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VOLUME 1
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**MCOCO
A COMPUTER PROGRAM FOR SEISMIC
ANALYSIS OF THE HTGR CORE**

**VOLUME I
USER'S AND THEORETICAL MANUAL**

**by
R. W. THOMPSON**

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

DATE PUBLISHED: APRIL 1978

GENERAL ATOMIC COMPANY

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ABSTRACT

This report presents documentation of the MCOCO (Multiple COre COlumn) computer program. The program was generated to perform dynamic analysis on a gas-cooled reactor core, which, structurally, is not only nonlinear, but also discontinuous. The report may be used as both a theoretical and user's manual for the MCOCO code. Input for the program consists of geometric and dynamic data (mass, spring constants, etc.). Output includes dowel forces, element collision forces, spring pack forces and core support floor forces. Core and boundary motion are also provided as output and, as an option, may be utilized to generate SC-4020 or CALCOMP plots. The code was originated by Dr. T. H. Lee, and the current version was developed by the author.

The report consists of two volumes. Volume 1 is the theoretical and user's manual, and Volume 2 is the sample problem output.

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1. INTRODUCTION

The core of General Atomic's large high temperature gas-cooled reactor (HTGR) consists of several thousand graphite elements arranged in columns within a prestressed concrete reactor vessel (PCRV). Each column is composed of stacked elements constrained in the horizontal direction by flexible dowels which allow unconstrained rotation and vertical translation. Gaps also may exist between columns. Analysis of this type structure during a seismic disturbance by standard structural dynamics techniques is not possible, since both nonlinearities and discontinuities exist. Consequently, impacts frequently occur. Methods were developed which obtain solutions to the problem by representing the system with the rigid body motion of each element (Refs. 1 and 2). Element and boundary motion completely define the coordinate variables of the rigid bodies. The total number of degrees of freedom are therefore significantly reduced relative to a finite element representation. Treating the elements as rigid bodies required that surface flexibility be defined by some means. This was accomplished by incorporating so called "impact mechanisms" (spring and parallel viscous damper) at pertinent locations on element surfaces (see Fig. 1). Dowels are also modeled as impact mechanisms. All forces, in fact, except spring pack loads when core barrel plates are present, may be modeled in this fashion. MCOCO utilizes this approach to analyze the HTGR core during a seismic disturbance. The program was developed to compute force and motion characteristics of a series of planar columns constrained within a rigid boundary. This represents the reactor core and PCRV (see Fig. 2). Vertical and horizontal sinusoidal or seismic excitations may be provided as input. Output consists of dowel and friction forces, horizontal and vertical impact loads, and core support post and spring pack loads.

NOTE: DOWELS AND SOCKETS ARE SHOWN OFFSET TO LEFT FOR CLARITY. IF DISPLAYED IN CENTER (WHERE THEY ARE LOCATED FOR COMPUTATIONAL PURPOSES) INTERFERENCE WITH CENTER VERTICAL IMPACT MECHANISM WOULD RESULT.

Figure 1. MCOCO Impact Mechanism Model

Figure 2. MCOCO Model of HTGR Core

All types of elements, excluding core barrel plates, are allowed three degrees of freedom (vertical and horizontal translation and rotation). Core barrel plates are allowed only horizontal translation and rotation.

The program has an optional restart capability which, if selected, prints and punches a restart deck. A summary of maximum and minimum output values is automatically printed at run termination.

An option also exists in the code which allows the user to plot core and boundary displacement. Amplification factors, for purposes of clarity, may be applied to element motion.

MCOCO was written in FORTRAN V for the UNIVAC 1110. Two versions of the program currently exist due to computer memory limitations. The first version will analyze, at most, nine fuel columns and two reflector columns and requires less than 70K storage on the 1110. Version two was developed to simulate the full array HTGR core and may contain twenty-four fuel columns, two reflector columns and two columns of core barrel plates. It requires 114K words of memory.

2. THEORETICAL MODEL

The MCOCO code models each element as a rigid mass. Springs and dampers at selected surface locations simulate flexibility and energy dissipation. Dowels are also represented in this fashion. Friction forces are calculated at the horizontal interface between the elements.

