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VOLUME II
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**CORE SEISMIC METHODS
VERIFICATION REPORT**

VOLUME II

**Prepared under
Contract DE-AT03-76ET35300
for the San Francisco Operations Office
Department of Energy**

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CORE SEISMIC METHODS VERIFICATION REPORT

VOLUME II

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

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FOREWORD

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

Section 1 - Introduction and Summary

Section 2 - Configuration and Seismic Input

Section 3 - Analytical Models

Section 4 - Test Program

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5. ELEMENT PROPERTIES AND CODE PARAMETERS

This section identifies the analytical code parameters and describes their calculation from graphite core component properties. The parameters were incorporated into the codes for correlation with seismic test data.

5.1. MODELING STRATEGY

Measured and calculated core component properties, forming the basis of the code parameters, were either static or dynamic in nature. Static properties included the element mass and dimensions, core gaps, the stiffness of the lateral spring packs, support posts, and dowels, and the lateral core column stiffness and breakaway force (used only for the CRUNCH-1D and CRUNCH-2D codes). Static properties were used to calculate all code parameters except those controlling the interelement collision dynamics.

The important dynamic properties of the core were considered to be the fuel element collision contact time and the coefficient of restitution, both measured in the fuel element collision tests. These properties were used to determine the spring stiffness and damping coefficient of the impact mechanisms for the mass elements in each analytical code. Core column effective damping for CRUNCH-1D and CRUNCH-2D was calculated from single column free vibration tests.

The static stiffness of the elements was not used as the impact mechanism stiffness because it did not yield an adequate interelement collision model. Static stiffnesses, however, were appropriately applied to the core spring packs, support posts, and fuel element dowels because

these structures approximated simple massless structures relative to the fuel elements with which they interact. Although static versus dynamic spring rate data were not compared for the core lateral spring pack hard stops, similarity of the fuel element dowel spring rates was verified from 1/5-scale dowel instrument calibration tests (Ref. 5.1-2). Support post stiffness is discussed further in Section 5.4.2.4.

Hence, a priority for the modeling strategy of the codes was to accurately model the interelement collision process. There were three main reasons for this priority:

1. The core configuration consisted of elements separated by gaps, which dictated that interelement collisions would occur.
2. Numerous collisions were observed and measured during seismic testing of arrays of elements.
3. Most of the measured collisions occurred at the edges or corners of the elements, making analytical prediction of these concentrated forces all the more important.

The core models were also required to satisfy additional criteria associated with the overall response of the core to seismic excitations as discussed in Section 6.1.

Parameter specifications for meeting the above requirements are described for each code in the following sections. Correlation of results with the test data is discussed in Section 6. Parameter specification was carried out simultaneously with investigation of the sensitivity of the codes to variations in the code parameters. This study included the effects of parameter variation and integration time step on the convergence and stability of the integration method. The sensitivity analyses are discussed in Section 7.

5.2. CRUNCH-1D

This section shows how the numerical values of the parameters in CRUNCH-1D were determined, and lists the values that were used in the correlation studies.

5.2.1. General Parameter Descriptions

5.2.1.1. Horizontal Strip Model. The first step in determining the parameters of CRUNCH-1D was to select the dimensions of the horizontal strip of core elements that represent the design or test core to be analyzed. This strip was considered to be located at the core midheight. The strip dimensions for tests of a single row of elements was simply the height and width of the elements being tested. The strip dimensions for the full core were not specified as easily since the reflector blocks and fuel elements are different sizes. Usually the strip was selected to have a height and width equal to the height and average width of a fuel element or reflector block (Figs. 5.2-1 and 5.2-2). Either model is valid, and other similar horizontal strip models could be justified. For the 1/5-scale, full-array test and dowel force test, the height and width of the strip were selected to be equal to the height and average width of a fuel element.

The full-array and dowel force tests also require a horizontal strip model to represent the core support floor. This is discussed in Section 5.2.4.

5.2.1.2. Column Parameters. Since CRUNCH-1D and CRUNCH-2D model the core as a strip of blocks at one level, parameters are introduced at each element to model the core column dynamics and provide a simplified connection to the core support floor.

a) STRIP WIDTH EQUAL TO AN AVERAGE FUEL BLOCK WIDTH

b) STRIP WIDTH EQUAL TO AN AVERAGE REFLECTOR BLOCK WIDTH

Fig. 5.2-1. CRUNCH-1D comparison of strip model widths

a) STRIP HEIGHT EQUAL TO A FUEL BLOCK HEIGHT

b) STRIP HEIGHT EQUAL TO A REFLECTOR BLOCK HEIGHT

Fig. 5.2-2. CRUNCH-1D comparison of strip model heights

This section presents the methods for computing the effective column mass, stiffness, breakaway force, and damping. The methods presented here apply for all CRUNCH-1D strip models, but the emphasis will be for a strip with dimensions equal to the height and average width of a fuel element.

5.2.1.2.1. Mass. The CRUNCH-1D column mass is computed by finding the mass contained within the intersection of the horizontal strip and a vertical column (Figs. 5.2-1 and 5.2-2). By selecting the strip dimensions to be equal to the height and average width of a fuel element, the CRUNCH-1D column mass is simply the mass of one fuel element. The CRUNCH-1D fuel column stiffness, damping, and breakaway force were therefore the properties of a single column.

Since only a small portion of the reflector block is contained within the strip width and height, its mass must be reduced using the following equation:

$$M_C = \frac{M_A}{R_W R_H} ,$$

where M_C = mass used in CRUNCH-1D,

M_A = actual mass of the block,

R_W = ratio of block width to strip width,

R_H = ratio of block height to strip height.

Due to the irregularity of the reflector blocks, an average value of block mass and width were used.

5.2.1.2.2. Stiffness. The column stiffness was computed by assuming that the column acts as a simply supported elastic beam until the

deflection reaches the point where the column buckles. The equation for calculating the stiffness of a simply supported column is:

$$K = \frac{48EI}{L^3} ,$$

where K = column stiffness,

E = element modulus of elasticity,

I = element area moment of inertia,

L = column height.

As with the mass, the reflector column stiffness must be scaled to account for the reflector block being larger than the strip width. The stiffness of columns that did not conform to the strip width was scaled as follows:

$$K_C = K_A/R_W ,$$

where K_C = stiffness used in CRUNCH-1D,

K_A = actual stiffness of the column,

R_W = ratio of block width to strip width.

5.2.1.2.3. Breakaway Force. The column breakaway force was defined as the product of the CRUNCH-1D model weight and the acceleration g-level required to hold a column in equilibrium at the point where gaps between the elements are about to open up. The following equation was used to determine this acceleration level (see Fig. 5.2-3):

$$\zeta \left(\frac{W_1}{2} + W_2 + \frac{W_3}{2} \right) = \frac{B}{L_1} \left(\frac{W_1}{2} + W_2 + W_3 + W_4 \right) + \frac{B}{L_3} \left(\frac{W_3}{2} + W_4 \right) ,$$

Fig. 5.2-3. CRUNCH-1D column buckling model

where ζ = acceleration g-level,
 B = width of column,
 L_1 = length of section i,
 W_1 = weight of section i,
 W_4 = column preload.

The acceleration g-level used in CRUNCH-1D was determined by assuming that the column buckled exactly in the center and that no column preload existed (i.e., $W_2 = W_4 = L_2 = 0$ and $L_1 = L_3$). These assumptions reduced the above equation to:

$$\zeta = \frac{4B}{L} ,$$

where L = total column height.

Multiplying the g-level by the sum of the element weights in the column yielded the following equation for breakaway force:

$$BF = \zeta W = \frac{4BW}{L} ,$$

where BF = breakaway force,
 W = CRUNCH-1D column weight.

Since the column weight had already been scaled to account for strip width, no further scaling was required.

5.2.1.2.4. Damping. Fuel column damping was based on 1/4-scale (Refs. 5.2-1 and 5.2-2) and 1/5-scale test data (see Section 4.6.6.2). The damping coefficient was calculated from the former because the latter was not available when the code correlation work began. The two sets of data were shown to be compatible using the scaling laws of Section 4.2.

The damping coefficient C as a function of damping ratio ξ , natural frequency f , and column mass M , is:

$$C = 4\pi \xi f M \quad . \quad (5.2-1)$$

The data in Table 5.2-1 present the column frequency and damping ratio response as a function of column preload and test rig input amplitude. These data are plotted in Fig. 5.2-4, and a linear least squares fit through the data yielded the following equation for the product ξf as a function of preload:

$$\xi f \Big|_{1/4} = 0.289 + 0.0012 P \Big|_{1/4}, \text{ (Hz)} \quad , \quad (5.2-2)$$

where P is the preload.

The data also show that ξf is approximately constant with column deflections up to 0.25 in., consistent with the use of constant damping coefficient C in CRUNCH-1D for any preload. For zero preload, Eq. 5.2-2 yields a value of 0.29 Hz for ξf .

The 1/5-scale column test data plotted in Fig. 4.6-10 exhibits similar trends of frequency and damping ratio versus column displacement. For a 0.2-in. column displacement and zero preload, the product ξf is equal to 0.30. Converting this value to 1/4-scale using the scaling laws of Section 4.2 results in a value of 0.28, which is in good agreement with the 1/4-scale data as shown in Fig. 5.2-4.

Preliminary studies indicate that better correlation is achieved by using a damping coefficient that is twice that found by the above method. This value is justifiable since the above method does not include the effect of interaction with adjacent columns and predicts forces larger than those measured during test (see Section 5.2). The following

TABLE 5.2-1
ONE-FOURTH-SCALE COLUMN RESPONSE TO SINUSOIDAL INPUT

Column Preload (lb)	Test Rig Displacement (in.)	Resonant Frequency (Hz)	Damp Ratio (%)	Product of Damping and Frequency (Hz)
30	1/16	4.7	7.0	0.33
30	1/8	4.3	7.5	0.32
30	1/4	3.8	8.6	0.33
20	1/16	4.5	6.8	0.31
20	1/8	4.0	7.6	0.30
20	1/4	3.7	8.8	0.33
2.5	1/8	3.3	8.9	0.29
2.5	1/4	2.6	11.2	0.29

Fig. 5.2-4. One-fourth scale column damping test data

equation, which includes the factor of 2.0, is recommended for computing fuel column damping:

$$C = 2(4\pi\xi fM) = 8\pi\xi fM \quad .$$

Since there are no test data for reflector column damping, a technique for estimating it had to be assumed. The technique used was to make the ratio of breakaway force to column damping force equal for both fuel columns and reflector columns. Using this technique, the reflector column damping is computed as follows:

$$C_{\text{refl}} = \left(\frac{BF_{\text{refl}}}{BF_{\text{fuel}}} \right) C_{\text{fuel}} \quad .$$

5.2.1.3. Interelement Parameters. The interelement parameters consist of the stiffness and damping associated with the collision of two elements (or columns). The interelement stiffness is determined by computing the stiffness required to produce the contact time measured in test. The following equation was used to compute interelement stiffness:

$$K = \left(\frac{\pi}{T_c} \right)^2 M \quad ,$$

where K = interelement stiffness,

T_c = contact time,

M = effective mass,

$$= \frac{M_1 M_2}{M_1 + M_2} \quad ,$$

M = mass of block i.

The interelement damping was selected to produce the coefficient of restitution measured in test. The equation for the damping coefficient associated with a two-element collision, given the damping ratio associated with that collision, is:

$$C = 2\xi\sqrt{KM} ,$$

where C = damping coefficient,

ξ = damping ratio,

K = interelement stiffness,

M = effective mass.

The equation for the damping ratio as a function of coefficient of restitution is:

$$\xi = \sqrt{\frac{1}{\left(\frac{\pi}{\ln CR}\right)^2 + 1}} ,$$

where CR = coefficient of restitution.

The addition of damping caused the contact time in CRUNCH-1D to be slightly greater than that measured in test. For graphite fuel elements, this difference was not large enough to warrant a more sophisticated method.

5.2.1.4. Core Support Floor Parameters. Core support floor parameters included core support floor mass and core support floor-to-ground damping. The first step in determining these parameters was to select a core support floor strip model. The width of the core support floor strip was equal to the width of the core midheight strip. For 1/5-scale test correlation, the strip height was set equal to the core support floor height, resulting in the core support floor strip height being 26% less than the

midheight strip. Parameter studies (Section 7.2.3) indicate that the CRUNCH-1D output forces were not very sensitive to small changes in core support floor height. However, eliminating the core support floor altogether caused large deviations in the correlation.

The core support floor mass for the CRUNCH-1D model was set equal to the product of the floor volume and the graphite density. A single floor mass model was used because of (1) simplicity, and (2) the 1/5-scale, full-array tests displayed regions of lumping in the core and floor with the floor apparently remaining lumped up to its resonant frequency of 5.1 Hz.

The core support floor-to-ground damping represents the energy losses associated with the core support blocks. This includes the energy losses due to collisions of the individual core support floor blocks (not accounted for in the single floor mass model) and friction losses in the core support structures. The core support floor-to-ground damping estimate was based on the observation that the 1/5-scale core displacement damped out in less than two cycles of motion. The equation for the decay rate of a linear spring-mass system is:

$$\frac{V}{V_0} = e^{-2n\pi\xi} ,$$

where V = final velocity,
 V_0 = initial velocity,
 n = number of cycles (integer),
 ξ = damping ratio.

Solving the above equation for ξ yields:

$$\xi = \frac{-1}{2n\pi} \ln \left(\frac{V}{V_0} \right) .$$

In order to estimate a damping value, it was assumed that 98% of the velocity was lost in two cycles of motion. This established a damping ratio of 0.31.

To convert this damping ratio to a floor-to-ground damping coefficient, the following expression was used:

$$C = 2\xi\sqrt{KM} \quad ,$$

where ξ = damping ratio = 0.31,

K = core support floor spring pack stiffness,

M = core support floor mass.

The parameter studies in Section 7.2.3 indicate that the results are not very sensitive to changes in core support mass. However, the results are sensitive to core support floor-to-ground damping. Consequently, this sensitivity must be accounted for when computing design loads.

5.2.1.5. Other Parameters. Other parameters of CRUNCH-1D include spring pack parameters, rigid link parameters, gaps, integration method, and time step. The actual spring pack mass and stiffness can be measured by test or computed by hand. Spring pack damping was specified based on the spring pack motion decay transient. If the spring pack spacing was different from that of the selected horizontal strip model, then these spring pack parameters must be scaled as follows:

$$SP_C = SP_A / (R_W R_H) \quad ,$$

where SP_C = spring pack parameter used in CRUNCH -1D,

SP_A = actual value of spring pack parameter,

R_W = ratio of horizontal spacing of spring packs
to strip width,

R_H = ratio of vertical spacing of spring packs to
strip height.

The rigid link connects the reflector blocks at each end of the core strip. The stiffness and damping of the link were computed using the techniques previously described for the other elements. The rigid link preload was computed as follows:

$$P = \rho WH \quad ,$$

where ρ = midheight pressure drop,

W = width of the horizontal strip,

H = height of the horizontal strip.

The rigid link gap and all other gaps were computed from geometric and thermal conditions.

The recommended numerical integration method is the central difference method. The recommended numerical integration time step is the smaller of 1/10 the smallest interelement contact time or 1/10 of the period of the highest linear natural frequency included in the CRUNCH-1D model. The accuracy associated with this time step is discussed in Section 7.1.

5.2.2. Test Model Parameter Input for CRUNCH-1D

The following sections describe the selection of parameters for the CRUNCH-1D models used for simulation of the seismic tests.

5.2.2.1. Collision Dynamics Tests. This section presents the CRUNCH-1D input parameters that were used for the collision dynamics correlation studies (Section 6.2.1). The weight of the 1/5-scale elements was 2.07 lb (Ref. 5.2-3).

For interelement collisions, the contact time was measured as 0.004 sec and the coefficient of restitution was approximately 0.36 (Section

4.3). Given these properties, the individual core element stiffness was computed as follows (Section 4.2.3):

$$K = \left(\frac{\pi}{T_C} \right)^2 M = 166,000 \text{ lb/in.} ,$$

where $T_C = 0.0004 \text{ sec}$,

$$M = \frac{M_1 M_2}{M_1 + M_2} = 2.68 \times 10^{-3} \text{ lb-sec/in.}^2 ,$$

$$M_1 = M_2 = 2.07 \text{ lb/(386 in./sec}^2) ,$$

and for the core element damping,

$$C = 2\xi\sqrt{KM} = 13.0 \text{ lb-sec/in.} ,$$

where

$$\xi = \frac{1}{\sqrt{\left(\frac{\pi}{1\text{in CR}} \right)^2 + 1}} = 0.309 ,$$

$$CR = 0.36 .$$

The integration time step (0.00004 sec) was selected to be 1/10 of the interelement contact time.

For bumper support collisions, the bumper contact time (0.00065 sec) and coefficient of restitution (0.396) were measured by test (see Ref. 5.2-4). The bumper stiffness and damping were computed using the same

equations as above, except now M is the mass of just one element. The bumper properties were:

Stiffness = 125,000 lb/in.

Damping = 14.7 lb-sec/in.

A nominal gap of 0.005 in. between the elements was specified for both the interelement and bumper support test arrays. Although no instrumentation was incorporated in the tests to measure small gaps between elements prior to impact, visual observation indicated the existence of gaps. Table 5.2-2 summarizes the CRUNCH-1D collision test input parameters.

5.2.2.2. Full-Array Test. The core midheight horizontal strip was selected such that its height (6.24 in.) was equal to that of a fuel element and its width (2.43 in.) was equal to the effective width of a fuel element (Fig. 5.2-5). This selection allowed each of the fuel columns to be represented by the mass of a single element. The reflector block and spring pack properties were reduced for use in CRUNCH-1D since there are on the average 2.97 fuel columns horizontally and 1.92 fuel elements vertically for each reflector block and spring pack. Table 5.2-3 summarizes the CRUNCH-1D input parameters obtained using this model. The remainder of this section presents a general discussion of how these parameters were computed. All of the equations used were previously presented in Section 5.2.1.

The element masses used in CRUNCH-1D were based on the following measured weights:

Spring pack plus core barrel plate = 21.3 lb

Average side reflector block = 26.2 lb

Fuel element = 2.07 lb

TABLE 5.2-2
CRUNCH-1D COLLISION TEST INPUT PARAMETERS

Interelement collision properties

Weight = 2.07 lb
Interelement stiffness = 166,000 lb/in.
Interelement damping = 13.0 lb-sec/in.

Bumper support collision properties

Stiffness = 125,000 lb/in.
Damping = 14.7 lb-sec/in.

Integration time step = 0.00004 sec

Interelement gaps = 0.005 in.

Fig. 5.2-5. CRUNCH-1D 1/5-scale, full-array strip model

TABLE 5.2-3
CRUNCH-1D FULL-ARRAY TEST INPUT PARAMETERS

Number of masses = 29

Integration time step = 0.00008 sec

Core midheight spring pack

Stiffness = 140 lb/in.

Damping = 0.23 lb-sec/in.

Core support floor spring pack

Stiffness = 134 lb/in.

Damping = 0.22 lb-sec/in.

Core support floor to ground damping = 2.5 lb-sec/in.

Mass Parameters

Mass Type	Element No.	Weight (lb)
Spring pack	1, 29	3.74
Reflector block	2, 28	4.60
Fuel element	3, 27	2.07
Core support floor	--	46.3

Interelement parameters

Mass Types	Damping (lb-sec/in.)	Stiffness (lb/in.)
Spring pack and reflector block	26.0	330,000
Reflector block and fuel element	18.0	228,000
Two fuel elements	13.0	166,000
Rigid link (two reflector blocks)	29.0	368,000

TABLE 5.2-3 (Continued)

Column parameters

Column Type	Stiffness (lb/in.)	Damping (lb-sec/in.)	Breakaway Force (lb)
Fuel	427	0.042	0.325
Reflector	2700	0.19	1.46

Gaps

Gaps Between	Gap (in.)
Core barrel plate and reflector block	0.0
Reflector block and fuel element	0.040
Fuel elements	0.048
Rigid link	0.870
Core support floor and spring pack	0.125

Because of the selection of horizontal strip size, the fuel element weight was used directly by CRUNCH-1D. The spring pack weight was scaled as indicated below:

$$W_C = W_A / (R_W R_H) = 3.74 \text{ lb} ,$$

where W_C = weight used in CRUNCH-1D,

W_A = actual weight = 21.3 lb,

R_W = ratio of horizontal spring pack spacing to strip width,

$$= 7.22 / 2.43 = 2.97,$$

R_H = ratio of vertical spring pack spacing to strip height

$$= 11.968 / 6.24 = 1.92.$$

The reflector block weight was scaled exactly as was the spring pack, yielding a CRUNCH-1D weight of 4.60 lb.

Fuel column stiffness was computed as follow:

$$K = \frac{48EI}{L^3} = 427 \text{ lb/in.}$$

where $E = 1 \times 10^6 \text{ lb/in.}^2$,

$I = 3.29 \text{ in.}^4$,

$L = 71.76 \text{ in.}$

The reflector column stiffness was computed in an identical manner. The area moment of inertia of the reflector column was estimated to be 62 in.⁴, which yielded a stiffness of 8000 lb/in. Scaling for the difference between the reflector block width and the strip width (2.97) yielded a CRUNCH-1D stiffness of 2700 lb/in.

