5	4.0/5	1/25
$\partial U_M / \partial g$	248	137	456	893	45	1986		937	1944	0.19
$\partial U_M / \partial f$	--	--	--	--	--	--	--	--	--	--

(a) Nominal value U_R contains indeterminate error due to malfunction of this instrument.

(b) Nominal value of $\bar{\theta} = 1.5$ degrees.

(c) Depends on response in test where error is calculated.

(d) Data contains excessive error; no further consideration given.

(e) Depends on test where error is calculated.

(f) For restrained (top) and free (bottom) hits.

U_R = the mean peak response within an interval of frequency or time calculated from two or more repeated tests. Since no repeated tests were performed on the in-core instruments, U_R is replaced by the single measurement U_R , which is the best estimate, per Section 10.3.4,

$\hat{S}_{G_c}$ = the fractional standard deviation of the computer digitization process (Table 10-7),

S_{N_R} = the random noise-to-signal ratio of the data,

g = input g-level,

f = input frequency,

S_g = the fractional standard deviation of the input g-level,

S_f = the fractional standard deviation of the input frequency,

S_{G_p} = the fractional standard deviation of the peak holder random error,

S_{G_v} = the fractional standard deviation of the calibration data about the RMS line, if applicable,

S_{G_s} = the fractional standard deviation of the summing circuit,

S_{G_g} = the fractional standard deviation of the core geometry affecting the instrument,

$\frac{\partial U_M(f,g)}{\partial g}$ = the change in the true core response with respect to input g-level, approximate from plots of the measured data, $\bar{U}_R$, with respect to g-level,

$\frac{\partial U_M(f,g)}{\partial f}$ = the change in the true core response of interest with respect to frequency, approximated by the frequency response of the measured data, $\bar{U}_R$,

In reference to Table 10-7, S_{G_c} was negligible and was dropped from further calculations.

For the rocking angle random error, the eddy current probe standard deviations were first calculated using Eq. 10-3 and then combined using the equation

$$\hat{s}_\theta \left[\sum_{i=1}^3 \left(\frac{\partial \theta}{\partial Z_i} \hat{s}_{Z_i} \right)^2 \right]^{1/2}$$

where Z_i is the measured eddy current probe displacement; the partial derivatives are defined in Ref. 30.

Although not given in Table 10-7, component errors were derived to calculate the overall random error of the core boundary LVDTs; however, velocity errors were calculated in Section 10.4 using repeated data. The table also shows the magnitude of the input g-level component error, which contains the weighting factor

$$\frac{\bar{g}}{\bar{U}_R} \frac{\partial U_M(f,g)}{\partial g} .$$

The two-sigma random errors of both the in-core instrument data and boundary instrument data (calculated earlier) are shown in Table 10-8.

10.5.2. Error Analysis Conclusions

The dowel force test error analysis was presented in three separate sections: (1) error identification, (2) statistical treatment of boundary instrument data from repeated tests, and (3) summation of component errors to form the total error for the in-core instrument data.

In assessing the errors, distinctions were made between systematic and random errors; in general, systematic errors were subtracted from the data where possible, leaving only random errors for statistical treatment.

Summary results are given in Table 10-8 for all test instrumentation. These results have been corrected to represent the hypothetical parent population made up of an infinite number of repeated tests. The error due to course sampling the dowel strain gages on fuel block 004-10 with no peak holder was included to extend the range of error for this instrument.

A first observation was that the random error in the boundary instrument data, computed from a sample of repeated tests, was generally less than that for the in-core data computed by estimating component errors, which were formed into a weighted RSS sum. This result lends confidence that the errors were properly identified and computed. It also suggests that the component error method is conservative.

The results in Table 10-7 illustrate that the largest contributor to the overall data error is instrument calibration error, followed by geometry error and rig input motion error. The other error sources in the table were negligible.

Calibration error was prominent in the blocks instrumented with strain gages for collision force measurement. As explained in Section 6, the

TABLE 10-8
DOWEL FORCE TEST TWO-SIGMA RANDOM ERRORS

Response	Two-Sigma Random Error (%)
Boundary spring pack force	8.2 to 16.2
Reflector block velocity	12.0
Reflector block displacement	6.2
Net fuel element dowel force ^(a)	21.0 to 22.0
Floor support block dowel force	20.0
Reflector block dowel force	22.8
Fuel element collision force (strain gage)	110.0
Fuel element collision force (load cell)	11.2 to 20.0
Rocking angle	28.0

(a) Fuel element 004-10 dowel force: 21.0% to 32.1%.
 Fuel element 001-6 dowel force: indeterminate;
 see Section 10.3.

design was highly sensitive to impact orientation and should not be considered in future core seismic testing. These results also suggest that an effort is justified to minimize calibration errors in future tests.

Geometry errors in the data were set by machining tolerances on the model elements and boundary spring position adjustment tolerances. Prior to future testing, an effort should be devoted to assessing the possible effect of geometry variations on the response of the mode.

Finally, although the rig input motion random errors of the time history tests from which the data errors were calculated were in the range of 0.65% to 1.87%, per Table 10-5, the in-core response error as a result of dynamic amplification was in the range of 1.4% to 6.4%, per Table 10-7. Although this error is reasonably small, specifications to keep the input excitation to a minimum in future core seismic tests should always be made based on the sensitivity of the response shown here.

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