The HTGR core and the corresponding MCOCO model are comprised of the following components:

- 1) Fuel or hexagonal reflector elements
- 2) Permanent reflector blocks
- 3) Core support elements
- 4) Core support posts
- 5) Spring packs
- 6) Core barrel plates (optional)
- 7) Rigid PCRV

All core elements, excepting core barrel plates, are allowed three degrees of freedom (horizontal and vertical translation and rotation). Core barrel plates may only translate horizontally and rotate. The PCRV may translate in the horizontal and vertical directions, but may not rotate.

The sign convention for fuel elements is shown in Figs. 1 and 4. The same convention is applicable to the floor; u is positive to the right, w positive upward and θ positive clockwise. PCRV sign convention is positive up and to the right.

All impact mechanism collision spring forces are positive. Friction and dowel forces are positive to the left on the lower face of an element and positive right on the upper face.

Element and spring packs are numbered from the bottom up. Columns, gaps and floor elements are numbered from right to left. (See Fig. 2.)

The following sections discuss in detail the various aspects of the MCOCO theoretical model. A list of symbols is contained in Section 6.

2.1 SURFACE DISPLACEMENTS

The primary advantage of modeling the HTGR core as a series of rigid bodies with local flexibilities at selected locations is the management of a potentially intractable situation. No additional degrees of freedom are required to define the displacement of a point on an element other than those for the center of gravity. This is made possible by the following transformations, from Ref. 2, for any point p on an element surface (see Fig. 3):

$$u_{ik}^p = u_{ik} + \bar{z}_{ik} \sin \theta_{ik} - \bar{x}_{ik} (1 - \cos \theta_{ik}) \quad (1)$$

$$w_{ik}^p = w_{ik} - \bar{x}_{ik} \sin \theta_{ik} - \bar{z}_{ik} (1 - \cos \theta_{ik}) \quad (2)$$

The velocity of the point is obtained simply by taking the first derivative of equations (1) and (2) with respect to time. Therefore,

$$\dot{u}_{ik}^p = \dot{u}_{ik} + \dot{\theta}_{ik} (\bar{z}_{ik} \cos \theta_{ik} - \bar{x}_{ik} \sin \theta_{ik}) \quad (3)$$

$$\dot{w}_{ik}^p = \dot{w}_{ik} - \dot{\theta}_{ik} (\bar{x}_{ik} \cos \theta_{ik} + \bar{z}_{ik} \sin \theta_{ik}) \quad (4)$$

Equations (1) through (4), then, define the displacements and velocities of an arbitrary point p (Fig. 3) on a fuel element surface. Other elements in the core, however, (core barrel plates, core support floor, etc.) can utilize the same expressions if geometric values corresponding to the elements of interest are employed. Figure 4 presents fuel element rotational geometry and dimensions. This figure depicts the effect of rotation on horizontal and vertical translation. It also gives certain definitions (fuel element half-width, half height) utilized in MCOCO. Again, Figure 4 may be used to define parameters for components other than fuel elements.

As shown in Fig. 1, MCOCO employs impact mechanisms on fuel elements, PRBs and core barrel plates at the following locations:

- 1) Horizontally at corners
- 2) Vertically at corners and centers
- 3) Left and right hand sides of dowels (shear springs)

Figure 3. Coordinate System and Rigid Body Displacement of Fuel Elements

Figure 4. Fuel Element Rotational Geometry and Dimensions

The $\bar{x}_{ik}$ and $\bar{z}_{ik}$ terms in equations (1) through (4) define coordinates relative to the element cg. For the surface impact forces shown on Fig. 5 for element ik, therefore, Table 1 can be generated. This table presents the values employed in the MCOCO code to define $\bar{x}_{ik}$ and $\bar{z}_{ik}$ in nonstaggered adjacent columns. It should be noted that in staggered adjacent columns (Fig. 6), there is one additional force defined ($FF_{i+1,j+1}$). This load is located on the model by defining impact locations in terms of normalized element half height, and provided as code input.