The spring packs were designed to have an initial stiffness of 800 lb/in. This stiffness must be scaled to account for the fact that the spring pack spacing was larger than the width of the CRUNCH-1D horizontal strip:

$$SP_C = SP_A / (R_W R_H) = 800 / (2.97 \times 1.92) = 140 \text{ lb/in.}$$

A damping ratio of 0.10 was assigned to the spring packs. Converting this to a damping coefficient yields:

$$C = 2\xi\sqrt{KM} = 2(0.1)\sqrt{\frac{800(21.3)}{386}} = 1.33 \text{ lb-sec/in.}$$

Adjustment for spring pack spacings yields 0.23 lb-sec/in.

The horizontal strip representing the core support floor was selected to have a width identical to the core midheight strip and a height equal to the core support floor height. The core support floor weight of 46.3 lb included the support floor spring pack weights. The support floor weight was computed by using 1/7 of the measured hexagonal support block weight (9.94 lb) for each of the fuel columns and scaling that weight to find the weights associated with the reflector blocks. The weight of the core support floor spring packs (15.3 lb) was less than that of the midheight spring packs (21.3 lb) because of a different core barrel plate arrangement. The spring packs were arranged in such a way that there was 0.168 spring pack per horizontal strip.

The core support floor spring pack properties were the same as the midheight spring pack properties, which were 800 lb/in. for stiffness and 1.33 lb-sec/in. for damping. Multiplying these by the spring pack spacing (0.168) yielded a stiffness of 134 lb/in., and a damping coefficient of 0.22 lb-sec/in.

Fuel column breakaway force was computed as follows:

$$BF = \frac{4BW}{L} = \frac{4(2.813)}{71.76} \times 2.07 = 0.325 \text{ lb} .$$

The reflector column breakaway force was computed similarly as follows:

$$BF = \frac{4BW}{L} = \frac{4(4.7)4.60}{71.76} = 1.46 \text{ lb} .$$

Since the scaled CRUNCH-1D reflector block weight was used to compute the reflector block breakaway force, no additional scaling was needed.

Fuel column damping was computed as follows:

$$C = 8\pi\xi fM = 0.042 \text{ lb-sec/in.} ,$$

where $\xi f = 0.323 + 0.0026P = 0.323/\text{sec}$,

$$P = 0.00 \text{ lb},$$

$$M = 2.07/386 \text{ lb-sec}^2/\text{in}.$$

The reflector column was obtained by setting the ratio of breakaway force to column damping force equal for both fuel columns and reflector columns. Using this technique, the reflector column damping was computed as follows:

$$C_{\text{Ref1}} = \frac{BF_{\text{Ref1}}}{BF_{\text{Fuel}}} C_{\text{Fuel}} = \frac{1.46}{0.325} (0.042) = 0.19 \text{ lb-sec/in.} ,$$

A contact time of 0.0004 sec was used for the computation of all interelement springs. All interelement damping coefficients were computed based on a coefficient of restitution of 0.36. This included the interelement springs and dampers that model collisions between the spring packs and reflector blocks, between reflector blocks and fuel elements, between fuel elements, and for rigid link collisions involving the two reflector blocks.

The core support floor-to-ground damping was computed as described in Section 5.2.4. A damping ratio of 0.31 was used; this ratio caused the core support floor to lose approximately 98% of its velocity in two cycles of motion. The damping coefficient was computed as follows:

$$\begin{aligned}C &= 2\xi\sqrt{KM} = 2.5 \text{ lb-sec/in.}, \\&= \text{damping ratio} = 0.31, \\K &= \text{core support floor spring pack stiffness} \\&= 134 \text{ lb/in.}, \\M &= \text{core support floor mass}, \\&= (46.3 \text{ lb})/(386 \text{ in./sec}^2).\end{aligned}$$

An integration time step of 0.00008 sec was used for the full-array test correlation since only spring pack forces were being correlated. The period of the spring pack natural frequency was 0.05 sec, which was very large when compared to an integration time step of 0.00008 sec. If interelement forces had been of interest, a numerical time step of 0.00004 sec (1/10 of the contact time) would be required.

All gaps were computed from the test design specifications and drawings.

5.2.2.3. Dowel Force Test. The input parameters for the dowel force test were identical to the full-array test except that the spring packs had hard stops after 0.2 in. of travel. The hard stop stiffness was computed to be 580,000 lb/in. and scaled to account for spring pack spacing exactly as it was for the full-array test. Table 5.2-4 presents the force-deflection tables for the spring packs with hard stops.

Since interelement forces were of interest for this test, a numerical integration time step (0.00004 sec) equal to 1/10 of the interblock contact time was used.

TABLE 5.2-4
CRUNCH-1D DOWEL FORCE TEST INPUT PARAMETERS (a)

Integration time step = 0.00004 sec

Core midheight spring pack force-deflection table

	Deflection (in.)	Force (lb)
1	0	0
2	0.2	28.0
3	1.2	100,000

Core support floor spring pack force-deflection table

	Deflection (in.)	Force (lb)
1	0	0
2	0.2	26.8
3	1.2	97,000

(a) All other parameters are the same as shown in Table 5.2-3.

5.2.2.4. Horizontal Array Test. A strip two elements wide (Fig. 5.2-6) was selected to model the horizontal array tests. The input parameters for this test were generated using the methods previously discussed. A contact time of 0.0004 sec and coefficient of restitution of 0.36 were used for both interelement and boundary collisions. Table 5.2-5 summarizes the horizontal array test input parameters.

5.3. CRUNCH-2D

This section defines the CRUNCH-2D code and discusses the methods used for their calculation. Many of the CRUNCH-2D parameters are the same, or are derived on the same basis, as the parameters in the CRUNCH-1D code.

5.3.1. General Parameter Descriptions

5.3.1.1. Horizontal Planar Array Model. The typical HTGR core model, shown in Fig. 3.3-1, represents a horizontal planar array of the core one element high. This array is considered to be located at the core mid-height as in the case of CRUNCH-1D. The CRUNCH-2D model generally consists of three basic elements: the hexagonal core elements, which can be either fuel elements or reflector blocks, the permanent side reflector blocks, and the artificial boundary blocks that model the hard boundary supports in the two-dimensional 1/5- and 1/2-scale, 73-block, horizontal array tests. In the CRUNCH-2D code, the width of the element need not be chosen since this dimension is included as part of the core model. The only geometrical parameter to be selected by the user is the height of the elements since the fuel elements and reflector blocks usually have different heights. This procedure is the same as that described in Section 5.2.1 for the CRUNCH-1D code.

5.3.1.2. Column Parameters. The column model parameters for the CRUNCH-2D code are similar to those for the CRUNCH-1D code. Basically, the model representing the column is a linear spring in parallel with a

Fig. 5.2-6. CRUNCH-1D strip model of 73-block, two-dimensional array

TABLE 5.2-5
CRUNCH-1D 1/5-SCALE HORIZONTAL ARRAY TEST PARAMETERS

Number of masses = 9

Integration time step = 0.00004 sec

Gaps = 0.04 in. (for a total 0.4 in. gap)

Mass

Elements 1 and 9 = 3.11 lb

Elements 2-8 = 4.14 lb

Spring pack

Stiffness = 497,000 lb/in.

Damping = 39.1 lb-sec/in.

Sweep rate = 0.5 decades/min

G Level = 0.75 g

Interelement Properties

Between Masses	Damping (lb-sec/in.)	Stiffness (lb/in.)
1 & 2 and 8 & 9	22.36	284,900
2 through 8	26.06	332,000

viscous damper. The spring has a maximum load limit representing the column break point. Above this limit, the spring force remains constant. This model was selected for both CRUNCH-2D and CRUNCH-1D codes to approximate the behavior of a stacked column of elements. The viscous damper represents the energy loss that occurs due to the column motion. The only difference in the representation of the column model between the CRUNCH-1D and CRUNCH-2D codes is that CRUNCH-1D has only a single direction of column action, while CRUNCH-2D includes three directions of column action. The following sections describe the various parameters of the column model. Where similarity exists between the CRUNCH-1D and CRUNCH-2D codes, references are made to Section 5.2.2 so that duplication of formula derivation can be avoided.

5.3.1.2.1. Mass. The CRUNCH-2D column mass is the mass contained within one column width of any individual element. For example, if the core model is selected based on the height of a fuel element, then the column mass is simply the mass of one fuel block. The column mass for the reflector block column is then reduced using the following formula:

$$M_C = \frac{M_A}{R_H} ,$$

where M_C = mass used in CRUNCH-2D,

M_A = actual mass of the element,

R_H = ratio of element height to horizontal layer height.

5.3.1.2.2. Stiffness. The single direction column used in the CRUNCH-1D code is shown in Fig. 5.3-1a. The model consists of the single element i and constant stiffness K_{1i} . Also shown in the figure are the viscous damping C_{1i} and maximum spring force (breakaway force) CF_{1i} . The column stiffness was computed by assuming it behaved as a simply supported

COLUMN BUCKLING MODEL

Fig. 5.3-1a. Single-direction column model (used in CRUNCH-1D code)

HEXAGONAL BLOCK COORDINATE SYSTEM

Fig. 5.3-1b. Three-direction column model (hexagonal block) (used in CRUNCH-2D code)

elastic beam until it broke at its midpoint. The column stiffness was calculated from

$$K = \frac{48EI}{L^3} ,$$

where K = column stiffness in a single direction,

E = element modulus of elasticity,

I = element area moment of inertia,

L = column length.

As with the column mass, the column stiffness for the reflector blocks must be scaled to account for the differences in height between the reflector block and fuel element using the same ratio as developed in Section 5.3.1.2.1.

Figures 5.3-1b and 5.3-2 show the three-direction column model used in CRUNCH-2D. A separate column stiffness computation was made in each of the three nonindependent coordinate directions (a, b, and c). Thus, a change in displacement, velocity, or acceleration in one of these directions results in changes along the other two directions. The effect on column stiffness from this coupling of coordinates was accounted for and is described in detail in Ref. 5.3-1. The added effect of the hexagonal cross-sectional geometry was not taken into account, however, since it was not considered worthwhile to develop a more complex model considering the many simplifying assumptions used in the present column model.

The permanent side reflector block column models used an independent radial and tangential coordinate system rather than the a, b, and c coordinates.

5.3.1.2.3. Breakaway Force. The column breakaway force used in the CRUNCH-2D code was derived in the same manner as that used in the CRUNCH-1D code. This was described in detail in Section 5.2.1.2.3. CRUNCH-2D,

Fig. 5.3-2. Core support floor and column model

however, uses a three-direction column model (Fig. 5.3-1b) as compared to the single direction model (Fig. 5.3-1a) used in CRUNCH-1D. Therefore, a separate breakaway force computation for CRUNCH-2D was made in each of three nonindependent coordinate directions. The effect of these coupled coordinate directions on the breakaway force is described in detail in Ref. 5.3-1.

5.3.1.2.4. Damping. The equation used to determine the fuel column damping coefficient C is taken from Section 5.2.1.2.4:

$$C = 4\pi f \xi M \quad , \quad (5.3-1)$$

where ξ = damping ratio or percent of critical damping,
 f = natural frequency,
 M = column mass.

The term ξf was derived for the 1/5-scale and for the full-scale core based on 1/4-scale column vibration test data. Applying the scale factor to the 1/4-scale equation, as was done in Section 5.2.1.2.4, the following equations are obtained for the 1/5-scale and full-scale core, respectively:

$$f_{(1/5)} = 0.323 + 0.0026 P_{(1/5)} \quad ,$$

$$f_{(full)} = 0.144 + 0.0000096 P_{(full)} \quad ,$$

where P is the column preload.

Once the values of ξf and M are known, the fuel column damping coefficient is evaluated using Eq. 5.3-1. Per Section 5.2.1.2.4, the actual damping coefficient input to the CRUNCH-1D code was twice that calculated by Eq. 5.3-1 to account for interaction with the adjacent columns (alongside the linear strip) which were not modeled. This factor

was not used in CRUNCH-2D since all adjacent columns were present in the two-dimensional model.

For the permanent side reflector column, the damping coefficient was calculated using the relationship developed in Section 5.2.1.2.4, where the damping coefficient was computed based on the product of the ratio of its breakaway force to the fuel column breakaway force and the fuel column damping coefficient.

5.3.1.3. Interelement Parameters. CRUNCH-2D uses a system with interelement springs and dampers. These interelement parameters were selected based on element-on-element and element-on-boundary collision test data, and represent those values that gave the best overall correlation with the collision test results. The interelement springs were determined based on the proper element contact time measured in test, as in Section 5.2. Since the CRUNCH-2D code treats each element face as having its own gap spring, the effective spring between elements is a combination of the two springs connected in series. Therefore, the code input was twice the value of the interelement spring stiffness.

The interelement damping coefficient calculation was based on the measured coefficient of restitution (CR) from tests in the same fashion as presented in Section 5.2.

5.3.1.4. Core Support Floor Parameters. Figure 5.3-2 shows the schematic representation of the core support floor and column model. The core support floor was modeled as a single mass for simplicity and based on a lumped floor mode, as noted previously for CRUNCH-1D. The constraint system on the floor, however, is more complicated here since all spring packs of the floor level (36 for the 1/5-scale, full-array test) act on this mass. Each hexagonal fuel element and permanent side reflector block were connected to the core support floor by a column model. The core support floor mass was restrained around the perimeter with the same spring

pack model that surrounded the permanent side reflector block ring in the core model. The difference between a core spring pack and a floor spring pack was a constant factor multiplied by the spring stiffness, damping ratio, and mass. This factor was a code input value. The core support floor mass was based on the sum of all of the masses contained within the horizontal layer of the core model. The core support floor-to-ground viscous damping was computed as described for the CRUNCH-1D floor mass in Section 5.2.1.4.

5.3.1.5. Other Parameters. These parameters included spring pack parameters, gap spacing, numerical integration time step, and integration methods. Figure 5.3-3 depicts a typical spring pack mathematical model as well as various key element properties within the spring pack system. In a typical 3000-MW HTGR core, the spring pack consists of a face plate and a boronated side shield and various gaps, springs, and dampers. For the 1/5-scale, full-array and dowel force tests, the spring pack model contained no face plate and a core barrel plate took the place of the side shield. However, in all cases the numerical values for the spring stiffness were computed from design drawings, and the gaps were selected according to the various operating conditions. As was done with the reflector blocks, the spring pack properties had to be scaled according to the ratio of its vertical height to the height of the fuel element layer.

Several numerical integration methods (i.e., Euler's method, Runge-Kutta, and the central difference) have been investigated; it was found that the central difference method gave the best overall solution to the problem and, therefore, this method was used in the CRUNCH-2D code. The recommended numerical integration time step, identical to that given in the CRUNCH-1D code, was based on the smaller value of 1/10 of the inter-block contact time or 1/10 of the natural period of the highest natural frequency in the CRUNCH-2D model.

IGAP1 INITIAL RADIAL GAP BETWEEN REFLECTOR BLOCK AND FACE PLATE
 IGAP2 INITIAL TANGENTIAL GAP BETWEEN REFLECTOR BLOCK AND FACE PLATE
 IGAP3 INITIAL RADIAL GAP BETWEEN FACE PLATE AND SPRING HOUSING
 IGAP4 INITIAL TANGENTIAL GAP BETWEEN FACE PLATE AND SPRING HOUSING
 IGAP5 INITIAL NO-LOAD GAP BETWEEN PLATE SPRING PLATES, 0.62 IN.
 IGAP6 INITIAL RADIAL GAP BETWEEN CORE SUPPORT FLOOR AND FACE PLATE
 IGAP7 INITIAL TANGENTIAL GAP BETWEEN CORE SUPPORT FLOOR AND FACE PLATE

HH HEIGHT OF COIL SPRING HOUSING, IN.
 HS DISTANCE FROM PCRV WALL OUT TO CG OF SIDE SHIELD, IN.
 WFP WEIGHT OF FACE PLATE, LB
 WSS WEIGHT OF SIDE SHIELD, LB
 ISS MOMENT OF INERTIA OF SIDE SHIELD, LB-IN²

FC1 FRICTION COEFFICIENT BETWEEN REFLECTOR BLOCK AND FACE PLATE
 FC2 FRICTION COEFFICIENT BETWEEN FACE PLATE AND SPRING HOUSING
 DCSR COIL SPRING RADIAL (AXIAL) DAMPING, LB-SEC/IN.
 DCST COIL SPRING TANGENTIAL (TRAVERSE) DAMPING, LB-SEC/IN.
 DPSR PLATE SPRING RADIAL (AXIAL) DAMPING LB-SEC/IN.
 DPST PLATE SPRING ROTATIONAL DAMPING, IN.-LB-SEC/RAD

KCSR COIL SPRING RADIAL (AXIAL) STIFFNESS, LB/IN.
 KCST COIL SPRING TANGENTIAL (TRAVERSE) STIFFNESS, LB/IN.
 KPSR PLATE SPRING RADIAL (AXIAL) STIFFNESS, LB/IN.
 KSPR PLATE SPRING RADIAL (AXIAL) HIGH LIMIT STIFFNESS, LB/IN.
 KPST PLATE SPRING ROTATIONAL STIFFNESS, IN.-LB/RAD
 KPCR SPRING HOUSING RADIAL (AXIAL) STIFFNESS, LB/IN.
 KCPT SPRING HOUSING TANGENTIAL (TRAVERSE) STIFFNESS, LB/IN.

Fig. 5.3-3. Spring pack mathematical model

5.3.2. Test Model Parameter Input for CRUNCH-2D

The numerical values selected for the CRUNCH-2D parameters were based on the results of the collision dynamics tests for both multiblock collisions and bumper collisions; the two-dimensional planar array tests; the 1/5-scale, full-array and dowel force tests; and the equation developed in Section 5.3.1. Sample calculations are not shown here since they are given in Sections 5.2.2.1 and 5.2.2.2. Tables 5.3-1, 5.3-2, and 5.3-3, however, list the numerical values of all the parameters used in the CRUNCH-2D code for the 1/5- and 1/2-scale correlation studies discussed in Section 6.3.

5.4. COCO

5.4.1. General Parameter Descriptions

The parameters of the COCO model shown in Fig. 5.4-1 were based on measured block properties and dynamic test data. The basic element and column models developed for COCO were also used in the multicolumn models. All code parameters are defined and discussed below.

5.4.1.1. Interelement Parameters. The basic COCO element, shown in Fig. 5.4-2, had three impact springs and dampers (impact mechanisms) for each surface. One mechanism was located at each corner and one at the center of each surface. Correlation with the basic rocking tests demonstrated that the vertical center impact mechanism should be eliminated from the model. Consequently, the models used for both COCO and MCOCO correlation contained only vertical corner springs and dampers; however, the option for incorporating the vertical center spring and damper has been retained in the code.

The stiffness and damping coefficients for the horizontal impact mechanisms were calculated by the same method employed in CRUNCH-1D and CRUNCH-2D. In particular, the stiffness was calculated such that the

TABLE 5.3-1
INPUT PARAMETERS FOR CRUNCH-2D 1/5- AND 1/2-SCALE PLANAR ARRAY TESTS

Input Parameters	1/5 Scale	1/2 Scale
Number of fuel elements	73	73
Number of boundary elements	18	18
Interblock contact time	0.0004 sec	0.001 sec
Integration time step	0.00004 sec	0.0001 sec
Weight of fuel elements	2.07 lb	32.4 lb
Interelement spring stiffness	332,000 lb/in.	826,300 lb/in.
Interelement damping (% of critical)	30.9	30.9

TABLE 5.3-2
INPUT PARAMETERS FOR CRUNCH-2D 1/5- SCALE, FULL-ARRAY TESTS

Input Parameters	Value
Number of fuel elements	577
Number of permanent side reflector blocks	36
Interblock contact time, sec	0.0004
Integration time step, sec	0.00004
Coefficient of restitution	0.36
Weight parameters	
Fuel element (block No. 1 to 577), lb	2.07
Reflector block (block No. 578 to 613), lb	13.65
Core support floor, lb	1210
Stiffness parameters	
Fuel element, lb/in.	332,000
Reflector block, lb/in.	2,181,400
Damping parameters	
Fuel elements and reflector blocks	0.309
Core support floor to ground, lb-sec/in.	65.33
Column parameters	
Fuel Column	
Stiffness, lb/in.	427.0
Damping, lb-sec/in.	0.021
Breakaway force, lb	0.325
Reflector column	
Stiffness, lb/in.	8000
Damping, lb-sec/in.	0.28
Breakaway force, lb	4.34
Gap Between	
Fuel elements in.	0.048
Reflector blocks, in.	0.028

TABLE 5.3-3
INPUT PARAMETERS FOR CRUNCH-2D 1/5-SCALE, FULL-ARRAY DOWEL FORCE TEST
SPRING PACK PARAMETERS

Inlet Parameters	Value
Initial radial gap between reflector block and face plate, IGAP1, in.	0.002
Initial tangential gap between reflector block and face plate, IGAP2, in.*	100.0
Initial radial gap between face plate and spring housing, IGAP3, in.*	100.0
Initial tangential gap between face plate and spring housing, IGAP4, in.*	100.0
Initial no-load gap between the plates of the plate spring, IGAP5, in.	0.200
Initial radial gap between core support floor and face plate, IGAP6, in.	0.002
Initial tangential gap between core support floor and face plate, IGAP7, in.*	100.0
Height of coil spring housing, HH, in.	0.000
Distance between PCRV wall to CG of side shield, HS, in.	3.825
Weight of face plate, WFP, lb	0.000
Weight of side shield, WSS, lb	11.10
Moment of inertia of side shield, ISS, lb-in.**2	30.00
Coil spring radial (axial) stiffness, KCSR, lb/in.	978,000
Coil spring tangential (transverse) stiffness, KCST, lb/in.	50,000
Plate spring radial (axial) stiffness, KPSR, lb/in.	416.7
Plate spring radial (axial) high limit stiffness, KSPR, lb/in.	302,100
Plate spring rotational stiffness, KPST, in-lb/rad	180,000
Spring housing radial (axial) stiffness, KCPR, lb/in.	0.000
Spring housing tangential (transverse) stiffness, KCPT, lb/in.	0.000
Friction coefficient between reflector block and face plate, FC1	0.000
Friction coefficient between face plate and spring housing, FC2	0.000
Coil spring radial (axial) damping coefficient, DCSR, lb-sec/in.	77.00
Coil spring tangential (transverse) damping coefficient, DCST, lb-sec/in.	0.000
Plate spring radial (axial) damping coefficient, DPSR, lb-sec/in.	0.690
Plate spring rotational damping coefficient, DPST, in.-lb-sec/rad	0.000

*These values were set abnormally high to prevent contact in the analysis.

Fig. 5.4-1. COCO column model

Fig. 5.4-2. COCO spring-damper model

model produced the contact time that was measured in test, and the damping coefficient was selected to produce the desired coefficient of restitution. The resultant values were equally divided between the two corner impact mechanisms on one vertical surface.

Initial analyses with COCO illustrated periods of rocking motion between the elements of the column yielding vertical impacts, and periods where vertical motion of the whole column occurred with the elements in total contact. For the latter case, it was appropriate to use the static stiffness of the elements to establish the vertical spring rate. This rate, however, was larger than the horizontal spring rate and by far larger than the core support post spring rate. Therefore, the core support post spring rate controlled the column resonant frequency in the vertical direction.

The element spring rates in the vertical direction were ultimately set to values similar to the horizontal element spring rates because no tests were conducted to measure the contact time for impact of the elements in the axial (vertical) direction. This was considered a good estimate since the axial and lateral block dimensions are similar. The only remaining concern was that the vertical resonant frequency of the column remains unaltered using the lower dynamic spring rate. This was verified by a separate calculation, which showed that a change of stiffness from 500,000 lb/in. (static) to 275,000 lb/in. (dynamic) lowered the vertical resonant frequency by less than 4%.

The input to the code requires the vertical stiffnesses to be measured from the center of mass of one element to the center of mass of the next. This stiffness is computed using the following equation for two springs in series:

$$K = 2 \left(\frac{K_T K_B}{K_T + K_B} \right) ,$$

where K = total stiffness to be divided equally between
the two corner springs,

K_T = stiffness of top element,

K_B = stiffness of bottom element.

The 2 in the equation means the total stiffnesses of the top and bottom elements are used rather than the stiffness of half the element.

The damping coefficients for the vertical impact mechanisms were based on test results for axial block collisions, which produced coefficients of restitution similar to those for collisions in the horizontal (lateral) direction. Using the method of Section 5.2.1.3,

$$C = 2\xi\sqrt{KM} \quad ,$$

where C = total damping coefficient to be divided equally
between the two corner springs,

M = effective mass,

$$= \frac{M_T M_B}{M_T + M_B} \quad .$$

Table 5.4-1 summarizes the damping and stiffness values actually used for 1/5- and full-scale elements. Values are given for both horizontal and vertical corner springs. The full-scale parameters were later obtained by scaling the 1/5-scale values.

5.4.2. Test Model Parameter Input for COCO

The following sections describe the selection of parameter values for the COCO model.

TABLE 5.4-1
BASIC COCO CORNER SPRING AND DAMPER PARAMETERS

Configuration	Direction	1/5-Scale (2.07 lb block)		Full-Scale	
		Stiffness (lb/in.)	Damping (lb-sec/in.)	Stiffness (lb/in.)	Damping (lb-sec/in.)
Full on full height element	Vertical	100,000	7.15	500,000	178.87
Full on half height element	Vertical	133,000	7.15	665,000	178.87
Full height element into rigid boundary	Horizontal	166,000	13.0	830,000	325.00
Half height element into rigid boundary	Horizontal	83,000	6.5	415,000	162.50
Half height element on half height element	Vertical	200,000	7.15	1,000,000	178.87

5.4.2.1. Dowels. The dowels (Fig. 5.4-1) provide shear connections between the elements. The dowel stiffness for the 1/5-scale, single-column test elements was designed to be 4000 lb/in., which was verified by test. It was assumed that only two dowels act simultaneously, so a stiffness of 8000 lb/in. was used in the code. A damping value of 1.79 lb-sec/in. was selected based on the assumption that the ratio of dowel stiffness to damping was the same as that for the horizontal impact springs.

5.4.2.2. Friction. A friction mechanism was incorporated at each vertical block spring in COCO, MCOCO, and COCOROD. This model was a viscous damper that had its maximum force limited to the normal force times the coefficient of friction. The viscous damper was used to provide numerical stability to the traditional friction model. The recommended damping coefficients for the friction mechanism were:

1/5 scale = 40 lb-sec/in.

Full scale = 1000 lb-sec/in.

Graphite coefficients of friction were as follows:

M = 0.2 (in air)

M = 0.6 (in helium)

5.4.2.3. Support Posts. The COCO model used for correlation with the 1/5-scale, single-column shake test represented the base support as a single vertical post as shown in Fig. 5.4-1. The stiffness of the post in the model was equal to 3400 lb/in., which was the sum of the post stiffnesses in the test. The post was given a parallel damper with a ratio corresponding to a coefficient of restitution of 0.36, using the mass of the column base element. This was

$$C = 2\xi\sqrt{KM} = 2(0.309)\sqrt{\frac{3400(2.14)}{386.1}} = 2.68 \text{ lb-sec/in.}$$

Since only one support was used, a rotational spring was affixed to the bottom block to approximate the rotational restraint of the posts. The expression for this spring is

$$K_{\theta} = 1/2 K_C X^2 \quad ,$$

where K_C is the support post stiffness (3400/2 lb/in.) and X is the separation between the supports.

$$K_{\theta} = 1/2 (3400/2) (2.69)^2 = 6150 \text{ in. lb/rad}$$

5.5. MCOCO

This section presents the parameters of MCOCO, a code that represents a strip of columns across the core. The block parameters previously derived for the single-column COCO model were also used for MCOCO.

5.5.1. General Parameter Descriptions

An MCOCO model with a total of 28 columns was developed for correlation with the 1/5-scale, dowel-force test. This model (shown in Fig. 3.5-3, Section 3.5) consisted of a vertical strip of columns based on the width of an average reflector block. A strip of 24 fuel columns was used in the model rather than the 25 columns in the test core because MCOCO requires three fuel columns (or one reflector column) on each core support block. The plan view of the test core is shown in Fig. 5.5-1. The permanent reflector block width at the core periphery is 7.226 in., while the effective width of a single hexagonal element is 2.434 in. Therefore, the number of hexagonal elements associated with a reflector block is:

$$\frac{7.226}{2.434} = 2.97$$

Fig. 5.5-1. Plan view of 1/5-scale test core

The spring rates, mass, etc., of each hexagonal element must be multiplied by 2.97 prior to input into the code. Computed forces must be divided by this value to obtain loads on a single element.

The individual components of the model are presented in the following order for discussion of the model parameters:

1. Hexagonal elements (full height, half height, three-quarter height)
2. Dowels
3. Plenum elements (special case of half height)
4. Permanent reflector blocks
5. Core barrel plates
6. Core support elements
7. Spring packs
8. Gaps

A summary of the parameters derived in this section is presented in Table 5.5-1.

5.5.2. Test Model Parameter Input for MCOCO

The following sections describe the selection of parameter values for the MCOCO model of the dowel force testing configuration.

TABLE 5.5-1
MCOCO 28-COLUMN 1/5-SCALE DOWEL FORCE TEST MODEL PARAMETERS

No. of fuel element columns	24
No. of reflector block columns	2
No. of core barrel plate columns	2
No. of core support blocks	10
No. of spring packs each side	7
No. of blocks in fuel column	14
No. of blocks in reflector column	6
No. of support posts each support block	2
Fuel element weight (2.97 blocks thick) lb	6.15
Fuel element width, in.	2.83
Fuel element, height, in.	6.24
Fuel element horizontal corner spring stiffness (inter-element - 2.97 blocks thick), lb/in.	246,500
Fuel element horizontal corner damping (interelement - 2.97 element thick), lb-sec/in.	19.36
Fuel element vertical corner spring stiffness (interelement - 2.97 element thick), lb/in.	297,000
Fuel element vertical corner damping (interelement - 2.97 blocks wide), lb-sec/in.	21.25
Fuel element dowel stiffness (interelement - 2.97 blocks thick), lb/in.	23,760
Fuel element dowel damping (interelement - 2.97 blocks thick), lb-sec/in.	1.87
Permanent reflector block weight, lb	26.2
Permanent reflector block width, in.	5.7
Permanent reflector block height, in.	11.968
Permanent reflector block horizontal corner spring stiffness, lb/in.	1,050,100
Permanent reflector block horizontal corner damping, lb-sec/in.	82.48
Permanent reflector block vertical corner spring stiffness, lb/in.	1,265,300
Permanent reflector block vertical corner damping, lb-sec/in.	90.53

TABLE 5.5-1 (Continued)

Permanent reflector block dowel stiffness, lb/in.	23,760
Permanent reflector block dowel damping, lb-sec/in.	1.87
Support block weight, lb	
1, 10	8.25
2 through 9	12.65
Support block width, in.	
1, 10	5.700
2 through 9	8.626
Support block height, in.	4.600
Support block horizontal corner spring stiffness, lb/in.	245,000
Support block horizontal corner damping, lb-sec/in.	19.36
Core barrel plate weight, lb	21.3
Core barrel plate width, in.	0.5
Core barrel plate height, in.	11.968
Core barrel plate horizontal corner spring stiffness, lb/in.	246,500
Core barrel plate horizontal corner damping, lb-sec/in.	19.36
Core support post vertical stiffness (each in model), lb/in.	1,222,400
Core support post vertical damping (each in model), lb-sec/in.	87.5
Core support post horizontal stiffness (each in model), lb/in.	0
Core support post horizontal damping (each in model), lb-sec/in.	0
Spring pack soft spring stiffness, lb/in.	800
Spring pack soft spring damping, lb-sec/in.	1.33
Spring pack hard spring stiffness, lb/in.	580,000
Travel distance before hard stop, in.	0.2
Gaps between hexagonal fuel elements, in.	
Interfaces 3, 27	0.060
Interfaces 4 through 26	0.050
Gaps between reflector blocks and core barrel plate, in.	0
Gaps between plenum elements, in.	
Interfaces 3, 27	0.046
Interfaces 4 through 26	0.040

TABLE 5.5-1 (Continued)

Gaps between spring packs and core barrel plate, in.	0
Gaps core support blocks, in.	0.016
Dowel gap, in.	0.0038
Coefficient of friction, in.	0.2
Coulomb friction slope, lb-sec/in.	40

5.5.2.1. Hexagonal Blocks. The elements of MCOCO that represent hexagonal core blocks are shown in Fig. 5.5-2. Shown in detail are mass, spring, and damper locations. The impact mechanisms act only in the plane of motion. The constants K_H , K_V , C_H , and C_V are single element horizontal and vertical spring rate and damping coefficients, respectively. The vertical spring rate was obtained directly from Table 5.4-1; however, the horizontal spring rate of 166,000 lb/in. was halved to account for two full height elements in mutual impact as opposed to one such element impacting a rigid boundary. Depending on the size of the elements colliding in the model, factors other than one half were used to set resultant spring rates and damping coefficients. Several of these factors are calculated below for illustration.

1. Half Height Elements

Horizontal spring and damping factor = 0.5

Vertical spring factor - half height to half height = $2 \left[\frac{2(2)}{2 + 2} \right] = 2.0$

Vertical spring factor - half height to three-quarter height (or vice versa) = $2 \left[\frac{2 \frac{4}{3}}{2 + \frac{4}{3}} \right] = 1.6$

Vertical spring factor - half height to full height (or vice versa) = $2 \left[\frac{2(1)}{2 + 1} \right] = 1.3333$

Vertical damping factor = 1.0

2. Three-Quarter Height Elements

Horizontal spring and damping factor = 0.75

Fig. 5.5-2. MCOCO mass, spring, and damper components

$$\begin{array}{l} \text{Vertical spring factor - three-quarter} \\ \text{height to three-quarter height} \end{array} = 2 \left[\frac{\frac{4}{3} \frac{4}{3}}{\frac{4}{3} + \frac{4}{3}} \right] = 1.3333$$

$$\text{Vertical damping factor} = 1.0$$

5.5.2.2. Dowels. The constants K_D and C_D in Fig. 5.5-2 are the dowel spring rate and damping coefficients, respectively. There is one effective dowel at the interface between vertically adjacent elements in this code. The dowel stiffness K_D was set equal to twice that of a single dowel embedded in a 1/5-scale test element on the assumption that only two of the three dowels at an interface resist shear forces simultaneously. Thus, K_D becomes:

$$K_D = 2 \times 4000 \times 2.97 = 23,760 \text{ lb/in.}$$

The dowel damping coefficient C_D was computed assuming the ratio of dowel spring rate to damping was the same as that for the lateral impact mechanisms. Hence,

$$C_D = \frac{23,760}{246,500} C_H ,$$

where $C_H = 19.36$. Substitution yields

$$C_D = \frac{23,760}{246,500} (19.36) = 1.87 .$$

5.5.2.3. Plenum Elements. The top row of hexagonal elements was half height and differed from other levels by the absence of a control rod element centered in each refueling region. Hence, only 6/7 of the mass of a refueling region was present in the plenum level. This necessitated

multiplication of plenum element parameters by 6/7 of the half-height values. Effective "thickness" in the plenum region was, therefore,

$$(6/7) (2.97) = 2.55 \quad .$$

The factor for the weight of a plenum element was 6/7 that for a half-height element, or:

$$(6/7) (0.5) = 0.429 \quad .$$

Other factors replacing those listed for half-height elements in Section 5.5.2, Item 1, were:

$$\text{Horizontal spring and damping factor} = 0.5 \left(\frac{6}{7} \right) = 0.429$$

$$\begin{aligned} \text{Vertical spring factor - half height} \\ \text{to half height} \end{aligned} = 2 \left[\frac{2 \left(\frac{6}{7} \right)^2}{2 \left(\frac{6}{7} \right) + 2} \right] = 1.846$$

$$\begin{aligned} \text{Vertical spring factor - full height} \\ \text{to half height} \end{aligned} = 2 \left[\frac{2 \left(\frac{6}{7} \right)^1}{2 \left(\frac{6}{7} \right) + 1} \right] = 1.263$$

$$\begin{aligned} \text{Vertical damping factor} \end{aligned} = 2 \left[\frac{\left(\frac{6}{7} \right)^1}{\left(\frac{6}{7} \right) + 1} \right] = 0.923$$

Plenum element dowel stiffness and damping were:

$$\text{Stiffness} = \frac{6}{7} (23,760) = 20,370 \text{ lb/in.}$$

$$\text{Damping} = \frac{6}{7} (1.87) = 1.60 \text{ lb/in.}$$

5.5.2.4. Permanent Reflector Blocks (PRB). No studies were conducted to determine "usable" spring rates for the PRBs. The method utilized to develop input for the code was to employ the same K/M ratio as for the hexagonal elements. Therefore,

$$K_{V_{PRB}} = K_V \frac{W_{PRB}}{W} , \quad (5.5 -1)$$

The weight of a PRB was 26.2 lb (Fig. 5.5-3). Hence, substitution into Eq. 5.5-1 yields:

$$\begin{aligned} K_{V_{PRB}} &= (2.97) (100,000) \frac{26.2}{(2.97) (2.07)} , \\ &= 1,266,000 \text{ lb/in.} \end{aligned}$$

The damping was therefore:

$$\begin{aligned} C_{V_{PRB}} &= C_V \frac{W_{PRB}}{W} , \\ &= 21.25 \frac{(26.2)}{(2.97) (2.07)} = 90.56 \text{ lb-sec/in.} \end{aligned}$$

In the MCOCO code, all values of spring constant and damping coefficient are multiples of full-height fuel element parameters. Therefore, for the PRB, vertical factors were:

$$\text{Spring rate} = \frac{1,266,000}{297,000} = 4.26 ,$$

$$\text{Damping} = \frac{90.56}{21.25} = 4.26 .$$

Fig. 5.5-3. Typical permanent reflector block (PRB)

In the horizontal direction:

$$\begin{aligned} K_{H_{PRB}} &= K_H \frac{W_{PRB}}{W} , \\ &= 2.97 (83,000) \frac{26.2}{(2.97) (2.07)} = 1,050,500 \text{ lb/in.} , \end{aligned}$$

$$\begin{aligned} C_{H_{PRB}} &= C_H \frac{W_{PRB}}{W} , \\ &= 19.36 \frac{26.2}{(2.97) (2.07)} = 82.5 \text{ lb-sec/in.} . \end{aligned}$$

Factors for horizontal springs and dampers were:

$$\text{Spring rate} = \frac{1,050,500}{246,500} = 4.26$$

$$\text{Damping} = \frac{82.5}{19.36} = 4.26 .$$

Weight, dimensions, and locations of the impact mechanisms for a typical PRB are shown in Fig. 5.5-3.

5.5.2.5. Core Barrel Plates. The core barrel plates are affixed directly to the spring packs as shown in Fig. 5.5-4. They are approximately the size of the PRB, 0.5 in. thick, and are made of steel. In the MCOCO code, the plates have only two degrees of freedom (horizontal translation and rotation). The stiffness used for the horizontal impact mechanism between the plate and the reflector block was the same as that used for the PRB.

Fig. 5.5-4. Core barrel plate

5.5.2.6. Core Support Blocks. There are two core support block configurations. The hexagonal block, shown in Fig. 5.5-5, supports fuel and control rod columns. The PRB support block is shown in Fig. 5.5-6. Both figures also present weight and dimension data. The actual hexagonal block supports seven columns (six fuel, one central control rod) and weighs 9.94 lb (see Fig. 5.5-5). The MCOCO model, on the other hand, supports three in the horizontal plane, 2.97 blocks in width, for a total of:

$$3 (2.97) = 8.91 \text{ elements} \quad .$$

The weight of the hexagonal support block for the MCOCO model is therefore:

$$W_{CSB} = \frac{8.91}{7} (9.94) = 12.65 \text{ lb} \quad .$$

The code used the weight of the PRB support block directly from Fig. 5.5-6. The floor blocks were supported by ball bearings mounted in bronze bushings (see Fig. 5.5-7). System flexibility can be approximated by two series springs (bearing and bushing). The calculated flexibility for this system with three bearings was approximately 4,000,000 lb/in. Maximum core support post spring rates, however, should not exceed values that yield a K/M ratio greater than those for the fuel elements. Therefore,

$$K_{SUP} = 297,000 \left[\frac{12.65}{(2.07) (2.97)} \right] = 611,200 \text{ lb/in.}$$

It should be noted that the fuel element vertical spring rate (297,000 lb/in.) was derived for elements in contact (series springs). Since the support post was in contact with a rigid boundary, the total spring rate was double the above value. Hence,

$$K_{SUPC} = 2(611,200) = 1,222,400 \text{ lb/in.}$$

WT = 9.94 LB

Fig. 5.5-5. Core support block for hexagonal core elements

WT = 8.25 LB

Fig. 5.5-6. Core support block for permanent reflector blocks

BEARING SUPPORT

Fig. 5.5-7. Bearing support for 1/5-scale, full-array test configuration

This value was the spring rate for one support post. Damping was computed from the expression:

$$C_{SUPC} = \xi \sqrt{2_{SUPC} M_{SUP}} \quad .$$

The square root appears in the above equation since the element is in contact with a boundary. Substitution of percentage of critical damping, spring rate, and mass in the above expression yields:

$$C_{SUPC} = 0.309 \sqrt{2(1,222,400) \left(\frac{12.65}{386.1} \right)} ,$$

$$= 87.5 \text{ lb-sec/in.}$$

K_{SUPC} and C_{SUPC} were utilized as the support post spring rate and damping in the MCOCO model.

5.5.2.7. Spring Packs. The MCOCO core strip was based upon a single PRB and associated single spring pack. Spring packs, however, were actually attached to the corners of one core barrel plate. It was assumed that each side resisted half the load. Spring packs were affixed to core barrel plates, as shown in Fig. 5.5-8. The spring pack model consisted of a bilinear spring, with spring rates K_1 and K_2 , as shown in the figure. Associated damping was computed as follows:

$$C_{SPK} = \xi \sqrt{K_{SPK} M_{CBP}}$$

where $\xi = 0.1$ as in CRUNCH-2D,

K_{SPK} was the initial spring rate and M_{CBP} was the core barrel plate mass. Hence,

$$C_{SPK} = 0.2 \sqrt{800 \frac{21.3}{386.1}} = 1.33 \text{ lb-sec/in.}$$

Fig. 5.5-8. Spring pack

5.5.2.8. Gaps. Core gaps were defined at the following locations:

1. Between hexagonal fuel elements.
2. Between PRB and fuel elements.
3. Between PRB and core barrel plates.
4. Between plenum elements.
5. Between spring packs and core barrel plates.
6. Between core support floor elements.