Once solutions have been obtained for equations (1) through (4), horizontal impact mechanism spring deflections can be computed as follows:

$$x = u_{ik}^p - a_{ij} - u_o \quad (i = 1) \quad (5)$$

and

$$x = u_{ik}^p - a_{ij} - u_{i-1,k}^p \quad (i = 2, 3, \dots, \text{NCOL}) \quad (6)$$

or

$$x = u_o - u_{ik}^p - a_{ij} \quad (i = \text{NCOL}+1) \quad (7)$$

In the vertical direction, at the lower face of element number one,

$$z = w_{FL_m}^p - w_{i1}^p \quad \begin{array}{l} (i = 1 \text{ and } \text{NCOL}, \text{ no core barrel} \\ \text{plates} \\ = 2 \text{ and } \text{NCOL}-1, \text{ core barrel} \\ \text{plates,} \\ m = 1 \text{ and } \text{NFL}) \end{array} \quad (8)$$

The indices for Eq. (8) indicate that z will be solved for the first element in a reflector column. For fuel columns, the same equation is utilized, but indices are as follows:

$$\begin{array}{l} i = 2, 3, \dots, \text{NCOL}-1, \text{ no core barrel plates} \\ = 3, 4, \dots, \text{NCOL}-2, \text{ core barrel plates} \\ m = 2, 3, \dots, \text{NFL}-1) \end{array}$$

i = INTERFACE OR COLUMN NUMBER
 j = IMPACT FORCE NUMBER AT AN INTERFACE
 k = ELEMENT NUMBER

$$FCH_{i,k} = FDS_{i,k} + FRI_{i,k}$$

Figure 5. Forces Acting on Fuel Elements in Non-staggered Adjacent Columns

Table 1

IMPACT FORCE COORDINATES FOR ELEMENT IK
IN NON-STAGGERED ADJACENT COLUMNS

Force	$\bar{x}_{ik}$	$\bar{z}_{ik}$
$FF_{i+1,j+1}$	$-b_{ik}$	h_{ik}
$FF_{i+1,j}$	$-b_{ik}$	$-h_{ik}$
$FF_{i,j+1}$	b_{ik}	h_{ik}
$FF_{i,j}$	b_{ik}	$-h_{ik}$
$FVL_{i,k}$	$-b_{ik}$	$-h_{ik}$
$FVC_{i,k}$	0	$-h_{ik}$
$FVR_{i,k}$	b_{ik}	$-h_{ik}$

Note: Above coordinates are applicable for elements in non-staggered adjacent columns only (Fig. 5). For staggered adjacent columns, additional coordinates are defined by program input.

Figure 6. Forces Acting on Fuel Elements in Staggered Adjacent Columns

Note in Fig. 7 that there are possibly nine vertical forces on top of each fuel column support floor element. Therefore, $w_{FL_m}^p$, in Eq. (8) must be computed for a point at each of the nine forces on the support element. For vertical spring compression at the lower faces of elements 2, 3...NE, the following expression is used:

$$z = w_{i,k-1}^p - w_{ik}^p \quad (i = 1, 2, \dots, \text{NCOL}, k = 2, 3, \dots, \text{NE}) \quad (9)$$

Velocities are also needed at the points for which displacements are calculated. These can be computed by taking the time derivative of Eqs. (5) through (9). Hence,

$$\dot{x} = \dot{u}_{ik} - \dot{u}_0 \quad (i = 1) \quad (10)$$

$$\dot{x} = \dot{u}_{ik}^p - \dot{u}_{i-1,k}^p \quad (i = 2, 3, \dots, \text{NCOL}) \quad (11)$$

$$\dot{x} = \dot{u}_0 - \dot{u}_{ik}^p \quad (i = \text{NCOL}+1) \quad (12)$$

$$\dot{z} = \dot{w}_{FL_m}^p - \dot{w}_{i1}^p \quad \begin{aligned} &(i = 1 \text{ and } \text{NCOL}, \text{ no core barrel} \\ &\quad \text{plates} \\ &\quad = 2 \text{ and } \text{NCOL}-1, \text{ core barrel plates} \\ &\quad m = 1 \text{ and } \text{NFL}) \end{aligned} \quad (13)$$

Also, as before, for Eq. (13)

$$\begin{aligned} &(i = 2, 3, \dots, \text{NCOL}-1, \text{ no core barrel plates} \\ &\quad = 3, 4, \dots, \text{NCOL}-2, \text{ core barrel plates} \\ &\quad = 2, 3, \dots, \text{NFL}-1) \end{aligned}$$

The same discussion of indices for Eq. (8) is applicable for $\dot{w}_{FL_m}^p$ in Eq. (13). Finally,

$$\dot{z} = \dot{w}_{i,k-1} - \dot{w}_{ik} \quad (i = 1, 2, \dots, \text{NCOL}, k = 2, 3, \dots, \text{NE}_i) \quad (14)$$