Gaps between elements in a refueling region of the test core were 0.032 in. (16 places). Between refueling regions, the gap was either 0.083 in. (4 places) or 0.071 in. (6 places). Total across-core gap (between reflector columns) was 1.27 in.

In the computer model (Fig. 3.5-3, Section 3.5), there were 25 gaps between columns. The 1.27 in. total was distributed as follows:

Interfaces 3 and 27 (Fig. 3.5-3): Gaps = 0.06 in.

Interfaces 4 through 26: Gaps = 0.05 in.

These values were confirmed by measurements in upper levels of the test core.

Gaps were not utilized between the PRB and the core barrel plates. Whatever gap existed in this area was included in the across-core gap.

Plenum elements were wider than elements in other layers. The approximate total across-core gap at the plenum level was 1 in.

The plenum row in the MCOCO model had the following distribution:

Interfaces 3 and 27 (Fig. 3.5-3): Gaps = 0.046 in.

Interfaces 4 through 26: Gaps = 0.040 in.

The code had an optional gap between spring packs and core barrel plates. Again, however, this gap was included in the total across-core gap. A value of zero was therefore provided as program input.

The design gap between core support blocks was 0.014 in. The test core had 10 gaps for a total of 0.14 in. The MCOCO model, with nine floor gaps, utilized 0.016 in. for a total of 0.144 in.

5.6. COCOROD

Only analysis with a full-scale column model has been conducted with the COCOROD code. Small-scale analyses have not been made since no test data were available for correlation. Control rod properties discussed here are approximate.

5.6.1. General Parameter Descriptions

5.6.1.1. Column

The coupling of a control rod with a fuel column did not alter the parameter values of the column. Therefore, the parameters of COCO given in Section 5.4 for the column remain valid. The parameters of the control rod model together with the canister-channel impact mechanism are discussed below (see Fig. 5.6-1).

5.6.1.2. Control Rod

The geometrical parameters of the control rod required as input data are depicted in Fig. 5.6-2. They are defined as follows:

h_B = height of canister.

b_B = width of canister.

b_F = width at stand-off fins.

Fig. 5.6-1. Analytical model of COCOROD

Fig. 5.6-2. COCOROD canister

h_F = distance between canister center of gravity and fin.

h_C = clearance between two adjacent canisters.

F_F = distance from fin to top of canister.

In addition to the above dimensions, the width of the channel (b_c) and the insertion position parameter were also required.

The canisters were interconnected by spherical joints. Friction acting around the ball generated joint moments in addition to forces. In the current version, the force-velocity variation was taken to be of the Coulomb type.

The generation of joint moments involved the following parameters:

m = Coulomb friction coefficient in ball joint

= 0.2 for the ordinary analyses

μ = Coulomb friction coefficient in ball joint

= 0.2 for ordinary analyses

= 0.4 to 0.6 for simulation of artificial stiffening effect

S = slope of friction force between negative and positive values

= 1000 lb-sec/in. (full scale)

d_J = diameter of ball, in.

The ball joints were supported by connecting rods, which were relatively flexible members (Fig. 5.6-3). The flexibility was provided by a two-way spring element representation. Depending upon the location of the spring element, the connecting rod stiffness values for a full-scale model varied in the following range:

k_H = 8,000 to 50,000 lb/in.

k_V = 10,000 to 80,000 lb/in.

Fig. 5.6-3. Connecting rod arrangement and ball joints

The above stiffness values were obtained by approximate methods, taking into account the deformation of the guide plates (Fig. 5.6-3). Each spring element had an associated damper in a parallel arrangement.

5.6.1.3. Channel Wall Impact Model

The channel-canister impact mechanism utilized a series of effective spring rates that accounted for the fact that the colliding components in this case were made of different materials.

Figure 3.6-1, Section 3.6, shows the three types of impact mechanisms, each with a different value of effective series stiffness k_E ; as follows:

Type of Impact	Definition of k_E
1	$\frac{k_{FIN} k_{CHB}}{k_{FIN} + k_{CHB}}$
2	$\frac{k_{CBY} k_{CHE}}{k_{CBY} + k_{CHE}}$
3	$\frac{k_{CCN} k_{CHB}}{k_{CCN} + k_{CHB}}$

where k_{FIN} = stand-off fin stiffness,
 k_{CBY} = canister body stiffness,
 k_{CCN} = canister corner stiffness,
 k_{CHE} = channel wall edge stiffness,
 k_{CHB} = channel wall body stiffness.

Damping was similarly formulated.

A sample of the more important properties used in the full-scale sample analysis is listed in Table 5.6-1.

TABLE 5.6-1
SAMPLE CASE PARAMETERS

Column element weight, lb	265
Element width, in.	14.20
Element height, in.	31.20
Element vertical corner spring stiffness, lb/in.	500,000
Element horizontal corner spring stiffness, lb/in.	875,000
Control rod element weight (one), lb	10
Control rod element width, in.	3.5
Control rod element length (one), in.	16.5
Cannister horizontal stiffness, lb/in.	100,000
Channel wall horizontal stiffness, lb/in.	500,000
Standoff fin horizontal stiffness, lb/in.	80,000
Lateral restraint stiffness of cable, lb/in.	50

5.7. REFERENCES

- 5.2-1. Skoff, R., "Scaled Column Vibration Test - L2284," General Atomic Company, unpublished data, July 28, 1970.
- 5.2-2. "Column Vibration Test Program 1," General Atomic Company, unpublished data, 1970.
- 5.2-3. Rakowski, J. E., "Specification for 1/5 Scale Model Dowel Force Test," General Atomic Company, unpublished data, December 18, 1974.
- 5.2-4. Hinch, S., et al., "Reactor Element Collision Behavior," Harvey Mudd College Engineering Clinic, August 23, 1973.
- 5.3-1. Shatoff, H. D., "Modification of CRUNCH-2D, Addition of Column Springs and Core Support Floor," General Atomic Company, unpublished data, August 2, 1977.

6. CORRELATION AND VERIFICATION OF THE CODES

6.1. CORRELATION CRITERIA

6.1.1. Method

Verification of the analytical models used in the HTGR core design was based on correlation of the analytical results with core seismic test data. In each model test, parameters having a significant effect on the response were varied. These parameters included the core support spring rate, core gap, type of excitation (sinusoidal or time history), frequency, excitation g-level, the direction of single-axis excitation, and the phase lag between simultaneous excitations along two orthogonal axes.

The verification procedure assumes that if a code can predict the test model response for a range of parameters, then the code can serve as a design tool for the HTGR core.

6.1.2. Correlation Requirements

6.1.2.1. General. The requirements specified in this section apply to the following codes: CRUNCH-1D, CRUNCH-2D, COCO, and MCOCO. The codes were correlated with time history response and sinusoidal response data. These correlation categories are addressed separately in the report. The following core seismic tests were used for code correlation:

1. 1/5- and full-scale multielement collision tests.
2. Full-scale element rocking tests.
3. 1/5- and 1/2-scale, two-dimensional, planar array tests.
4. 1/2-scale, two-dimensional, two-axis planar array tests.

5. 1/5-scale, single-column test.
6. 1/5-scale, full-array test and dowel force test.

The data selected from the tests were expressed as a function of the parameters mentioned in Section 6.1.1. Correlation cases are summarized in the overall correlation chart of Table 6.1-1, with respect to the appropriate code, parameter, and test.

6.1.2.2. Time History Correlation Requirements. The objective of this correlation study was to verify that the codes reproduced the test model response given for the same time history excitation. Correlation was obtained for time history inputs representing several soil site conditions and g-levels. The following test data represent primary HTGR core design parameters:

1. Core element deflections and velocities (including element rocking angles).
2. Boundary support forces.
3. Element impact forces.
4. Dowel shear forces.
5. Number of significant occurrences.

In most cases, the above response appeared as a succession of discrete peaks within the duration of the time history input. These peaks were compared with the code results. Time-independent correlation was also performed by comparing the frequency distributions of the time history peak response for support forces, element forces, and dowel forces as shown in Fig. 6.1-1. This parameter is important in the fatigue assessment of the core element, and was derived from all peak values greater than 15% to 20%

TABLE 6.1-1
CODE CORRELATION CHART

Code/Response	Test	Input Excitation	Input Magnitude (a)	Frequency Range (b) (Hz)	Core Gap (in.)	Phase Angle (c)	Test No.	Tape No. (d) (Tape 10)	Instrument Position	Remarks
CRUNCH-1D										
1. Element velocity	1/5-scale inter- element collision and bumper tests	Constant velocity	12-50 ips 12-43 ips	-- --	-- --	-- --	3 4	-- --	-- --	Interelement impact tests with 1 on 3 elements, 4 elements off a bumper.
2. Boundary support force	1/5-scale, full- array test	Time history	0.10	--	1.23	--	3M	4708,5196,5250	1/8-1(e)	Shocks 3 & 8, maximum forces.
a. Soft support			0.15				2M		1/8-1	
			0.25				3M		1/8-1	
			0.30						1/8-1	
			0.35						1/8-1	
			0.50				5M		1/8-1	
b. Hard support	1/5-scale, dowel- force test	Time history	0.25		1.23	--	11,16,21	4708,5196,5250	RB level 6	Shock 4, maximum forces.
3. Element impact forces (number of events only)	1/5-scale, dowel- force test	Time history	0.25	--	1.23	--	8,13,18	4619,4866,5079	(1-7)/7-5(f)	Shock 4, forces as a function of g-level for 3 core locations.
			0.20		1.23		9,14,19	4619,4866,5079	(92-171)/7-5	
			0.15		1.23		10,15,20	4708,5196,5250	(332-411)/7-5	
			0.10		1.23		11,16,21	4708,5196,5250		
			0.25		1.23		21	5079,5250	(332-411)/7-5	
4. Resonant frequency										Frequency distribution.
a. Hard boundary support force level	1/5-scale, planar array test	Sine sweep	0.75	2.2-15	0.40	--	4	7240	1	Sweep up.
b. Soft boundary support force level	1/5-scale, full- array test	Sine sweep	0.50 0.30	1.0-10 1.0-10	1.23 1.23	-- --	4 1		1/8-1 1/8-1	Sweep up. Sweep up.

TABLE 6.1-1 (Continued)

Code/Response	Test	Input Excitation	Input Magnitude(a)	Frequency Range(b) (Hz)	Core Gap (in.)	Phase Angle(c)	Test No.	Tape No. (d) (Tape 10)	Instrument Position	Remarks																		
CRUNCH-2D																												
1. Boundary support force (number of events only)	1/5-scale, planar array	Time history	0.5	--	0.10 0.20 0.30 0.40 0.40	--	1	2628	Elements 2,55,71, 72 and 73	Shock 3 (across flats) excitation																		
							2	2628																				
							3	7814																				
							4	4895																				
							8	4989																				
2. Interelement impact forces	1/2-scale, planar array	Time history	0.71	--	0.50	0.601	5,18,28	6808,6114,5118	Elements 2,19,55, 67,71,72	Shock 3 (orthogonal axes)																		
							38	4055,3939,3229																				
							1/5-scale, dowel force test	Time history			0.25	--	1.23	--	16	5146	RB elevation 6	Shock 4										
																			1/5-scale, planar array	Time history	0.5	--	0.10 0.20 0.30 0.40	--	2 3 4 4	2628 7814 4894 4895	Interfaces 26/37 and 57/65	Shock 3
1/5-scale, dowel force test	Time history	0.25	--	1.23	--	11,16,21	4708,5146,5250	Core midheight	Shock 4																			
										3. Resonant frequency	a. Boundary force level	1/5-scale, planar array test	Sine sweep	0.75	2.2-15	0.40	--	4	7240	1	Sweep up							
																						b. Boundary force level (soft support)	1/5-scale, full array test	Sine sweep	0.50	1.25-10	1.23	--

TABLE 6.1-1 (Continued)

Code/Response	Test	Input Excitation	Input Magnitude(a)	Frequency Range(b) (Hz)	Core Gap (in.)	Phase Angle(c)	Test No.	Tape No. (d) (Tape 10)	Instrument Position	Remarks
COCO										
1. Rocking angle and frequency	Full-scale, basic rocking test	Initial displacement	10 degrees	--	--	--	--	--		3 elements in a column, top element initial rocking angle = 10 deg, followed by a 2-element rock down from 10 degrees.
2. Support force	1/5-scale, single column shake test	Time history	0.5	--	0.25	--	19	7440	Elements, interfaces 7, 1/2, 10/11	Shock 3, horizontal; shock 3, horizontal & vertical;
3. Dowel force										
4. Rock down force			0.25/0.50	--	0.25	0	36	4269		
5. Number of force of the above			0.25/0.50	--	0.25	0	37	4475		
6. Resonant frequency										
a. Support post load	1/5-scale, single column shake test	Sine sweep	0.5 g	5-50	0.1	--	17B	2513	Base	Sweep up
b. Horizontal deflection	1/5-scale, single column shake test	Sine sweep	0.05 g	0.5-10		--	7C	4624/2163	Elevation 7	Column vibration with no boundary impact.
MCOCO										
1. Rocking angle	1/5-scale, Dowel force test	Time history	0.25	--	1.23	--	11,16,21	4708,5196,5250	Core center, midradius & boundary, 3 elevations	Shock 4.
2. Element impact force										
3. Dowel force										
4. Boundary support force	1/5-scale, full-array test	Time history	0.25	--	1.23	--	37		1/8-1	Shocks 3 and 8, maximum forces
5. Resonant frequency/ boundary support force level (soft support)		Sine sweep	0.5	1.0-10	1.23	--	4	--	Boundary, reflector block elevation 6	Sweep up.

(a) g-levels refer to nominal value, fixture level for sine sweep or sine dwell, equivalent ground g-level for time history.

(b) Frequency range obtained from test.

(c) Phase angle between two inputs is expressed in degrees for sine dwell and in seconds lag for time history.

(d) Test and tape number is consistent with GA test report designation.

(e) Indicate: incore instrument position/elevation - support instrument plan.

(f) Indicate: incore instrumentation (position of columns)/elevation - support instrumentation elevation.

Fig. 6.1-1. Typical frequency distribution of dowel force response - time history input

of the maximum value, which gave assurance that the data lay above the instrument noise level. Depending on the range between maximum load and minimum load level, three to four load intervals were chosen for realistic comparison of peak responses. In this way, the random test data error would not exceed the value of the load interval.

The overall maximum values as a function of g-level and/or core gap were compared. Also, the profiles of the maximum response, in-core and along the boundary supports, were correlated as appropriate.

Correlation was also performed for variations of additional parameters that govern the HTGR core seismic design. These included changes in boundary support stiffness and changes in the time history earthquake waveform as represented by the OBE and the SSE.

Excitation directions corresponding to across-flats and across-corners of the hexagonal core elements were included in the correlation cases for the two-dimensional horizontal model (CRUNCH-2D).

CRUNCH-2D and the single-column model COCO were also correlated with data from simultaneous two-axis excitation (two-horizontal-axis excitation and one-horizontal-axis and one-vertical-axis excitation, respectively). The two-axis correlation cases included a time offset between the two orthogonal input directions.

6.1.2.3. Frequency Response Correlation Requirements. The objective of this correlation study was to verify that the codes reproduced the test model resonant frequencies and mode shapes. This is important since an error in the resonant frequency could substantially affect the magnitude of the seismic load response. This is evident from the PCRV floor response spectra where sharp spectrum peaks for different soil conditions appear in a frequency range which, for some cases, coincides with the core resonant frequencies.

The frequency response of the test models was obtained from sinusoidal "sweeps." Correlation with this data was obtained by simulating the sweep analytically. Since the sweep is very costly to perform on large computer models, a series of sinusoidal dwells at discrete frequencies were sometimes used to obtain the resonance curve. Due to the nonlinear characteristics of the core, there is an instability region defined by the sweep up and sweep down resonance curves, as illustrated in Fig. 6.1-2. Sine dwell correlation was not performed here because either of the two response levels in the region may be obtained for a given sine dwell.

The predominant resonant frequency measured in the 1/5-scale, full-array test was associated with a lumped core mode at a resonant frequency of approximately 4.0 Hz, and was used to correlate CRUNCH-1D, CRUNCH-2D, and MCOCO. CRUNCH-1D and -2D were also correlated with the resonant frequencies of the planar-array tests.

The single-column COCO code was correlated with the core vertical frequency response from the single-column shake test. This verification also applied to the multicolumn MCOCO model.

6.1.3. Acceptance Criteria

6.1.3.1. General. The code will meet the acceptance criteria for correlation if the correlation error for any response, e_j , is less than a specified acceptance error, E_j . The correlation error was defined as:

$$e_j = |U_{aj} - U_{tj}| \quad , \quad (6.1-1)$$

where U_{aj} = analytical results (jth response quantity), and

U_{tj} = experimental mean value of the jth response quantity.

Fig. 6.1-2. Typical nonlinear core resonance showing spring-hardening effects

Where repeated data were not available, the experimental mean represented the data from one test run. The test data for correlation included: (1) maximum response (e.g., the overall maximum for the test run or the maximum at a specific core location), (2) the mean value associated with the time history response frequency distribution (e.g., Fig. 6.1-1), and (3) a linear or higher order mean curve fit to data recorded as a function of a test parameter (e.g., response versus excitation g-level).

When the analysis was compared to single data points, the codes were required to satisfy the relationship:

$$e_j \leq E_j \quad (6.1-2)$$

When the analysis was compared to a mean curve fit of data points represented as a function of a test parameter or frequency distribution, the codes were required to satisfy the following relationship:

$$\frac{\left(\frac{1}{I} \sum_{i=1}^I e_{ij}^2 \right)^{1/2}}{\bar{U}_{tj}} \leq E_j \quad (6.1-3)$$

where e_{ij} = code correlation error for the j th response,
 I = total number of points compared,
 $\bar{U}_{tj}$ = the experimental mean value over the range of the response.

The numerical values for the acceptance error E_j for use with Eqs. 6.1-2 and 6.1-3 are given in Table 6.1-2. It shows values of E_j corresponding to each response parameter. The acceptance criteria also include requirements for predicting the position of the maximum response value at the core support boundary or in the core. These requirements are shown as "other error criteria" in Table 6.1-2.

TABLE 6.1-2
ACCEPTANCE ERRORS FOR CODE CORRELATION

Response Quantity	Acceptance Criteria	
	Acceptance Error E_j	Other
Frequency response		
Resonant frequency	15	
Resonance displacement (magnitude)	25	
Resonance velocity (magnitude)	33	
Time history response		
Frequency (of events) distribution	30	
Element deflection	25	
Element velocity	33 (27) (a)	
Element rocking angle	40	
Boundary support force (hard)	40	} Maximum within $\pm$ one support location.
Boundary support force (soft)	27	
Element impact force	29 (40)	} Maximum within $\pm$ one element in a hori- zontal or vertical array.
Element dowel force	37 (40)	
Element rocking load	N/A (40)	
Column support force	N/A (40)	

(a) For correlation with tests other than 1/5-scale, full-array, and dowel force tests. (Full-array and dowel force test results apply if no alternate number given.)

E_j was estimated on the basis that exact correlation between analysis and test cannot be achieved due to the inherent errors in the test data, analytical solution, and modeling techniques. This is reflected in the following expression:

$$E_j = 2\sqrt{\epsilon_{tj}^2 + \epsilon_{cj}^2} + C, \quad (6.1-4)$$

where ϵ_{tj} = error in the experimental mean value,
 ϵ_{cj} = numerical integration error,
 C = analytical modeling inaccuracy.

Of these, ϵ_{tj} and ϵ_{cj} are random and independent and were estimated with good accuracy as demonstrated below.

The random error of the experimental mean ϵ_{tj} is defined by the relationship:

$$\epsilon_{tj} = \frac{\hat{S}_u}{\sqrt{n}}, \quad (6.1-5)$$

where $\hat{S}_u$ = random error in the test data,
 n = number of repeated tests used to establish $\hat{S}_u$,
 j = the j th core response quantity.

The method of obtaining $\hat{S}_u$, outlined in Section 4.1.11, is summarized for all important parameters in Table 6.1-3. The calculated values of ϵ_{tj} based on Eq. 6.1-5 are given in Table 6.1-4.

Table 6.1-5 presents a summary of the code numerical integration errors. Error calculations for the CRUNCH-1D code are presented in Section 7.1, but the errors apply equally to the other core seismic codes. The errors in Table 6.1-5 for dowel force, support post load, deflection, and velocity represent best estimates.

TABLE 6.1-3
TEST MODEL RANDOM ERROR^(a) SUMMARY

Response Quantity	Collision Dynamics Test	1/5-Scale, 2D Test	1/2-Scale, 2D Test	1/2-Scale, 2D, Two- Axis Test	Single- Column Test	1/5-Scale, Full-Array Test	Dowel Force Test
1. Resonant frequency	--	1.0	1.0	1.0	1.0	1.0	1.0
2. Lateral core support force	--	17.0	14.0	18.0	15.0	6.0 ^(b)	6.0 ^(b)
3. Vertical core support force	--	--	--	--	15.0	--	--
4. Core deflection	--	8.0	7.0	8.0	--	3.0	3.0
5. Core velocity	11.0	10.0	9.0	12.0	--	15.0	15.0
6. Element relative displ. (rocking angle)	--	--	--	--	8.0	--	14.0
7. Element impact force	--	--	--	14.0	15.0	--	5.0
8. Element dowel force	--	--	--	--	23.0	--	10.0

(a) All errors are represented as percentages equivalent to one standard deviation, $\hat{S}_u$.

(b) Hard boundary support.

(c) Errors in items 2 through 8 were obtained from time history data.

TABLE 6.1-4
 ERRORS IN THE EXPERIMENTAL MEAN^(a) (ϵ_{tj})

Response Quantity	Collision Dynamics Test	1/5-Scale, 2D Test	1/2-Scale, 2D Test	1/2-Scale, 2D, Two- Axis Test	Single- Column Test	1/5-Scale, Full-Array Test	Dowel Force Test
1. Resonant frequency	--	1.0	1.0	1.0	1.0	1.0	1.0
2. Lateral core support force	--	17.0	14.0	18.0	21.0	12.0 (soft)	6.0 (hard)
3. Vertical core support force					21.0		
4. Core deflection	--	8.0	7.0	8.0		3.0	3.0
5. Core velocity	3.0	10.0	9.0	12.0		15.0	15.0
6. Element relative displ. (rocking angle)					8.0		28.0
7. Element impact force				14.0	21.0		10.0
8. Element dowel force				23.0			20.0

(a) Errors are expressed as percentages, on a one-standard basis.

TABLE 6.1-5
ANALYTICAL CODE NUMERICAL ERRORS^(a) (ϵ_c)

Core Response	Error(b) (%)
1. Hard spring pack force	10
2. Soft spring pack force	0.5
3. Interelement force	5
4. Dowel force ^(c)	5
5. Support post load	5
6. Velocity	5
7. Deflection	5
8. Rocking angle	5
9. Resonant frequency	0.5

(a) Based on CRUNCH-1D.

(b) Errors are on a 1σ basis.

(c) Errors in items 4 through 9 are estimates.

C, which is a systematic error caused by inaccuracies in modeling, was estimated conservatively at 15%. This conforms with practical knowledge of analytical modeling accuracy.

The random error portion in Eq. 6.1-4 contains a factor of 2, which means that two standard deviations are employed in deriving E_j . This means that the code calculated values should correlate within the criteria at least 95% of the time for acceptable correlation. Some modifications to the E_j -calculated values were made as follows:

1. The maximum acceptance error was set at 40%. This means that some test data containing large errors, such as fuel element impact forces measured with strain gages, would not be correlated with analysis.
2. The acceptance error on the resonant frequency was limited to 15% for compatibility with the NRC guidelines on acceptable variance in resonant frequency calculations (Ref. 6.1-7).
3. The acceptance error on the frequency-of-events distribution of response during a time history was arbitrarily set at 30% because response frequency variations were not investigated for test and analysis.
4. The acceptance error on the hard stop boundary support force was increased to the 40% limit, acknowledging that an undetermined additional systematic error was present in the test data from the substantial variation of the spring pack load within the radial adjustment tolerance of the support.

6.2. CODE CORRELATION WITH TIME HISTORY TEST DATA

6.2.1. CRUNCH-1D

This section presents the correlation of CRUNCH-1D with the collision dynamics tests (Section 4.2), the 1/5- and 1/2-scale two-dimensional tests (Section 4.4), the full-array test (Section 4.7), and the dowel force test (Section 4.8). The code input parameters used for the correlation are specified in Section 5.2.

6.2.1.1. Collision Dynamics Tests. The first section presents correlation with tests where one element collides with two or more elements. The second section presents correlation for two or more elements colliding with a bumper.

6.2.1.1.1. Interelement Collisions. Interelement collision tests are defined as tests that involve one element colliding with two or more stationary elements. The CRUNCH-1D interelement springs and dampers were previously selected to duplicate the two-element-collision coefficient of restitution and contact time. Correlation with the interelement tests was performed to show that the CRUNCH-1D collision model adequately simulated interelement collisions since this behavior was predominate in the core model response.

Figures 6.2-1 through 6.2-4 present correlation for one element colliding into three elements, all 1/5 scale. Each figure presents the final velocity of a single element plotted versus the initial velocity of the impacting element. The final velocities have been "normalized" by the initial velocity of the impacting element. This normalization consists of increasing, by the same ratio, the final element velocities measured in the test, so that the final momentum of all the elements is equal to the initial total momentum. This correction is necessary to properly compare test and analysis.

*SCALED TO 100% INITIAL MOMENTUM

Fig. 6.2-1. CRUNCH-1D velocity correlation - block 1 of a 1 on 3 collision

*SCALED TO 100% INITIAL MOMENTUM

Fig. 6.2-2. CRUNCH-1D velocity correlation - block 2 of a 1 on 3 collision

*SCALED TO 100% INITIAL MOMENTUM

Fig. 6.2-3. CRUNCH-1D velocity correlation - block 3 of a 1 on 3 collision

*SCALED TO 100% INITIAL MOMENTUM

Fig. 6.2-4. CRUNCH-1D velocity correlation - block 4 of a 1 on 3 collision

The correlation errors for the above comparisons are given in Table 6.2-1. The correlation error ranges from 0.03 to 0.08, well below the multielement collision acceptance error of 0.27.

6.2.1.1.2. Bumper Collisions. Bumper collision tests include all tests where one or more elements collided with a bumper. The stiffness and damping properties for the bumper were computed using the contact time and coefficient of restitution data obtained from tests where a single element collided with the bumper. The correlation with tests where two or more elements collided with a bumper were used to further validate the interelement collision model.

Figures 6.2-5 through 6.2-8 present 1/5-scale correlation for four elements colliding with a bumper. The data in each figure are presented as for the interelement collision cases.

The correlation errors for the above comparisons are given in Table 6.2-2. The correlation error for each element is between 0.20 and 0.22, which is within the correlation acceptance criterion of 0.27.

The CRUNCH-1D correlation with the planar array tests dealt only with sine sweep data. Results of the correlation are discussed separately in Section 6.3.

6.2.1.2. Full Array and Dowel Force Tests

6.2.1.2.1. Soft Boundary Support Forces. The CRUNCH-1D results were compared with the soft spring pack forces measured in the 1/5-scale, full-array test. The results are presented in Fig. 6.2-9 where the model excitation was shock No. 8 (Fig. 4.1-22), representing an OBE on a soft soil site. The maximum correlation error given in Table 6.2-3 was computed to be 0.17, which lies below the acceptance error of 0.27 for this response

TABLE 6.2-1
CRUNCH-1D CORRELATION ERRORS - 1/5-SCALE INTERELEMENT COLLISION TESTS

Element No.	Initial Velocity (in./sec)	CRUNCH-1D U_a (in./sec)	Average Test Value U_{tm} (in./sec)	e_i (b)	$\bar{U}_{tm}$ (c)	$\sqrt{\frac{1}{n} \sum_{i=1}^n e_i^2}$	$\chi^{(d)}$	E_j	Acceptance (e)
1	10	19.8	21.8	2.0					
1	20	21.6	20.7	0.9					
1	30	21.5	19.6	1.9					
1	40	20.0	18.5	1.5	20.2	1.6	0.081	0.27	A
2	10	23.1	24.3	1.2					
2	20	23.6	23.6	0.0					
2	30	23.5	23.0	0.5					
2	40	21.6	22.3	0.7	23.3	0.7	0.032	0.27	A
3	10	25.3	26.1	0.8					
3	20	24.7	26.0	1.3					
3	30	25.2	25.9	0.7					
3	40	25.2	25.7	0.5	25.9	0.9	0.033	0.27	A
4	10	31.8	27.5	4.3					
4	20	30.0	29.3	0.7					
4	30	29.8	31.0	1.2					
4	40	33.2	32.8	0.4	30.2	2.3	0.075	0.27	A

(a) 1 on 3 elements.

$$(b) e_i = |U_a - U_{tm}|$$

$$(c) \bar{U}_{tm} = \frac{1}{n} \sum U_{tm}$$

$$(d) \chi = \frac{\sqrt{\frac{1}{n} \sum_{i=1}^n e_i^2}}{\bar{U}_{tm}}$$

(e) A = acceptable
NA = not acceptable

Fig. 6.2-5. Velocity - block A of four blocks into a bumper

Fig. 6.2-6. Velocity - block B of four blocks into a bumper

Fig. 6.2-7. Velocity - block C of four blocks into a bumper

Fig. 6.2-8. Velocity - block D of four blocks into a bumper

TABLE 6.2-2
CRUNCH-1D CORRELATION ERRORS - 1/5-SCALE BUMPER COLLISION TESTS

Block No.	Initial Velocity (in./sec)	CRUNCH-1D U_a (in./sec)	Average Test Value U_{tm} (in./sec)	e_i (a)	$\bar{U}_{tm}$ (b)	$\sqrt{\frac{1}{n} \sum_{i=1}^n e_i^2}$	χ (c)	E_j	Acceptance (d)
A	10	8.3	14.4	6.1	16.1	3.3	0.21	0.27	A
A	20	13.0	15.5	2.5					
A	30	15.8	16.6	0.8					
A	40	17.4	17.7	0.3					
B	10	8.2	10.4	2.2	12.0	2.4	0.20	0.27	A
B	20	12.7	11.5	1.2					
B	30	15.4	12.6	2.8					
B	40	16.7	13.6	3.1					
C	10	7.7	10.1	2.4	11.0	2.2	0.20	0.27	A
C	20	11.7	10.7	1.0					
C	30	13.7	11.3	2.4					
C	40	14.6	11.9	2.7					
D	10	5.4	7.5	2.1	7.2	1.6	0.22	0.27	A
D	20	7.0	7.3	0.3					
D	30	7.9	7.1	0.8					
D	40	9.2	6.9	2.3					

$$(a) e_i = |U_a - U_{tm}|$$

$$(b) \bar{U}_{tm} = \frac{1}{n} \sum U_{tm}$$

$$(c) \chi = \frac{\sqrt{\frac{1}{n} \sum_{i=1}^n e_i^2}}{\bar{U}_{tm}}$$

(d) A = acceptable
NA = not acceptable

Fig. 6.2-9. CRUNCH-1D correlation with soft spring pack boundary force - 1/5-scale, full-array test - shock 8

TABLE 6.2-3
CRUNCH-1D CORRELATION WITH LATERAL SUPPORT FORCES - 1/5-SCALE, FULL-ARRAY TEST^(a)

Shock No.	g Level	CRUNCH-1D U_a (lb)	Test U_{tm} (lb)	e_i (b)	U_{tm} (c)	$\sqrt{\frac{1}{n} \sum_{i=1}^n e_i^2}$	χ (d)	E_j	Acceptance (e)
8 ^(a)	0.10	82	13	69					
8	0.15	173	163	10					
8	0.20	364	350	14					
8	0.25	550	525	25					
8	0.30	688	610	78					
8	0.35	789	693	96					
8	0.50	1007	862	145	459	77	0.17	0.27	A
3 ^(f)	0.10	55	10	45					
3	0.15	89	28	61					
3	0.25	330	411	81					
3	0.30	498	481	17					
3	0.35	643	563	80					
3	0.50	877	758	119	375	74	0.20	0.27	A

(a) OBE, soft soil (Fig. 4.1-22)

$$(b) e_i = |U_a - U_{tm}|$$

$$(c) \bar{U}_{tm} = \frac{1}{n} \sum U_{tm}$$

$$(d) \chi = \frac{\sqrt{\frac{1}{n} \sum_{i=1}^n e_i^2}}{\bar{U}_{tm}}$$

(e) A = acceptable
NA = not acceptable

(f) SSE, soft soil (Fig. 4.1-17)

quantity. Figure 6.2-10 presents similar results for correlation of shock 3 (Fig. 4.1-17) representing an SSE on a soft soil site. Since the correlation error for this case, 0.20, also satisfied the criteria, it was concluded that the CRUNCH-1D code was verified for use in the prediction of soft boundary support loads over a range of excitation g-levels.

6.2.1.2.2. Hard Boundary Support Forces. CRUNCH-1D results were compared to the dowel force test hard boundary support forces, using shock 4 of Fig. 4.1-27, at 0.26 g. The results in Table 6.2-4 indicate that the code correlation errors are just less than the acceptance error of 40%, satisfying the criteria. It is believed that the larger correlation errors for this response were due to the hard boundary support loads being very sensitive to small changes in excitation g-level and the adjustment tolerances of the spring pack.

6.2.1.2.3. Interelement Forces. Interelement forces produced by CRUNCH-1D for shock No. 4 of the dowel force test were compared to the data measured at the boundary, midradius, and center of the test model. The maximum analytical and experimental forces for this shock, represented as a function of the input g-level, are shown in Figs. 6.2-11 through 6.2-13 for the three core locations. The correlation analysis of these results is summarized in Table 6.2-5, from which it was concluded that the correlation criteria were not satisfied for CRUNCH-1D prediction of interelement forces.

The data in the table illustrate that larger correlation errors exist for the comparison of the smaller forces. As a general rule, experimental forces of less than 25% of the maximum measured in a given time history were not correlated. Since all forces shown in Table 6.2-5 are maximums, this rule does not apply.

The frequency distribution of the CRUNCH-1D experimental interelement forces near the core boundary are shown in Fig. 6.2-14. The results apply

Fig. 6.2-10. CRUNCH-1D correlation with soft spring pack boundary force - 1/5-scale, full-array test - shock 3

TABLE 6.2-4
CRUNCH-1D CORRELATION WITH 1/5-SCALE, DOWEL-FORCE
TEST HARD BOUNDARY SUPPORT FORCES^(a)

CRUNCH-1D Result (1b)	Test Data (1b)	$ e_i $ (b) (1b)	$\bar{U}_{tm}$ (c) (1b)	$\sqrt{\frac{1}{n} \sum_{i=1}^n e_i^2}$	χ (d)	E_j	Acceptance (e)
Right side: 900	1300	400	1467	579	0.40	0.40	A
	1525	625					
	1575	675					
Left side: 1680	2510	830	2703	1032	0.38	0.40	A
	2790	1110					
	2810	1130					

(a) Input excitation is dowel force test shock 4, Fig. 4.1-27.

(b) $e_i = |U_a - U_{tm}|$

(c) $\bar{U}_{tm} = \frac{1}{n} \sum_{i=1}^n U_{tm}$

(d) $\chi = \frac{\sqrt{\frac{1}{n} \sum_{i=1}^n e_i^2}}{\bar{U}_{tm}}$

(e) A = acceptable
NA = not acceptable

Fig. 6.2-11. Comparison of CRUNCH-1D interelement forces at the core center with dowel force test data - shock 4

Fig. 6.2-12. Comparison of CRUNCH-1D interelement forces at the core midradius with dowel force test data - shock 4

Fig. 6.2-13. Comparison of CRUNCH-1D interelement forces at the core boundary with dowel force test data - shock 4

TABLE 6.2-5
CRUNCH-1D INTERELEMENT FORCE CORRELATION WITH DOWEL FORCE TEST DATA^(a)

Core Location	g Level	CRUNCH-1D U_a (lb)	Test U_{tm} (lb)	e_i (b) (lb)	$\bar{U}_{tm}$ (c) (lb)	$\sqrt{\frac{1}{n} \sum_{i=1}^n e_i^2}$	χ (d)	E_j	Acceptance (e)
Boundary	0.24	250	193	57	77.5	5.1	0.66	0.32	NA
	0.185	130	63	67					
	0.143	58	35	23					
	0.0992	65	19	46					
Mid-radius	0.24	144	100	44	46.2	48.1	1.04	0.32	NA
	0.185	108	66	42					
	0.143	72	0	72					
	0.0992	0	19	19					
Center	0.24	149	151	2	64.3	40.8	0.63	0.32	NA
	0.185	92	42	50					
	0.143	50	0	50					

(a) Shock No. 4, OBE, soft soil, Fig. 4.1-27.

$$(b) e_i = |U_a - U_{tm}|$$

$$(c) \bar{U}_{tm} = \frac{1}{n} \sum_{i=1}^n U_{tm}$$

$$(d) \chi = \frac{\sqrt{\frac{1}{n} \sum_{i=1}^n e_i^2}}{\bar{U}_{tm}}$$

(e) A = acceptable
NA = not acceptable

Fig. 6.2-14. CRUNCH-1D and dowel force test interelement load frequency distributions

for shock 4 of the dowel force test at 0.24 g. The correlation analysis of these data is summarized in Table 6.2-6, from which it was concluded that the frequency content of the interelement forces was not adequately simulated by CRUNCH-1D. An explanation for the larger number of impacts produced by the analysis is that the core damping in the code is too low. This also explains why predicted in-core forces always are higher than those obtained from the test. The distributions at lower input g-levels showed even worse correlation.

6.2.2. CRUNCH-2D

The analytical results of CRUNCH-2D were correlated with test data from the 1/5- and 1/2-scale, planar-array tests and the dowel force test.

6.2.2.1. 1/5-Scale, Planar-Array Tests. The CRUNCH-2D analogy of the 1/5-scale, planar-array test model is shown in Fig. 6.2-15. The core elements were numbered to correspond exactly to those used in the test. Measurements were conducted for elements 2, 55, 71, 72, and 73 and at two interelement faces (elements 26-37 and elements 57-65) along the center strip of the test model as indicated in the figure. The total across-core gap for these tests ranged from 0.10 in. to 0.40 in. in increments of 0.10 in. For the CRUNCH-2D model, these total gaps were initially spread uniformly throughout the core. The CRUNCH-2D parameters input for this analysis are given in Section 5.3.

Correlation of maximum boundary support forces was performed for the above four across-core gaps. The time history input was shock No. 3 used in the 1/5-scale, planar-array tests (Fig. 4.1-17), which represents an SSE on a soft soil site. The excitation was applied in the across-flats direction of the elements.

TABLE 6.2-6
CORRELATION OF CRUNCH-1D AND DOWEL FORCE TEST INTERELEMENT FORCE FREQUENCY DISTRIBUTIONS

Shock No.	Interelement Load Range (lb)	CRUNCH-1D U_a (No. of Events)	Test U_{tm} (No. of Events)	e_i (a)	Test Total Events	e_i Total Events	χ	E_j	Acceptance (b)
4 (c)	50-100	5	2	3					
	100-170	2	1	1					
	170-260	2	2	0					
	Total Events	9	5		5	4	0.80	0.30	NA

(a) $e_i = |U_a - U_{tm}|$

(b) A = acceptable
NA = not acceptable

(c) 0.24 g, OBE, soft soil, Fig. 4.1-27.

Fig. 6.2-15. CRUNCH-2D model for correlation with 1/5-scale, planar-array test data

The results of the correlation analysis are presented in Table 6.2-7. The correlation errors fell well within the limit in the four boundary locations considered, in the direction of excitation. A consistently large correlation error was achieved at a support location that lies at an angle to the excitation, showing that further investigation of the biaxial response is needed.

CRUNCH-2D interelement forces were also compared to the 1/5-scale, planar-array test data as summarized in Table 6.2-8. The results in the table show that the correlation errors are either less than, or relatively close to, the acceptance error for this response.

The effect of a change in the direction of the excitation on the planar array boundary forces was investigated for the same shock at a boundary gap of 0.40 in. The correlation results in Table 6.2-9 show that the CRUNCH-2D analysis correlated with the data at 50% of the boundary locations considered.

6.2.2.2. 1/2-Scale, Planar-Array Tests. The CRUNCH-2D analogy to the 1/2-scale, planar-array test model is shown in Fig. 6.2-16. The test model element configuration was basically the same as that of the 1/5-scale, planar-array model; however, excitation could be applied simultaneously along two orthogonal axes. The locations where measurements were taken on the model are shown in the figure.

For comparisons of CRUNCH-2D results and test data, the excitation was shock No. 3 of Fig. 4.1-17 applied simultaneously with the x-axis motion leading that on the y-axis by 0.601 sec. This time lag corresponded to a cross correlation coefficient for these waveforms equal to 0.25. The peak level was 0.71 g and the across-core gap was 0.50 in.