In Eqs. (10) through (14), $\dot{u}_{ik}$ and $\dot{w}_{ik}^p$ are values obtained from solutions of Eqs. (3) and (4). Equations (5) through (14) define surface deformations and relative velocities for all impact mechanisms above floor level. However, inspection of Fig. 7 shows that the same type of expressions can easily be generated for core floor elements. Therefore, for the floor:

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$$FCH_{i,k} = FDS_{i,k} + FRI_{i,k}$$

$m = 2, 3, 4, \dots$ NFL (NUMBER OF FLOOR ELEMENTS)

$$n = m+2j$$
$$jj = 0, 1, 2, \dots, NFL$$

UARM_{1,1} = UARM_{m,2} = 0.0 IF REFLECTOR AND FUEL COLUMNS ARE SYMMETRICAL RELATIVE TO FLOOR

(2) NORMALIZED TO BFL WITH SIGN TO PRODUCE PROPER MOMENT (LEFT OF CG NEGATIVE, RIGHT POSITIVE).

Figure 7. Forces and Moment Arms for the Two Types of Core Support Floor Elements

$$u_{FL_m}^p = u_{FL_m} + \bar{z}_{FL_m} \sin \theta_{FL_m} - \bar{x}_{FL_m} (1 - \cos \theta_{FL_m}) \quad (15)$$

$$w_{FL_m}^p = w_{FL_m} - \bar{x}_{FL_m} \sin \theta_{FL_m} - \bar{z}_{FL_m} (1 - \cos \theta_{FL_m}) \quad (16)$$

$$\dot{u}_{FL_m}^p = \dot{u}_{FL_m} + \dot{\theta}_{FL_m} (\bar{z}_{FL_m} \cos \theta_{FL_m} - \bar{x}_{FL_m} \sin \theta_{FL_m}) \quad (17)$$

$$\dot{w}_{FL_m}^p = \dot{w}_{FL_m} - \dot{\theta}_{FL_m} (\bar{x}_{FL_m} \cos \theta_{FL_m} + \bar{z}_{FL_m} \sin \theta_{FL_m}) \quad (18)$$

$$x_{FL} = u_{FL_m} - a_{FL_m} - u_{FL_{m-1}} \quad (m = 1, 2, \dots, NFL) \quad (19)$$

$$x_{FL} = u_0 - a_{FL_m} - u_{FL_m}^p \quad (m = NFL+1) \quad (20)$$

$$z_{FL} = w_{FL_m}^p \quad (21)$$

$$\dot{x}_{FL} = \dot{u}_{FL_m}^p - \dot{u}_{FL_{m-1}}^p \quad (m = 1, 2, \dots, NFL) \quad (22)$$

$$\dot{x}_{FL} = \dot{u}_0 - \dot{u}_{FL_m}^p \quad (m = NFL+1) \quad (23)$$

$$\dot{z}_{FL} = \dot{w}_{FL_m}^p \quad (24)$$

In Eqs. (19) and (23), for $m = 1$, $u_{FL_0}^p \equiv u_0$ and $\dot{u}_{FL_0}^p \equiv \dot{u}$. Also, in (19) and (20), a_{FL_m} is either upper or lower gap, whichever is appropriate. Equations (5) through (24) define surface deformations and relative velocities for all impact mechanisms in the MCOCO HTGR core model.

2.2 DOWEL DEFORMATIONS

The dowels in MCOCO and the HTGR core are tapered. In the code, they are represented by tangent ogives. This compares with straight tapered dowels that were utilized in scale models and exist in the actual core.

Figure 8 presents the arrangement for dowels and sockets in the program. Dowel deformations are computed for either of two cases. For deflections which close the left dowel gap (relative displacement to right--see Fig. 9):

$$x_D = u_{ik}^p - u_{i,k-1}^p - a_{D_L} + b_{ik} (\cos \theta_{ik} - \cos \theta_{i,k-1}) \quad (25)$$

In Eq. (25), if $x < 0$, it is set to zero. For displacements which close the right dowel gap (relative displacement to left--again, see Fig. 9):

$$x_D = u_{ik}^p - u_{i,k-1}^p + a_{D_R} - b_{ik} (\cos \theta_{ik} - \cos \theta_{i,k-1}) \quad (26)$$

In (26), if $x > 0$, it is set to zero.