TABLE 6.2-7
CRUNCH-2D CORRELATION WITH BOUNDARY SUPPORT FORCES - 1/5-SCALE TEST ^(a)

Element No.	Gap (in.)	CRUNCH-2D U_a (lb)	Test ^(b) U_{tm} (lb)	e_i ^(c) (lb)	$\bar{U}_{tm}$ (lb)	$\sqrt{\frac{1}{n} \sum_{i=1}^n e_i^2}$	χ ^(d)	E_j	Acceptance ^(e)
2	0.10	270	315	45	432.5	86.2	0.20	0.40	A
	0.20	321	450	129					
	0.30	330	435	105					
	0.40	536	530	6					
71	0.10	265	280	15	430	112.0	0.26	0.40	A
	0.20	270	420	150					
	0.30	353	475	122					
	0.40	433	545	112					
72	0.10	327	350	23	410	108.0	0.26	0.40	A
	0.20	269	400	131					
	0.30	365	490	125					
	0.40	285	400	115					
73	0.10	286	210	76	341.3	67.5	0.20	0.40	A
	0.20	331	390	59					
	0.30	352	300	52					
	0.40	386	465	79					

TABLE 6.2-7 (Continued)

Element No.	Gap (in.)	CRUNCH-2D U_a (lb)	Test ^(b) U_{tm} (lb)	e_i ^(c) (lb)	$\bar{U}_{tm}$ (lb)	$\sqrt{\frac{1}{n} \sum_{i=1}^n e_i^2}$	χ ^(d)	E_j	Acceptance ^(e)
55	0.10	187	40	147	96.3	90.2	0.94	0.40	NA
	0.20	173	100	73					
	0.30	172	130	42					
	0.40	177	115	62					
Average of the above cores	0.10-0.40				342	92.8	0.27	0.40	A

(a) Shock 3, 0.5 g, Fig. 4.1-17.

$$(b) \bar{U}_{tm} = \frac{1}{n} \sum_{i=1}^n U_{tm}$$

$$(c) e_i = |U_a - U_{tm}|_i$$

(d)

$$\chi = \frac{\sqrt{\frac{1}{n} \sum_{i=1}^n e_i^2}}{\bar{U}_{tm}}$$

(e) A = acceptable when $\chi \leq E_j$
 NA = not acceptable when $\chi > E_j$

TABLE 6.2-8
CRUNCH-2D CORRELATION WITH IN-CORE FORCES - 1/5-SCALE TWO-DIMENSIONAL TEST^(a)

Element Interface	Gap (in.)	CRUNCH-2D U_a (lb)	Test ^(b) U_{tm} (lb)	e_i (c)	$\bar{U}_{tm}$	$\sqrt{\frac{1}{n} \sum_{i=1}^n e_i^2}$	χ (d)	E_j	Acceptance ^(e)
26-37	0.10	185	200	15	280	125.5	0.45	0.40	NA
	0.20	227	300	73					
	0.30	299	180	119					
	0.40	232	440	208					
57-65	0.10	224	330	106	400	148.3	0.37	0.40	A
	0.20	229	430	201					
	0.30	317	490	173					
	0.40	270	350	80					

(a) 0.5 g time history, Shock 3, across-flats excitation.

$$(b) \bar{U}_{tm} = \frac{1}{n} \sum_{i=1}^n \bar{U}_{tm}$$

$$(c) e_i = |U_a - U_{tm}|$$

$$(d) \chi = \frac{\sqrt{\frac{1}{n} \sum_{i=1}^n e_i^2}}{\bar{U}_{tm}}$$

(e) A = acceptable when $\chi \leq E_j$
NA = not acceptable when $\chi > E_j$

TABLE 6.2-9
CRUNCH-2D COMPARISON WITH 1/5-SCALE, PLANAR-ARRAY BOUNDARY FORCES
ACROSS-CORNERS EXCITATION^(a)

Boundary Location	Gap (in.)	CRUNCH-2D U_a (lb)	Test U_{tm} (lb)	e_i (b)	χ (c)	E_j	Acceptance (d)
73	0.4	596	505	91	0.18	0.40	A
72	0.4	559	395	164	0.41	0.40	NA
71	0.4	574	265	309	1.17	0.40	NA
2	0.4	305	350	45	0.13	0.40	A

(a) Shock 3, 0.5 g, SSE, Fig. 4.1-17.

(b) $e_i = |U_a - U_{tm}|$

(c) $\chi = \frac{e_i}{U_{tm}}$

(d) A = acceptable
NA = not acceptable

Fig. 6.2-16. CRUNCH-2D model for correlation with 1/2-scale planar-array test data

Fig. 6.2-17. CRUNCH-2D model for correlation with dowel force test data

Results of the correlation analysis for boundary forces and interelement forces are given in Tables 6.2-10 and 6.2-11. The correlation errors for boundary forces were generally far in excess of the acceptance error and the CRUNCH-2D interelement forces correlated in only 4 out of 14 cases, showing that further investigation of the biaxial response is needed.

6.2.2.3. Dowel Force Test. The CRUNCH-2D analogy to the 1/5-scale, full-array model is shown in Fig. 6.2-17. The CRUNCH model represents a horizontal slice through the elements at the core midheight. The numbering system of the elements and spring packs shown in the figure corresponds to the numbering systems used in the dowel force test. For the correlation cases that follow, the excitation was dowel force test shock No. 4 (Fig. 4.1-27), at 0.24 g, representing an OBE on a soft soil site.

6.2.2.3.1. Spring Pack Support Forces. The maximum spring pack forces for the excitation are plotted in Fig. 6.2-18. The results illustrate that the maximum forces occur in line with the excitation. Good agreement is shown between the maximum test and analytical results yielding a correlation error of 0.13 versus the acceptance error of 0.40. Again, CRUNCH-2D considerably underestimated the response along the orthogonal axis.

6.2.2.3.2. Interelement Forces. CRUNCH-2D interelement forces were compared with the dowel force test data measured at the core center, mid-radius, and in the vicinity of the core boundary. Results of the correlation analysis in Table 6.2-12 reveal satisfaction of the criteria only at the center core location.

It was concluded that CRUNCH-2D requires additional investigation and comparison with test data before code verification can be stated.

TABLE 6.2-10
CRUNCH-2D CORRELATION WITH BOUNDARY SUPPORT FORCES
1/2-SCALE PLANAR ARRAY TESTS, TWO-AXIS INPUT^(a)

Element No.	Gap (in.)	CRUNCH-2D U_a (lb)	Test U_{tm} (lb)	e_i (b)	χ (c)	E_j	Acceptance (d)
2	0.50	4112	2083	2029	0.97	0.40	NA
19	0.50	3001	1635	1366	0.84	0.40	NA
55	0.50	3514	1224	2290	1.87	0.40	NA
67	0.50	3511	2440	1071	0.44	0.40	NA
71	0.50	3451	1594	1857	1.16	0.40	NA
72	0.50	4606	2143	2463	1.15	0.40	NA

(a) Shock 3 of Fig. 4.1-17 applied on x' and y' axes (Fig. 6.2-16).
 x' leads y' by 0.601 sec, 0.71 g peak, 0.50 cross-core gap.

(b)
$$e_i = |U_a - U_{tm}| \quad i$$

(c)
$$\chi = \frac{e_i}{U_{tm}}$$

(d) A = acceptable
NA = not acceptable

TABLE 6.2-11
CRUNCH-2D CORRELATION WITH IN-CORE FORCES - 1/2-SCALE, PLANAR-ARRAY TEST, TWO-AXIS INPUT^(a)

Test No.	Interblock Face	Peak CRUNCH-2D Value U_a (1b)	Peak Test Value U_{tm} (1b)	e_i (b)	χ (c)	E_j	Acceptance ^(d)
1	57-65	3050	447	2603	5.85	0.40	NA
	61-65	1115	1422	307	0.22		A
1a	57-65	3050	1018	2032	2.00		NA
	72-65	3695	1999	1696	0.85		NA
2	26-37	2726	387	2339	6.04		NA
	31-37	1888	987	901	0.91		NA
3	67-64	2289	1854	435	0.23		A
	71-64	2963	792	2171	2.74		NA
3a	56-64	2697	773	1924	2.49		NA
	61-64	1984	1980	4	0.002		A
4	55-51	1948	634	1314	2.07		NA
	60-51	1829	679	1150	1.69		NA
4a	41-51	2078	365	1713	4.69		NA
	47-51	1521	1089	432	0.40		A

(a) Shock 3 of Fig. 4.1-17, applied on x' and y' axes (Fig. 6.2-16). x' leads y' by 0.601 sec, 0.71 g peak, 0.50 cross-core gap.

(b) $e_i = |U_a - U_{tm}|$

(c) $\chi = \frac{e_i}{U_{tm}}$

(d) A = acceptable
NA = not acceptable

Fig. 6.2-18. CRUNCH-2D and dowel force test spring pack force comparison

TABLE 6.2-12
CRUNCH-2D CORRELATION WITH IN-CORE FORCES - DOWEL FORCE TEST ^(a)

Location	CRUNCH-2D U_a (1b)	Test U_{tm} (1b)	e_i ^(b)	χ ^(c)	E_j	Acceptance ^(d)
Center of core	182	143	39	0.27		A
Midradius	212	91.2	120.8	1.32	0.29	NA
Boundary	198	146	52	0.36		NA

(a) Shock 4, Fig. 4.1-27, 0.25 g, soft soil.

(b) $e_i = |U_a - U_{tm}|$

(c) $\chi = \frac{e_i}{U_{tm}}$

(d) A = acceptable
NA = not acceptable

6.2.3. COCO

Correlation of the COCO computer program was conducted with the following test data:

1. Rocking time history data from three full-scale elements in a column.
2. Single- and two-axis time history data from the 14-element single column test.

For correlation of the time history results, the data were taken from tests where the single column impacted the test rig boundary.

The COCO model and parameters representing the core column are described in Sections 3.4 and 5.4.

6.2.3.1. Full-Scale Element Rocking Tests. It was observed in the initial model development that the rocking phenomenon is almost entirely a function of rigid body dynamics. Modification of element flexibility or damping had little or no effect on rocking characteristics (see Fig. 5.4-2). On the other hand, geometric variations (e.g., rocking width, elimination of the center impact mechanism, etc.) produced significant changes in rocking period and amplitude.

Rocking angle transient decay behavior is compared for test and analysis of two elements rocking on a fixed base element in Figs. 6.2-19 and 6.2-20. Figure 6.2-19 shows the top element initially displaced and Fig. 6.2-20 the bottom element initially displaced before being released. Correlation analysis of the analytical results and data in Fig. 6.2-19 is summarized in Table 6.2-13. COCO predicts behavior similar to the test data, and produces a rocking frequency that exceeds that of the test specimen by approximately 5%, thereby satisfying the criteria. However, from

Fig. 6.2-19. COCO comparison with data from full-scale rocking test No. 14

Fig. 6.2-20. COCO comparison with data from full-scale rocking test No. 11

TABLE 6.2-13
COCO COMPARISON TO FULL-SCALE, BASIC ROCKING TEST DATA

Region (g)	COCO $ U_a $ (deg)	Test U_{tm} (deg)	e_i (a)	$\bar{U}_{tm}$ (b)	$\sqrt{\frac{1}{n} \sum_{i=1}^n e_i^2}$	χ (c)	E_j	Acceptance (d)
0-1	9.6	9.8	0.2	5.4	2.1	0.38	0.40	A (See Fig. 6.2-19)
	7.3	9.2	1.9					
	2	5.5	3.5					
	0.6	2.5	1.9					
	1.5	0	1.5					
1-2	3.2	2.1	1.1	1.26	1.1	0.86	0.40	NA (See Fig. 6.2-19)
	2.7	2.7	0					
	1	0	1					
	2.5	1	1.5					
	0.7	0.5	1.2					

$$(a) e_i = |U_a - U_{tm}|$$

$$(b) \bar{U}_{tm} = \frac{1}{n} \sum_{i=1}^n U_{tm}$$

(c)

$$\chi = \frac{\sqrt{\frac{1}{n} \sum_{i=1}^n e_i^2}}{\bar{U}_{tm}}$$

(d)

A = acceptable
NA = not acceptable

this data COCO rocking angle was exceeded by 86% after the first cycle, which is a violation of the criteria. Figure 6.2-20 shows similar results.

6.2.3.2. Single Column Test. Tests 19, 36, and 37 were used for time history correlation of COCO. Test parameters are given in Table 6.2-14. To reduce computer costs, only portions of the wave forms shown in Figs. 4.1-27 and 4.1-30 were used to obtain data for correlation. These portions are shown in Figs. 6.2-21 and 6.2-22.

Comparisons were made with the following test data:

1. Column base block dowel force (interface 1/2).
2. Boundary impact force on element 7 (right hand face).
3. Rocking load at base of element 11 (right corner).
4. Dowel force on element 10 (interface 10/11).

The comparison of COCO results with the test data is shown in Figs. 6.2-23 through 6.2-34. On a time history basis it is generally observed that the analytical data points produce the same envelope shape as the test data although considerable deviation in magnitude exists in several instances. Frequency-of-events distributions for items 1, 2 and 4, test 36, are given in Tables 6.2-15 through 6.2-17. Generally poor correlation of the frequency distributions was exhibited. As in the case of CRUNCH-1D, more events were predicted by the analysis.

Table 6.2-18 presents the results of the correlation of maximum response from Figs. 6.2-23 through 6.2-34. All but two values produce correlation errors satisfying the criteria.

These comparisons also showed that large correlation errors were experienced due to the hard boundary supports employed in the test, making the response data very sensitive to small changes in excitation g-level

TABLE 6.2-14
COLUMN SHAKE TESTS SELECTED FOR TIME HISTORY CORRELATION
WITH COCO COMPUTER PROGRAM

Test Number ^(a)	g-Level Hor. Vert.	Boundary Gap ~ in. ^(b)	Top Block Gap ~ in. ^(b)	Bottom Block Gap ~ in. ^(b)	Comment
19	0.5 0	0.25	0.0	0.0	Horizontal (only) excitation
36	0.50 0.25	0.25	0.25	0.125	Simultaneous two- axis excitation
37	0.75 0.5	0.25	0.25	0.125	Simultaneous two- axis excitation

(a) Numbers correspond to tests described in Ref. 6.4-2.

(b) Nominal values. Actual gaps were nominal $\pm$ several mils and varied from the bottom of the top of the column. Individual gaps were measured at the four corners (top and bottom, left and right) of elements 1 through 14 for each test.

Fig. 6.2-21. Portion of the single column test horizontal time history waveform used for code correlation

Fig. 6.2-22. Portion of the single column test vertical time history waveform used for code correlation

Fig. 6.2-23. Comparison of COCO results with interface 1/2 dowel force from single column shake test No. 19

Fig. 6.2-24. Comparison of COCO results with interface 10/11 dowel force from single column shake test No. 19

Fig. 6.2-25. Comparison of COCO results with element No. 7 boundary force from single-column shake test No. 19

Fig. 6.2-26. Comparison of COCO results with interface 10/11 rocking force from single column shake test No. 19

Fig. 6.2-27. Comparison of COCO results with interface 1/2 dowel force from single column shake test No. 36

Fig. 6.2-28. Comparison of COCO results with interface 10/11 dowel force from single column shake test No. 36

Fig. 6.2-29. Comparison of COCO results with element 7 boundary force from single column shake test No. 36

Fig. 6.2-30. Comparison of COCO results with interface 10/11 rocking force from single column shake test No. 36

Fig. 6.2-31. Comparison of COCO results with interface 1/2 dowel force from single column shake test No. 37

Fig. 6.2-32. Comparison of COCO results with interface 10/11 dowel force from single column shake test No. 37.

Fig. 6.2-33. Comparison of COCO results with element 7 boundary force from single column shake test No. 37

Fig. 6.2-34. Comparison of COCO results with interface 10/11 rocking force from single column shake test No. 37

TABLE 6.2-15
COCO COMPARISON OF BASE BLOCK DOWEL FORCE FREQUENCY DISTRIBUTION
SINGLE COLUMN SHAKE TEST NO. 36 (a)

Load Range (lb)	COCO U_a (No. of Events)	Test U_{tm} (No. of Events)	e_i (b)	Test $\bar{U}_{tm}$	$\sqrt{\frac{1}{n} \sum_{i=1}^n e_i^2}$	χ	E_j	Acceptance (c)
55-45	0	2	2	2.5	2.6	1.1	0.30	NA
45-35	2	4	2					
35-25	4	2	2					
25-14	6	2	4					
Total Events	12	10						

(a) Simultaneous horizontal and vertical excitation 0.5 gH, 0.25 gV.

(b) $e_i = |U_a - U_{tm}|$

(c) A = acceptable
NA = not acceptable

TABLE 6.2-16
COMPARISON OF ELEMENT 11 DOWEL FORCE FREQUENCY DISTRIBUTION - SINGLE COLUMN SHAKE TEST NUMBER 36^(a)

Load Range (1b)	COCO U_a (No. of Events)	Test U_{tm} (No. of Events)	e_i (b)	Test $\bar{U}_{tm}$	$\sqrt{\frac{1}{n} \sum_{i=1}^n e_i^2}$	χ	E_j	Acceptance (c)
85-60	1	0	1					
60-45	2	2	0					
45-35	2	3	1					
35-25	6	4	2					
25-15	7	3	4	2.4	2.1	0.87	0.30	NA
Total Events	18	12	6	18	6	0.33	0.30	NA

(a) Simultaneous horizontal and vertical excitation 0.5 gH, 0.25 gV.

(b) $e_i = |U_a - U_{tm}|$

(c) A = acceptable
NA = not acceptable

TABLE 6.2-17

COCO COMPARISON OF ELEMENT 7 IMPACT FORCE FREQUENCY DISTRIBUTION - SINGLE COLUMN SHAKE TEST NO. 36^(a)

Load Range (1b)	COCO U_a (No. of Events)	Test U_{tm} (No. of Events)	e_i (b)	Test $\bar{U}_{tm}$	$\sqrt{\frac{1}{n} \sum_{i=1}^n e_i^2}$	χ	E_j	Acceptance ^(c)
375-300	0	1	1					
300-250	1	1	0					
250-200	2	1	1					
200-150	0	0	0					
150-100	3	1	2					
100-50	4	2	2	1	1.3	1.3	0.30	NA
Total Events	10	6						

(a) Simultaneous horizontal and vertical excitation 0.5 gH, 0.25 gV.

(b) $e_i = |U_a - U_{tm}|$ (c) A = acceptable
NA = not acceptable

TABLE 6.2-18
COMPARISON OF COCO MAXIMUM RESPONSE RESULTS WITH SINGLE COLUMN SHAKE TEST DATA

Response	Test No. (a)	COCO U_a (lb)	Test U_{tm} (lb)	e_i (b)	$\chi = e_f/U_{tm}$	E_j	Acceptance (c)
Dowel force 1/2	19	8.5	10.5	2	0.19	0.40	A
Dowel force 10/11	19	96	69	30	0.43	0.40	NA
Impact force 7	19	137	198	61	0.31	0.40	A
Rocking load 10/11	19	83	138	55	0.40	0.40	A
Dowel force 1/2	36	38	53	15	0.28	0.40	A
Dowel force 10/11	19	87	48	39	0.81	0.40	NA
Impact force 7	19	252	370	118	0.32	0.40	A
Rocking load 10/11	19	73	53	20	0.38	0.40	A
Dowel force 1/2	37	54	60	6	0.10	0.40	A
Dowel force 10/11	19	87	64	23	0.36	0.40	A
Impact force	19	355	400	45	0.11	0.40	A
Rocking force 10/11	19	64	137	73	0.53	0.40	A

(a) See Tables 4.6-4 and 4.6-6.

(b) $e_i = |U_a - U_{tm}|$

(c) A = acceptable
NA = not acceptable

and support adjustment tolerances. However, good correlation with time history force data from the single column test is not overly important in view of the objective to qualify the single column for use in a multi-column array. Hence the more important aspect is the single column verification in correlation with the frequency response test data. This is described in Section 6.3.2.

6.2.4. MCOCO

The results of MCOCO were compared with dowel force test data. At the present time, code correlation has not been completed due to the large costs associated with running MCOCO, which has slowed down the effort. The following, therefore, represents the initial comparison with the test data.

The waveform of shock 4 in the dowel force test (Fig. 4.1-27) was used to calculate results for MCOCO correlation. Because of the high computation costs, only the portion of the waveform between 1.0 and 2.0 sec was utilized. Figure 6.2-35 illustrates the time history and the portion that was input to the analysis. The dowel force test showed that the maximum response occurred in this interval, and it was demonstrated by the CRUNCH-1D code that the first second of the waveform could be deleted without significantly affecting the maximum response.

6.2.4.1. Core Locations. Dowel force test data were recorded in a single fuel region that was sequentially located at the core center (test 11), midradius (test 16), and core boundary (test 21). Corresponding locations of the MCOCO model (a full-core strip) were designated by the letters shown in Fig. 6.2-36. The test and analytical model locations are referenced explicitly in Table 6.2-19.

6.2.4.2. Correlation. A summary of the analytical results and test data is given in Table 6.2-20 for fuel element collision forces, dowel forces and rocking angles, and boundary support forces. The analytical results

Fig. 6.2-35. Time history displacement input - 1/5-scale, full-array dowel force test

Fig. 6.2-36. MCOCO 1/5-scale, full-array core model

TABLE 6.2-19
RELATIONSHIP BETWEEN TEST INSTRUMENTATION POSITIONS
AND ANALYTICAL MODEL REFERENCE

Instrument Position ^(a)	Parameter	MCOCO Model Reference ^(b)
4-11	Rocking angle, deg	A
1-7	Rocking angle, deg	B
7-5	Rocking angle, deg	C
596	Rocking angle, deg	D
5-7	Interelement impact force, lb	E
6-4	Interelement impact force, lb	F
4-10	Interelement impact force, lb	G
4-10	Dowel force, lb	H
7-4	Dowel force, lb	I
CSB	Dowel force, lb	J
596	Dowel force, lb	K
1-5	Left spring pack force, lb	L
19-5	Right spring pack force, lb	M

(a) Reference Fig. 4.1-5.

(b) Reference Fig. 6.2-36.

TABLE 6.2-20
COMPARISON - 1/5-SCALE FULL-ARRAY DOWEL FORCE TEST
(COMPARISON OF PEAK VALUES DURING 1 TO 2 SEC PERIOD; 0.25 g, SHOCK 4)

Parameter	(a) MCOCO Model Ref	Test 11 Core Center				Test 16 Mid Radius				Test 21 Core Boundary			
		Analysis (U _a)	Test (U _{tm})	e(b)	E _j (c)	Analysis (U _a)	Test (U _{tm})	e(b)	E _j (c)	Analysis (U _a)	Test (U _{tm})	e(b)	E _j (c)
Rocking angle	A	-0.9	-0.65	0.28	0.40	--	--	--	0.40	--	--	--	0.40
Rocking angle	B	0.94	1.38	0.32	0.40	-1.27	-1.63	0.22	0.40	-1.74	-1.72	0.01	0.40
Rocking angle	C	1.02	0.85	0.2	0.40	-0.55	-0.86	0.36	0.40	-0.73	-0.52	0.4	0.40
Rocking angle	D	0.88	0.56	0.57	0.40	--	--	--	0.40	--	--	--	0.40
Fuel element collision force, lb	E	165	143.0	0.15	0.29	130	80.0	0.62	0.29	168	182.0	0.08	0.29
Fuel element collision force, lb	F	48	12.7	2.78	0.29	49	6.3	6.8	0.29	68	80.0	0.15	0.29
Fuel element collision force, lb	G	--	--	--	0.29	367	267.0	0.37	0.29	375	457.0	0.18	0.29
Dowel force, lb	H	11.3	11.8	0.04	0.37	18.6	7.8	1.38	0.37	31.0	24.0	0.29	0.37
Dowel force, lb	I	--	--	--	0.37	8.3	2.0	3.15	0.37	10.1	7.4	0.36	0.37
Dowel force, lb	J	--	--	--	0.37	--	--	--	0.37	23.7	8.7	1.72	0.37
Dowel force, lb	K	--	--	--	0.37	103	93	0.11	0.37	43.4	70.0	0.38	0.37
Left spring pack, lb	L	1262	2505	0.5	0.40	1262	2781	0.35	0.40	1262	2781	0.55	0.40
Right spring pack, lb	M	1002	1474	0.32	0.40	1002	1518	0.34	0.40	1002	1287	0.22	0.40

(a) See Table 6.2-19.

(b)
$$e = \frac{|U_a - U_{tm}|}{|U_{tm}|}$$
 is the correlation error.

(c) E_j is the allowable correlation error from Section 6.1.

are superimposed on the test data in Figs. 6.2-37 through 6.2-67. Figures 6.2-68 through 6.2-71 illustrate the deflected configuration of this (analytical) core model at four successive times within the 1-sec truncated time history. No direct comparison with core deflection test data was performed other than through observation. The analytical model exhibited lumped core motion similar to that observed in the test.

All response values in Table 6.2-19 are maximums occurring within the 1.00 to 2.00 sec interval. The analytical results in the table were calculated either right at the instrument positions, or within a range of ± 1 element away, horizontally or vertically, as indicated in the acceptance error table.

The following conclusions were made based on the results in the table:

1. MCOCO adequately predicts rocking angles since the correlation criteria for this response were satisfied in seven out of the eight cases presented. The case not satisfying the criteria corresponded to a permanent side reflector block rather than a fuel element. Direct comparison of analytical and experimental rocking angles is illustrated in Figs. 6.2-38 through 6.2-45.
2. A comparison of fuel element collision forces and test data at locations E, F, and G is shown in Figs. 6.2-46 through 6.2-53. Overall correlation was not conclusive, but the results show acceptable correlation near the core boundary.
3. The comparison of analytical and experimental dowel forces at core locations H, I, and J is illustrated in Figs. 6.2-54 through 6.2-61. Only fair correlation of this response is revealed in Table 6.2-20 since the criteria are met in only four of the eight cases presented.

Fig. 6.2-37. MCOCO comparison with spring pack forces - 1/5-scale dowel force test

Fig. 6.2-38. MCOCO comparison with rocking angles at level 11, test 4 - 1/5-scale, dowel-force test, (A)

Fig. 6.2-39. MCOCO comparison with rocking angles at level 7, test 11 - 1/5-scale, dowel-force test, (B)

Fig. 6.2-40. MCOCO comparison of rocking angle at elevation 7, test 11 - 1/5-scale, dowel-force test, (C)

Fig. 6.2-41. MCOCO comparison of reflector block rocking angle, test 11 - 1/5-scale, dowel-force test, (D)

Fig. 6.2-42. MCOCO comparison of rocking angle at level 7, test 16, 1/5-scale, dowel-force test, (B)

Fig. 6.2-43. MCOCO comparison of rocking angle at level 5, test 16 - 1/5-scale, dowel-force test, (C)

Fig. 6.2-44. MCOCO comparison with rocking angle at level 7, test 21 - 1/5-scale, dowel-force test, (B)

Fig. 6.2-45. MCOCO comparison with rocking angle at level 5, test 21 - 1/5-scale, dowel-force test, (C)

Fig. 6.2-46. MCOCO comparison of core element impact forces, level 7, test 11 - 1/5-scale, dowel-force test, (E)

Fig. 6.2-47. MCOCO comparison of fuel element impact force at elevation 4, test 11 - 1/5-scale, dowel-force test, (F)

Fig. 6.2-48. MCOCO comparison of fuel element impact force at level 7, test 16 - 1/5-scale, dowel-force test, (E)

Fig. 6.2-49. MCOCO comparison of fuel element impact force, level 4, test 16 - 1/5-scale, dowel-force test, (F)

Fig. 6.2-50. MCOCO comparison of fuel element impact force at level 10, test 16 - 1/5-scale, dowel-force test, (G)

Fig. 6.2-51. MCOCO comparison with fuel element impact force at level 7, test 21 - 1/5-scale, dowel-force test, (E)

Fig. 6.2-52. MCOCO comparison with fuel element impact force at level 4, test 21 - 1/5-scale, dowel-force test, (F)

Fig. 6.2-53. MCOCO comparison with fuel element impact force, level 10, test 21 - 1/5-scale, dowel-force test, (G)

Fig. 6.2-54. MCOCO comparison with dowel force at level 10, test 21 - 1/5-scale, dowel-force test, (H)

Fig. 6.2-55. MCOCO comparison with dowel force at level 4, test 21 - 1/5-scale, dowel-force test, (I)

DOWEL FORCE, INSTRUMENT CSB TEST 21 SOIL 3 (SHOCK 4) 0.24G

Fig. 6.2-56. MCOCO comparison with core support block dowel force, test 21 - 1/5-scale, dowel-force test, (J)

Fig. 6.2-57. MCOCO comparison with reflector block dowel force, test 21 - 1/5-scale, dowel-force test, (K)

DOWEL FORCE, INSTRUMENT 4-10 TEST 16 SOIL 3 (SHOCK 4) 0.24G

Fig. 6.2-58. MCOCO comparison of dowel force at level 10, test 16 - 1/5-scale, dowel-force test, (H)

Fig. 6.2-59. MCOCO comparison of dowel force at level 4, test 16 -
1/5-scale, dowel-force test, (I)

Fig. 6.2-60. MCOCO comparison of reflector block dowel force test 16 - 1/5-scale, dowel-force test, (K)

Fig. 6.2-61. MCOCO comparison with dowel forces at elevation 10, test 11 - 1/5 scale dowel-force test, (H)

Fig. 6.2-62. MCOCO comparison with left boundary support forces at level 5, test 11 - 1/5-scale, dowel-force test, (L)

Fig. 6.2-63. MCOCO comparison with right boundary force at level 5, test 11 - 1/5-scale, dowel-force test, (M)

Fig. 6.2-64. MCOCO comparison of left boundary support force at level 5, test 16 - 1/5-scale, dowel-force test, (L)

Fig. 6.2-65. MCOCO comparison with right boundary support force at level 5, test 16 - 1/5-scale, dowel-force test, (M)

Fig. 6.2-66. MCOCO comparison with left boundary support force at level 5, test 21 - 1/5-scale, dowel-force test, (L)

Fig. 6.2-67. MCOCO comparison with right boundary support force at level 5, test 21 - 1/5-scale, dowel-force test, (M)

MCOCO 1/5 SCALE-26 COLUMNS WITH CORE BARREL PLATES

T= 1.30G

Fig. 6.2-68. MCOCO simulated core reflection after 30 sec, 1/5-scale, full-array model, dowel force test shock 4, 0.24 g

MCOCO 1/5 SCALE-26 COLUMNS WITH CORE BARREL PLATES

Fig. 6.2-69. MCOCO simulated core deflection after 45 sec, 1/5-scale, full-array model, dowel force test shock 4, 0.24 g

MCOCO 1/5 SCALE-26 COLUMNS WITH CORE BARREL PLATES

T= 1.700

Fig. 6.2-70. MCOCO simulated core deflection after 0.7 sec, 1/5-scale, full-array model, dowel force test shock 4, 0.24 g

MCOCO 1/5 SCALE-26 COLUMNS WITH CORE BARREL PLATES

Fig. 6.2-71. MCOCO simulated core deflection after 1 sec, 1/5-scale, full-array model, dowel force test shock 4, 0.24 g

4. Boundary forces computed at each side of the MCOCO model are compared to the test data in Figs. 6.2-62 through 6.2-67. Correlation of these results was concluded to be fairly good since the criteria were met in 75% of the cases presented.

The analysis of the analytical results and test data discussed above led to the conclusion that MCOCO correlated reasonably well for the cases so far investigated. Further correlation of this code must be completed before verification can be substantiated. This task will be accomplished with the use of the anticipated array processor unit, which is briefly described in Section 3.7.

6.3. CODE CORRELATION WITH FREQUENCY RESPONSE TEST DATA

The resonant frequency associated with the lumped core mode of the 1/5-scale, full-array test model was the primary response quantity of interest for correlation of CRUNCH-1D, CRUNCH-2D, and MCOCO. In the following sections, the CRUNCH codes are compared with 1/5-scale, planar-array data, and the COCO code with 1/5-scale, single-column test data.

6.3.1. CRUNCH Code Comparison With 1/5-Scale, Planar-Array Test Data

Boundary forces measured at three locations in the 1/5-scale, planar-array sine sweep tests were compared with the resonant frequency predictions of the CRUNCH-1D and CRUNCH-2D (planar array) models.

In Fig. 6.3-1, the CRUNCH-1D boundary force frequency response is shown with that recorded at element number 2 (Fig. 6.2-15). The sudden drop in the test data response identifies the lumped mode resonant frequency. During testing, this event was associated with breakup of the lumped-element mode. As shown in the figure, CRUNCH-1D predicts this

Fig. 6.3-1. CRUNCH-1D boundary force versus 1/5-scale, planar-array test data, element No. 2

frequency at approximately 10 Hz, for which the correlation error is 41%. Hence, the correlation criteria were not satisfied in this case since the acceptance error on resonant frequency for all models is 15%.

The magnitude of the boundary support force did not correlate well either since the response level is approximately 46% higher for the code, as compared to an acceptance error of 40%. The nature of this comparison suggests that the boundary support stiffness for this CRUNCH-1D model is too large and damping too low. Adjusting these parameters would result in both a lower resonant frequency and boundary response level.

The CRUNCH-2D boundary support force frequency response was compared with that of the 1/5-scale, planar-array test at the three locations identified in Figs. 6.3-2 through 6.3-4. These figures show that both the resonant frequency and resonance response level predictions made by the code satisfy the correlation criteria. The correlation error on resonant frequency for each boundary location lies between 5.5% and 8%, in comparison to a 15% acceptance error. The correlation error of the (resonance) boundary force ranged from 52% to 22% for an average of 37%, with a boundary force acceptance error of 40%. Based on these results, CRUNCH-2D showed satisfactory correlation with planar array frequency response.

6.3.2. COCO Comparison With 1/5-Scale, Single-Column Test Data

Horizontal and vertical frequency response characteristics of the COCO code were compared with single-column shake test data. Horizontal displacements at the column midheight, relative to the boundary, are compared in Fig. 6.3-5. The sine sweep of this test was set at the low level of 0.05 g to induce column vibration with no boundary impact. The COCO results were produced using sine dwells at this g-level.

Fig. 6.3-2. CRUNCH-2D boundary force on element No. 2 versus 1/5-scale, planar-array test data

Fig. 6.3-3. CRUNCH-2D boundary force on element No. 71 versus 1/5-scale, planar-array test data

Fig. 6.3-4. CRUNCH-2D boundary force on element No. 72 versus 1/5-scale, planar-array test data

Fig. 6.3-5. COCO horizontal deflection frequency response versus single column test data, column midheight, no boundary impact

For the small amplitude vibration shown in the figure, the test produced a horizontal resonant frequency of approximately 2.9 Hz. The COCO resonant frequency shown in the figure was approximately 2.7 Hz. This result satisfies the correlation criteria. However, the relatively large resonance displacement produced by the code presents an error on displacement of approximately 100%, which is far in excess of the acceptance error. This error was found to be due to the high sensitivity of free column displacements to small changes in input g-level about the small nominal value of 0.05 g. Hence the lack of correlation in this case was not considered to represent a deficiency of the code.

The COCO prediction of column support post load frequency response is compared to single column test data in Fig. 6.3-6. The test data resonance behavior exhibits a spring-softening system, and the resonance curve shown is the sweep-up curve. The COCO resonance of 26 Hz in the figure was calculated using a series of five sine dwells at 0.5 g. The correlation error associated with this result is less than 12%, satisfying the correlation criterion on frequency; however, the code-calculated resonance force level exceeds the support post acceptance error.

6.3.3. Code Comparisons, 1/5-Scale, Full-Array Test Data

The bulk of the frequency response analysis was performed with CRUNCH-1D, CRUNCH-2D, and MCOCO comparisons to the 1/5-scale, full-array test model. Figure 6.3-7 shows the boundary force frequency response of these codes in comparison to the test data for a 0.5 g sine sweep. The results for each code were produced with sine sweep inputs of 0.5 or 1.0 decade per minute sweep rates. The faster rate could be used without any significant difference in the response.

A resonant frequency of approximately 3.75 Hz was predicted by CRUNCH-1D for the 0.5 g sine sweep. In comparison to the experimental resonant frequency of 4.0 Hz, this represents a correlation error of

Fig. 6.3-6. COCO column support force frequency response versus single column test data

Fig. 6.3-7. Code boundary support force frequency response versus 1/5-scale, full-array test data

6.25%, which satisfies the criteria based on a 15% acceptance error. The CRUNCH-1D boundary force level at resonance, however, was too far below the test data to produce satisfactory correlation.

The CRUNCH-2D prediction of the frequency response compares equally well with the data since the resonant frequency is essentially the same as that for CRUNCH-1D.

The MCOCO response in Fig. 6.3-7 is represented as the boundary support force frequency response at reflector block level 6 in the core. As of this date, resonance has not been achieved for a sine sweep up to 4.4 Hz. Hence, conclusions regarding the frequency response of MCOCO are deferred pending further correlation analysis. Lumped mode behavior, however, was clearly illustrated by the MCOCO simulations.

Overall conclusions regarding the correlation of all the core seismic codes are summarized in Section 1.

6.4. REFERENCES

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7. SENSITIVITY STUDIES

This section presents a series of studies performed to determine the sensitivity of the analytical results to numerical integration error and changes in the code input parameters. These studies were required to evaluate both the accuracy of the codes and the effect of the input parameters, which may not be well defined. The studies were conducted with CRUNCH-1D since this code is considerably less expensive to run than the other core seismic codes. Tables 7.0-1 and 7.0-2 are presented to summarize the results of the studies.

7.1. NUMERICAL SENSITIVITY

An assumption basic to most numerical integration techniques is that the slope and magnitude of the function to be integrated are continuous over the time interval. If this is not true, then additional numerical error will be introduced into the analysis. For the fuel element impact mechanism shown in Fig. 7.1-1, the damping force component has a large discontinuity at the beginning and end of the impact. The slope of the stiffness force is also discontinuous. The effects of these discontinuities on a two-block collision and on a full-array analysis are investigated below.

7.1.1. Two-Block Collision

In Section 5.2.6, the 1/5-scale interblock stiffness and damping coefficients were computed to yield a coefficient of restitution of 0.36, assuming an exact integration. However, a significant numerical error results when using an approximate technique to integrate over the force discontinuities at the beginning and end of each impact. The numerical error associated with these discontinuities depends on the size of the

TABLE 7.0-1
CRUNCH-1D SENSITIVITY SUMMARY RESULTS - 1/5-SCALE,
FULL-ARRAY MODEL SIMULATION - 0.24 g TIME HISTORY INPUT

Code Parameter/ Model Property	Code Response Quantity	Exceeds Code Numerical Error (a)	
		Hard Boundary Support	Soft Boundary Support
Coefficient of restitution	SPF ^(b)	no	no
	IF ^(c)	no	no
Contact time	SPF	no	no
	IF	1.4 yes	1.6 yes
Column stiffness	SPF	no	no
	IF	no	no
Column damping	SPF	1.2 yes	no
	IF	yes	1.25 yes
Column breakaway force	SPF	1.4 yes	2.0 yes
	IF	1.2 yes	1.5 yes
Core support floor height	SPF ^(d)	1.5 yes	no
	IF ^(d)	no	no
Floor-to-ground damping	SPF ^(d)	1.1 yes	1.1 yes
	IF ^(d)	1.1 yes	no

(a) See figures in Section 7.

(b) Spring pack force.

(c) Interelement force.

(d) At floor level.

TABLE 7.0-2
CRUNCH-1D SENSITIVITY SUMMARY RESULTS - 1/5-SCALE, FULL-ARRAY
MODEL SIMULATION - 0.5 g SINE SWEEP INPUT

Code Parameter/ Model Property	Code Response Quantity	Parameter Variation (%)	Resonant Frequency Variation (%)	Resonance Magnitude Variation (%)
Across-core gap	Soft spring pack force	+11.4	-4.3	+7.7
Column damping	Soft spring pack force	-50	+5.6	+31

A) DAMPING COMPONENT

B) STIFFNESS COMPONENT

Fig. 7.1-1. Impulse force discontinuities

integration time step and on the time at which the discontinuities occur during the time step. Since discontinuities can occur at any time during an integration time step, a range of error can be determined for each time step size considered. The location of the discontinuities within the time step was varied by varying the initial gap separating two fuel elements undergoing collision. The results of the study showed the following:

1. For an integration time step of 0.00004 sec, the resultant coefficient of restitution varied from 0.27 to 0.42 (exact integration yields 0.36).
2. An integration time step of 0.00004 sec results in an impact force variation of 235 to 295 lb (exact integration yields 281 lb).
3. The numerical error generated while integrating over these discontinuities decreases with decreasing time step size.

Figure 7.1-2 illustrates the range of coefficient of restitution, which was computed numerically with an integration time step of 0.00004 sec. Although this range could be reduced by decreasing the size of the step, it was concluded that the effort was not justified because the test values of coefficient of restitution, which were used to derive the damping coefficient of the impact mechanisms in the first place, vary over a range that is nearly twice that due to the numerical error.

7.1.2. Full Array Time History Analysis

A displacement time history function representing a reduced version of shock 4 (at 0.24 g) of the 1/5-scale dowel force test was used to investigate the numerical sensitivity for full-array model analysis. The numerical sensitivity was evaluated by making small changes to the integration

Fig. 7.1-2. Composite coefficient of restitution versus impact velocity

time step and computing the mean and standard deviation of the resulting maximum spring pack and interblock forces. The results of this study are summarized in Table 7.1-1.

The results show that the stiff, or high frequency, structures (hard stop supports and fuel elements) were far more sensitive to perturbations in the integration time step than the soft, or low frequency, structures (soft spring packs). These results also show that introduction of soft boundary springs into the model tends to lower the numerical error in the fuel element collision forces. It was also found that the numerical errors associated with forces below the peak response were somewhat larger; however, results are presented only for the maximum forces because these were of primary interest.

7.2. CODE INPUT PARAMETERS

This section presents a series of studies performed to determine the sensitivity of the CRUNCH-1D code results to changes in the input parameters. For the majority of the cases studied, the model excitation consisted of a time history displacement representing shock 4 of the 1/5-scale, dowel-force test, from 1 to 2.5 sec into the waveform. Both test and analysis indicated that the maximum model response was achieved in this time frame, and analysis indicated that eliminating the first second of the waveform changed the peak response by less than 10%. Sine sweep excitation of the model was also used to investigate its frequency response.

Analyses were conducted on a core model having both soft and hard spring pack supports. The following parameters were investigated:

1. Interelement contact time.
2. Interelement coefficient of restitution.
3. Column stiffness.

TABLE 7.1-1
 NUMERICAL SENSITIVITY OF THE CRUNCH 1-D FULL-ARRAY
 MODEL RESULTS TO PERTURBATIONS ABOUT AN INTEGRATION
 TIME STEP OF 0.00004 SEC

Force	Mean (lb)	2 σ Range (lb)	2 σ Error (%)
Hard stop spring pack	1339	1065 - 1613	20
Soft spring pack	204	201 - 207	1
Interelement collision	284 ^(a) 281 ^(b)	251 - 315 ^(a) 260 - 302 ^(b)	12 ^(a) 8 ^(b)

(a) Model with hard stop spring packs.