There is a dowel damper and, in order to utilize dowel damping forces, first derivatives of (25) and (26) with respect to time must be computed. Therefore,

$$\dot{x}_D = \dot{u}_{ik}^p - \dot{u}_{i,k-1}^p - b_{ik} \dot{\theta}_{ik} \sin \theta_{ik} + b_{ik} \dot{\theta}_{i,k-1} \sin \theta_{i,k-1} \quad (\text{left gap}) \quad (27)$$

$$\dot{x}_D = \dot{u}_{ik}^p - \dot{u}_{i,k-1}^p + b_{ik} \dot{\theta}_{ik} \sin \theta_{ik} - b_{ik} \dot{\theta}_{i,k-1} \sin \theta_{i,k-1} \quad (\text{right gap}) \quad (28)$$

An assumption was made to set all terms containing $\dot{\theta} \sin \theta$ in Eqs. (27) and (28) to zero. There is very little information available on dowel damping and it is believed that the rotational velocity contribution (when multiplied by the sine of a small angle) will be negligible. Hence, Eqs. (27) and (28) were reduced to the following single expression:

$$\dot{x}_D = \dot{u}_{ik}^p - \dot{u}_{i,k-1}^p \quad (\text{right or left gap}) \quad (29)$$

Figure 8. Tapered Dowel Geometry in MCOCO

a_{D_L} = LEFT DOWEL GAP
 a_{D_R} = RIGHT DOWEL GAP

Figure 9. Dowel Gap Definition

Equation (3) is again utilized to calculate the values of $\dot{u}_{ik}^p$ and $\dot{u}_{i,k-1}^p$. The following coordinates are used in (3) for the computations:

$$\bar{z}_{ik} = -h_{ik}$$

$$\bar{z}_{i,k-1} = h_{i,k-1}$$

$$\bar{x}_{i,k} = x_{i,k-1} = 0$$

Substitution of these three values into (3) and the results into (29) produces

$$\dot{x}_D = \dot{u}_{ik} - \dot{\theta}_{ik} h_{ik} \cos \theta_{ik} - \dot{u}_{i,k-1} - \dot{\theta}_{i,k-1} h_{i,k-1} \cos \theta_{i,k-1} \quad (30)$$

2.3 COLLISION FORCES

Core collision forces are computed for impact mechanisms at the following locations:

- 1) Horizontally at upper and lower corners of each fuel, hex reflector, permanent reflector and core support floor element. Also, horizontally at upper and lower corner of interior faces of core barrel plates (see Figs. 5, 6, 7, 10 and 11).
- 2) Vertically at center and corners of horizontal interface between fuel, hex reflector, permanent reflector and core barrel plate elements. Also, vertically at center and corners of upper surface of reflector column support floor elements (see Figs. 5, 6, 7, 10 and 11).
- 3) Vertically and horizontally at support post locations on lower face of floor elements (see Fig. 7).
- 4) Vertically at horizontal interface between lower surface of three fuel elements (at center and both corners) and upper surface of fuel column support floor element (see Fig. 7).
- 5) Horizontally at the dowels and sockets. A dowel is located on the upper surface of each fuel, hex reflector, permanent reflector, reflector column support floor and core barrel plate element. Three dowels are located on the upper surface of each fuel column support floor element.

SYSTEM OF FORCES IS FOR RIGHT HAND PERMANENT REFLECTOR BLOCK (PRB).
 FOR LEFT HAND PRB, FF's AND FSP WILL BE MIRROR IMAGES OF THOSE SHOWN.
 FF_{i+1,j+1}, FF_{i+1,j+2}, ETC, ARE AT SAME VERTICAL LOCATIONS.

* FF_{i,j} WHEN CORE BARREL PLATES ARE PRESENT, FSP_k WHEN PLATES ARE ABSENT

i = 1 OR NCOL (NUMBER OF COLUMNS), WITHOUT CORE BARREL PLATES

= 2 OR NCOL - 1, WITH CORE BARREL PLATES

j = IMPACT FORCE NUMBER AT AN INTERFACE

k = ELEMENT NUMBER

$$FCH_{i,k} = FDS_{i,k} + FRI_{i,k}$$

Figure 10. Forces Acting on Permanent Reflector Blocks

SYSTEM OF FORCES IS FOR RIGHT HAND CORE BARREL PLATE. FOR LEFT HAND PLATE, FF's AND FSP's WILL BE MIRROR IMAGES OF THOSE SHOWN.

$i = 1 \text{ OR } \text{NCOL (NUMBER OF COLUMNS)}$

$j = \text{IMPACT FORCE NUMBER AT AN INTERFACE}$

$k = \text{ELEMENT NUMBER}$

DOUBLE HEADED ARROWS INDICATE SPRING PACKS WILL REACT TO TENSILE OR COMPRESSIVE LOADS.

$$FCH_{i,k} = FDS_{i,k} + FRI_{i,k}$$

Figure 11. Forces Acting on Core Barrel Plates

- 6) Horizontally at intermediate locations on the interior surface of permanent reflector blocks. These forces result from corner impacts with hex reflector elements (see left side of PRB in Fig.10) and are defined for hex reflectors in 1), above.

The collision forces described above and loads in the spring packs (Figs. 2, 10 and 11) completely define the loading system in the MCOCO computer program.

Collision forces are calculated from the expression

$$F_c = F_s + F_D \quad (31)$$

where index subscripts are omitted for clarity. In Eq. (31), for horizontal surface impacts of fuel elements,

$$F_s = kx \quad (32)$$

and

$$F_D = c\dot{x} \quad (33)$$

where x and $\dot{x}$ are defined by Eqs. (5), (6), or (7) and (10), (11), or (12), respectively. For vertical surface, core floor, and dowel impacts, x and $\dot{x}$ are replaced by appropriate displacements and velocities (e.g., z and $\dot{z}$, x_{FS} and $\dot{x}_{FS}$, etc.)

If values less than zero are computed for deflections of collision springs, there is no contact and collision forces are set to zero.

2.4 FRICTION FORCES

Coulomb friction forces are computed at horizontal interfaces between these elements above the support posts (i.e., fuel, floor, reflectors, etc.). Friction is the minimum value obtained from either of the following two expressions:

$$FRI = S\dot{x}_D \quad (34a)$$

or

$$FRI = \mu F_N \frac{\dot{x}_D}{|\dot{x}_D|} \quad (34b)$$

Again, index subscripts were omitted for clarity. In Eqs. (34) and (35), $\dot{x}_D$ is defined by Eq. (3) and is the relative velocity between element interfaces. F_N in (34b) is computed from the equation

$$F_{N_{ik}} = F_{VL_{ik}} + F_{VC_{ik}} + F_{VR_{ik}} \quad (35)$$

and is the total vertical force at an interface (Refer to Figs. 5, 6, etc.). The solid lines in Fig. 12 illustrate the manner in which the code computes friction forces.

Equation (34a) is employed in order to prevent computational difficulties when integrating across the step function shown as dashed lines in Fig. 12 at $\dot{x}_D = 0$.

The dowel shear forces and friction forces are summed at each interface by means of the expression

$$F_{CH_{ik}} = F_{RI_{ik}} + F_{DS_{ik}} \quad (36)$$

See Figures 5, 6, 7, 10 and 11.

2.5 FLUID DYNAMIC DAMPING

An option is provided in the code which allows computation of two forces and one moment resulting from fluid dynamic drag. The forces and moment resist motion in any or all of the three degrees of freedom for each element above floor level. It is assumed that floor elements have no fluid dynamic damping forces associated with them.

The equations utilized to compute the damping consist of user provided coefficients multiplied by the square of the velocity, with proper signs.

Therefore,

$$D_u = -C_u \dot{u}|\dot{u}| \quad (37)$$

$$D_w = -C_w \dot{w}|\dot{w}| \quad (38)$$

$$D_\theta = -C_T \dot{\theta}|\dot{\theta}| \quad (39)$$

D_u , D_w , and D_θ react through and about each element center of gravity so as not to produce an unbalanced moment.