(b) Model with soft spring packs.

4. Column damping.
5. Column breakaway force.
6. Core support floor-to-ground damping.
7. Core support floor height.

The results were presented in graphical form, with the response variation compared to the code numerical error, which was discussed in Section 7.1.2. The numerical error is plotted as the 2σ variation about the response corresponding to the nominal parameter value.

7.2.1. Interelement Parameters

This section presents the results of the sensitivity of spring pack force and interelement force to changes in interelement contact time (during collision) and coefficient of restitution. Figures 7.2-1 through 7.2-3 show the sensitivity of the maximum interelement force and spring pack force versus a range of coefficients of restitution. Results are presented for both hard and soft spring packs. The range of input was selected to coincide with the scatter of the test data. These data, in Section 4.2, indicate that coefficients of restitution can vary from 0.3 to 0.45. The results of the studies show that the maximum forces are not very sensitive to changes of coefficient of restitution in this range. For the interelement force, only two points fall outside the range of numerical error given in Table 7.1-1 and also shown in the figures. These are the hard spring pack interelement force at a coefficient of restitution of 0.25 and the soft spring pack interelement force at 0.45. All spring pack force variations were within the range of variations due to numerical sensitivity.

The second interblock parameter varied was contact time. Because of the lack of 1/5-scale test results, 1/2-scale test contact times (Fig. 4.2-12) were scaled to determine the expected range of contact time for the 1/5-scale blocks. The test results indicate that the contact time

Fig. 7.2-1. CRUNCH-1D element No. 28 impact force versus coefficient of restitution

Fig. 7.2-2. CRUNCH-1D spring pack force versus coefficient of restitution - soft spring pack

Fig. 7.2-3. CRUNCH-1D spring pack force versus coefficient of restitution - hard spring pack

varies from 0.00055 to 0.00033 sec as the interblock relative velocity varies from 12 to 30 in./sec. Figure 7.2-4 indicates that the variations in spring pack forces with contact time are less than those from numerical error for both the hard and soft spring packs. Consequently, it was concluded that the spring pack forces were relatively insensitive to change in contact time.

The results shown in Fig. 7.2-5 indicate that the interelement force varies significantly when the contact time is varied from 0.0003 to 0.0005 sec. Hence it was concluded that this variation be accounted for when evaluating the loads output from the seismic codes.

7.2.2. Core Column Parameters

In this section, the sensitivity of spring pack force and interelement force to variations of column stiffness, damping, and breakaway force is investigated for the CRUNCH-1D code. These studies also apply to CRUNCH-2D, but not to COCO and MCOCO since these codes do not use these parameters as input.

Column stiffness was computed by assuming that the column acts as a simply supported beam until the deflection reaches the point where the column buckles. This is the maximum theoretical stiffness of the column and does not account for geometric variations. Sensitivity studies were run to determine the effect of reducing the column stiffness to $3/4$, $1/2$, and $1/4$ of this theoretical value. The results, shown in Figs. 7.2-6 and 7.2-7, indicate that in all cases the maximum forces remain within the expected range of numerical error.

Column damping ratio was obtained from $1/5$ -scale, single-column tests and scaled down, $1/4$ -scale column damping test data using the scaling laws in Section 4.1.3. The resultant value, however, was doubled because it

Fig. 7.2-4. CRUNCH-1D spring pack force versus contact time

Fig. 7.2-5. CRUNCH-1D element No. 28 impact force versus contact time

Fig. 7.2-6. CRUNCH-1D maximum interelement force versus column stiffness

Fig. 7.2-7. CRUNCH-1D spring pack force versus column stiffness

yielded better correlation with a CRUNCH-1D simulation of the 1/5-scale, full-array tests. The sensitivity analyses for this parameter were performed over a range of one-fourth to four times the reference value of 0.18 used in the analysis. The results are also applicable to CRUNCH-2D.

Figure 7.2-8 shows that the variation of soft spring pack load to variation of column damping ratio in the range of one-half to twice the nominal value is similar to that of the numerical error. Hence the variation of these forces due to damping was not of concern. However, the variation of load on the spring packs having hard stops far exceeded the numerical error range, especially since the hard stops became inactive at higher damping values. Since effective column damping is not a well-defined quantity, and its effect on this load is significant, it was concluded that this property should always be accounted for when evaluating hard spring pack loads.

Figure 7.2-9 indicates that doubling or halving the column damping ratio results in approximately a 40% change in the interelement forces. This variation exceeds the numerical error for the hard and soft boundary support design. Therefore, column damping variation should be accounted for in the evaluation of interelement forces by CRUNCH-1D.

The effect of column breakaway force on spring pack load is shown in Figs. 7.2-10 and 7.2-11. In all cases, the variations are larger than the expected numerical error, making the breakaway force a significant parameter to be considered when evaluating the response of CRUNCH-1D. The effect is particularly noticeable for the right side of the core, with a soft spring pack design. In contrast to the left spring pack load, which decreases for all changes in breakaway force away from the nominal value quoted in Section 5, the right spring pack decreases with increasing breakaway force. This behavior has not been investigated in detail.

Fig. 7.2-8. Spring pack force versus column damping

Fig. 7.2-9. CRUNCH-1D interelement force versus column damping

Fig. 7.2-10. CRUNCH-1D left spring pack force versus column breakaway force

Fig. 7.2-11. Right spring pack force vs column breakaway force - soft spring pack

The above conclusions regarding the significance of column breakaway force can be extended to the interelement force response shown in Fig. 7.2-12.

7.2.3. Core Support Floor Parameters

Two core support floor parameter sensitivity studies were run for CRUNCH-1D. First, the core support floor strip height was varied and, secondly, the core support floor to ground damping magnitude was varied. Figures 7.2-13 and 7.2-14 present the results of varying the core support floor strip height through a range of 1/2 to 2 from the nominal value. The results for the hard stop spring pack configuration indicate that increasing the core support floor strip height by 50% can cause more than a 50% reduction in the hard spring pack forces, while the same study shows that doubling or halving the strip height produces changes of interblock load and soft spring pack load that remain within the range of numerical sensitivity. The results for the soft spring packs were considered more significant because this design is similar to that proposed for future HTGRs.

Figures 7.2-15 and 7.2-16 show the effect of core support floor damping on spring pack and interelement forces. The results show that all forces with the exception of interelement forces with soft supports were sensitive to changes in core support floor damping. Therefore, support floor damping must be accounted for when evaluating the forces output from CRUNCH-1D.

7.2.4. Frequency Response Analyses

The effect of input parameter variation on the frequency response of CRUNCH-1D was investigated by applying a 0.5 g sine-sweep to the model.

Figure 7.2-17 shows that the (soft) spring pack frequency response was not significantly affected by small changes in the across-core gap, since

Fig. 7.2-12. Interelement force versus column breakaway force

Fig. 7.2-13. CRUNCH-1D left spring pack force versus support floor strip height

Fig. 7.2-14. CRUNCH-1D maximum interelement force versus support floor strip height

Fig. 7.2-15. CRUNCH-1D left spring pack force versus core support floor damping

Fig. 7.2-16. CRUNCH-1D interelement force versus core support floor damping

Fig. 7.2-17. CRUNCH-1D soft spring pack force frequency response versus cross core gap

an 11.4% increase in the gap results in a 4.3% decrease in resonant frequency and a 7.7% increase in load response. Figure 7.2-18 shows that halving the column damping results in only a 5.6% increase in the resonant frequency; however, the resonance spring pack load experienced a 31% increase. This behavior is to be distinguished from the small change in soft spring pack load with respect to column damping calculated in the time history analysis and depicted in Fig. 7.2-8. The reason is that the frequency content of the time history input likely does not coincide with the model resonant frequency.

Fig. 7.2-18. CRUNCH-1D soft spring pack force frequency response versus column damping

8. APPLICATION TO DESIGN

This section describes the output from the core seismic codes and outlines how this information is interpreted in the seismic design of HTGR core components.

8.1. GENERAL

The first step in establishing a seismic design basis for the HTGR core components is to run the core seismic computer codes for the full range of input parameters representing all operating and environmental conditions over the projected life of the core. Design parameters of the core and associated core component design loads are produced from this analysis.

Code parameters that reflect the core operating conditions and change with time over the life of the core include, but are not limited to, the across-core gap and the fuel element modulus of elasticity. The latter is represented in the fuel element impact mechanism spring stiffness.

Analyses will also be run to investigate the effect a change in core component detail design has on core design loads. For example, the maximum dowel force occurring for a three-or-four-dowel configuration on a fuel element may be evaluated, or the maximum boundary force investigated for a change in spring pack design or change in spring pack spacing. The core response to seismic excitation as a function of site soil stiffness is also investigated using the core seismic codes.

An extensive parameter study as outlined will most likely be conducted with the simplest core seismic model, CRUNCH-1D. After determining the controlling core parameters that produce the maximum response in CRUNCH-1D

(i.e., spring pack loads and flat-on fuel element collision forces), the more sophisticated (and expensive) models, CRUNCH-2D, MCOCO, and COCOROD, will be used to determine the final design loads. The validity of this process is based on the seismic response of the CRUNCH-1D model being similar to that of the other models, a fact verified by correlating all the codes with the experimental test data.

The following paragraphs present a more detailed description of the use of the seismic code output in determining specific core component design loads and core response quantities, which must meet design allowables.

8.2. HEXAGONAL ELEMENTS

Hexagonal graphite elements are of three basic types: fuel elements, control rod elements, and replaceable reflector elements. The control rod elements are perforated by large diameter holes for the control rods along with the fuel holes and coolant channels; therefore, these are probably the most critical for impact loads produced by seismic motion. However, since other loadings will be combined with seismic loadings, it is necessary to provide design loads for all of the elements.

The loads used for seismic design of each type of hexagonal core elements are as follows:

1. Single face, flat-to-flat, horizontal impact forces.
2. Edge and corner horizontal impact forces and angles of contact.
3. Simultaneous horizontal impact forces of types 1 and 2 on several element faces.

4. Vertical flat-to-flat forces.
5. Vertical edge and corner impact forces and angles of contact.
6. Dowel and socket loads.

These loads are obtained from the computer programs as described in the following paragraphs.

8.2.1. Flat-to-Flat Horizontal Forces

Flat-to-flat horizontal impact forces are obtained from the CRUNCH-1D, CRUNCH-2D, and MCOCO computer codes. The CRUNCH-1D code is limited to flat-to-flat impacts (Fig. 3.2-1) and this output is used directly. In MCOCO, the blocks have separate edge springs on the vertical faces and the sum of these spring forces is output (see Fig. 3.4-2). The CRUNCH-2D code is also limited to flat-on impacts but will be used to determine biaxial effects since the forces on all six faces of the elements are output.

8.2.2. Horizontal Edge and Corner Forces

Figure 8.2-1 illustrates the element spring models implemented in the seismic codes. The horizontal edge and corner forces can be derived from the velocity output of CRUNCH-1D using the spring ratio techniques described in Ref. 8.2-2. The basic assumption of this technique is that velocities in the actual core are independent of the impact configuration of the elements. Using the equations of motion, the properties of the blocks (including translational and rotational inertia) and the ratios of the corner, edge, and flat-on spring stiffnesses are computed to convert the horizontal impact loads from the codes to the appropriate edge and corner loads.

CRUNCH -1D MODEL

COCO MODEL

SIDE EDGE MODEL

CORNER IMPACT

m = MASS OF BLOCK
 k_t = BLOCK STIFFNESS
 $\dot{x}$ = HORIZONTAL VELOCITY
 F_{c1} = SPRING FORCE

m = MASS OF BLOCK
 k_c = BLOCK EDGE STIFFNESS
 x = HORIZONTAL VELOCITY
 $\dot{\theta}_{cs}$ = ANGULAR VELOCITY
 I_s = MASS MOMENT OF INERTIA
 F_{co} = SPRING FORCE

m = MASS OF BLOCK
 k_e = BLOCK SIDE EDGE STIFFNESS
 $\dot{x}$ = HORIZONTAL VELOCITY
 $\dot{\theta}_{ca}$ = ANGULAR VELOCITY ABOUT VERTICAL AXIS
 I_a = MASS MOMENT OF INERTIA ABOUT VERTICAL AXIS
 F_{c2} = SPRING FORCE

m = MASS OF BLOCK
 k_{ce} = BLOCK CORNER STIFFNESS
 $\dot{x}$ = HORIZONTAL VELOCITY
 $\dot{\theta}_s$ = ANGULAR VELOCITY
 $\dot{\theta}_a$ = ANGULAR VELOCITY ABOUT VERTICAL AXIS
 I_s = MOMENT OF INERTIA
 I_a = MASS MOMENT OF INERTIA ABOUT VERTICAL AXIS
 F_{c1} = SPRING FORCE

Fig. 8.2-1. Core seismic code element spring models

MCOCO calculates top and bottom edge loads on the elements. Corner loads can be approximated by factoring the edge load to obtain the corner loads using the same technique described above. Although CRUNCH-2D calculates element loads at an angle to the excitation, it is limited to flat-on impacts as mentioned previously, and the edge and corner impacts on each face can be obtained in the same manner as for the faces in CRUNCH-1D. Multiple face impacts are discussed in more detail in the following paragraph.

8.2.3. Multiple Face Impacts

Multiple face impacts are a phenomenon that can only be analyzed with the CRUNCH-2D code. There are six faces on the hexagonal block, and it is possible that all six faces are loaded simultaneously. CRUNCH-2D runs have been made comparing the maximum face loads with the most severe sets of simultaneous face loads. More investigation in this area is planned for the future. In the limited number of runs made so far, no peak face loads have occurred with significant simultaneous adjacent face impacts. However, multiple face loading is important for blocks with less than peak-level loads.

8.2.4. Vertical Flat-to-Flat Forces

The vertical flat-to-flat forces are computed by the MCOCO model. The elements at the lower core elevations are loaded by the dead weight of the elements above them, and added to this load is the inertia load of the elements due to the vertical component of the seismic excitation. Reduced MCOCO models are being investigated for use in this application.

8.2.5. Vertical Edge and Corner Forces

Vertical edge and corner impact forces are output from MCOCO. Vertical edge loads are output directly (see Fig. 3.4-2) and the vertical corner loads are computed in the manner described in Section 8.2.2.

8.2.6. Dowel and Socket Loads

Fuel element dowel and socket loads in the direction of the seismic excitation are output from MCOCO. Dowel forces normal to this direction can be determined as follows.

The dowel force data recorded in the 1/5-scale, dowel-force test (Ref. 8.2-1) contain the frequency distribution of the x and y dowel force components and the frequency distribution of the modulus of these components. In assuming that these distributions are typical throughout the core, and given that the frequency content of the seismic excitation used in the analysis is the same or similar to that of the tests (per Ref. 8.2-1), y-axis dowel force distributions for design can be extrapolated from these data using the MCOCO x-axis dowel force.

The use and validity of the above method require further verification.

8.3. PERMANENT REFLECTOR BLOCKS AND LATERAL SUPPORT SYSTEM

The permanent reflector blocks form a ring around the graphite core elements, absorbing the impact of the elements on one side and transmitting the load to the lateral spring packs. The permanent reflector blocks contain vertical dowels and sockets in addition to tangential keys, which provide ring continuity (Fig. 8.3-1). The seismic loads of importance acting on the reflector blocks are:

1. Radial spring pack loads on outside corners.
2. Tangential spring pack loads.
3. Horizontal impact forces from other permanent reflector blocks.
4. Horizontal impact forces from hexagonal reflector blocks.
5. Vertical flat-to-flat impact forces.

Fig. 8.3-1. Permanent reflector block models

6. Vertical edge and corner impact forces and angles of contact.
7. Dowel and socket loads.
8. Tangential key loads.

8.3.1. Radial Spring Pack Loads

Radial spring pack loads in line with the seismic excitation are output from each of the seismic codes. MCOCO will be employed to calculate the final radial spring pack loads in the direction of the seismic excitation, at all core elevations, and the response of the spring packs to combined horizontal and vertical seismic excitation. The radial loads on the spring packs aligned at an angle to the excitation will subsequently be calculated by CRUNCH-2D.

8.3.2. Tangential Spring Pack Loads

Tangential (or circumferential with respect to the core) loads are transmitted to the spring packs because the pad at the end of each spring pack protrudes into a vertical slot cut into the outside face of each permanent side reflector block. These tangential loads are output only from CRUNCH-2D. Since this code models a planar section of the core at the midheight elevation, tangential spring pack loads at other elevations are currently not available. However, the CRUNCH-2D model can represent a planar section at any desired elevation by modification of code parameters, especially the core column spring stiffness, breakaway force, and damping ratio. This modification will be undertaken if a detailed distribution of tangential spring pack loads away from the core midheight elevation is deemed to be necessary.

8.3.3. Horizontal Hexagonal Reflector Block Forces

The horizontal impact forces at the interface of the hexagonal reflector blocks and permanent side reflector blocks are expected to be significant only for the hexagonal blocks. These forces are calculated by

each of the codes in the same manner as described for the hexagonal elements in Section 8.2.

8.3.4. Horizontal Side Reflector Block Forces

With the exception of the tangential or circumferential loads transmitted in the plane of the reflector ring, the horizontal side reflector block impact forces are equivalent to the radial spring pack forces and hexagonal reflector block forces previously described in Sections 8.3.1 and 8.3.3. Tangential side reflector block loads are evaluated only by CRUNCH-2D.

8.3.5. Vertical Permanent Reflector Block Forces

Vertical forces on the permanent reflector blocks are output by MCOCO in the same format as discussed for the fuel elements in Sections 8.2.4 and 8.2.5. Edge and corner loads are computed by the element spring ratio method discussed in Section 8.2.2.

8.3.6. Permanent Side Reflector Block Key Loads

Loads transmitted by the permanent side reflector block keys shown in Fig. 8.3-1 are currently not computed by the core seismic codes. A proposed method for their evaluation utilizes the deflection output of the CRUNCH-2D model. The key loads are computed by taking the difference in the radial deflection between the permanent side reflector blocks, subtracting the free travel tolerance, and multiplying by the key stiffness.

8.4. CORE SUPPORT BLOCKS AND POSTS

The core support structure includes support blocks, each of which supports a fuel region consisting of seven core columns. Each support block is, in turn, supported by three posts, which engage sockets in the

underside of the support blocks (Fig. 2.2-5). The vertical response and dead weight of the core applies loads to the support posts and blocks.

The important design loads are as follows:

1. Support post loads and positions.
2. Socket loads on support blocks.
3. Horizontal impact loads between support blocks.
4. Vertical impact loads on support blocks from hexagonal reflector blocks.

8.4.1. Support Post Loads and Positions

MCOCO is used to determine the support post loads and the location of the load on the top of the posts. The local load location is important because the offset of the vertical post load produces a bending moment on the posts. The combination of horizontal and vertical seismic motion also produces core element rocking forces on the core support blocks, which contributes to the total core support post load.

8.4.2. Socket Loads

The support block socket loads are calculated directly from the core support post loads. Definition of the post offset in the socket is especially important in this case because it significantly alters the stress pattern in the socket.

8.4.3. Core Support Block Horizontal and Vertical Impact Loads

The MCOCO core support block model contains upper and lower edge springs. These loads are part of the MCOCO output. The maximum horizontal loads are presently added to the other support loads without regard to phasing. The code also provides the vertical loads resulting from rocking impact of the hexagonal elements that rest on the support blocks.

8.5. CONTROL ROD LOADS

Control rods are contained inside each fuel element control column. The rods are composed of free hanging links, which swing during a seismic event and impact the internal walls of the graphite elements. The design loads of importance are as follows:

1. Canister impact loads.
2. Stand-off fin impact loads.
3. Shear loads in balljoints.
4. Vertical loads in the flexible cable.

The above loads are calculated only by COCOROD. This code models a single fuel column with one rod. MCOCO will be used to establish the critical core column gaps and surrounding core column motion, which is input to COCOROD as boundary motion for calculation of the above control rod forces.

8.6. CORE DISPLACEMENTS AND ROTATIONS

The displacement behavior of the core is used in the core design as follows:

1. Determination of maximum core upper plenum deflection and maximum support post travel distance.

2. Determination of column deflection modes for control rod design and to satisfy criteria for control rod insertion.
3. Establishment of core geometry variation for gas flow perturbations and core performance.

8.6.1. Maximum Support Post Travel

The core support system is designed to accept a limited amount of travel. The total displacements are computed in MCOCO and are a combination of free gap travel, spring pack deflection, and graphite block deformation.

8.6.2. Deflection Modes for Control Rods

The control rods are designed as flexible linked structures that can be inserted into the core during a seismic event. The configuration of the core elements is calculated by MCOCO for the basic column distortions, and CRUNCH-2D calculates horizontal deflections normal to the axis of seismic excitation.

8.6.3. Geometric Effects on Gas Flow

The displacement output of MCOCO and CRUNCH-2D will also be used for fluid flow analyses and the effects on core physics.

8.7. REFERENCES

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