Figure 12. Friction Force versus Relative Velocity Between Element Interfaces

Prior to the start of a simulation, initial conditions are automatically computed which place each element in the core in static equilibrium. An optional preload may be placed on the upper center of each element in the plenum row. Deflections of the impact springs are calculated for a static load consisting of weights of elements above the springs, plus the preload. The computations assume that there is no initial element rotation.

$$w_{FL\ m} = - \frac{(FC_m + w_{FL\ m})}{(2\ SPOSTZ)} \quad (40)$$
$$TOWT_i = \sum_{k=1}^{NE_i} W_{ik} \quad (i=1,2,3,\dots,NCOL, \text{ no core barrel plates, (41)})$$

= 2,3,4...NCOL-1, core barrel plates)

$$FC_m = TOWT_i + PL \quad \begin{array}{l} (i=1 \text{ and } NCOL, \text{ no core barrel plates,} \\ =2 \text{ and } NCOL-1, \text{ core barrel plates,} \\ m=1 \text{ and } NFL) \end{array} \quad (42a)$$
$$FC_m = 3PL + \sum TOW_i \quad \begin{array}{l} (i=2,3,4 \text{ or } 5,6,7 \text{ or } \dots NCOL-1, \\ \text{no core barrel plates} \\ =3,4,5 \text{ or } 6,7,8 \text{ or } \dots NCOL-2, \\ \text{core barrel plates} \\ m=2,3,\dots NFL-1) \end{array} \quad (42b)$$
$$FPOSTZ_{m,1} = FPOSTZ_{m,2} = SPOSTZ \left(\frac{w_{FSm}}{2} \right) \quad (m=1,2,3,\dots,NFL) \quad (43)$$

Here, the second subscripts 1 and 2 indicate right and left support post, respectively.

For elements above the floor level, preload and column weight above and including element k in column i is calculated from the equation :

$$RW_{ik} = PL + \sum_{k=i}^{NE_i} W_{ik} \quad \begin{array}{l} (i=1,2,3,\dots,NCOL, \text{ no core barrel plates} \\ =2,3,4,\dots,NCOL-1, \text{ core barrel plates}) \end{array} \quad (44)$$

Static spring compression due to preload and dead weight is, therefore,

$$D_{ik} = \frac{RW_{ik}}{(2VSF_{ik} + VSFC_{ik})} \quad (45)$$

The absolute vertical displacement is then computed from either of the following expressions:

$$w_{i1} = W_{FS_m} - D_{i1} \quad \begin{array}{l} (i=1 \text{ or } NCOL, \text{ no core barrel plates} \\ =2 \text{ or } NCOL-1, \text{ core barrel plates,} \\ m=1 \text{ or } NFL) \end{array} \quad (46a)$$

$$\begin{array}{l} (i=2,3,4 \text{ or } 5,6,7 \text{ or } \dots,NCOL-1, \text{ no core barrel plates,} \\ =3,4,5 \text{ or } 6,7,8 \text{ or } \dots,NCOL-2, \text{ core barrel plates,} \\ m=2,3,4,\dots,NFL-1) \end{array}$$

or

$$w_{ik} = w_{i,k-1} - D_{ik} \quad (k > 1) \quad (46b)$$

Equations (46a) and (46b) calculate displacements for elements resting on the floor and above it, respectively. The two sets of indices are applicable for reflector or fuel elements, respectively.

There is no initial element rotation or horizontal displacement. Hence, all values of u_{ik} and θ_{ik} are set to zero.

2.7 PLENUM AND BOUNDARY CONSTRAINTS

Three types of constraints may be applied individually or collectively to elements in the upper plenum row and those adjacent to the boundary. The constraints consist of springs (two linear, one rotational) which link certain elements and restrain others in the top row and next to the PCR. See Fig. 13, which depicts the constraints that may be applied to a typical ten column core model. No damping constant is associated with these springs.

The two forces and one moment which restrict element motion are:

$$F_K = k_K x_K \quad (47)$$

$$F_R = k_R x_R \quad (48)$$

$$M_\theta = k_\theta \theta \quad (49)$$

Once again, index subscripts were omitted for clarity. In Eqs. (47) and (48), x_K and x_R are relative displacements between designated plenum elements in Fig. 13 or core barrel plates and boundary, respectively. Expressions for x_K and x_R are generated by means of eqs. (1) and (2) and are similar to the expressions for x in (5) through (7). θ in Eq. (49) is simply the element rotation.

2.8 EQUATIONS OF MOTION

Derivation of the equations of motion is made tractable by assigning the locations of horizontal impact forces as program input. Vertical forces are automatically placed at the center and corners of an element. Vertical corner forces may be moved inboard, if necessary, by modifying CP (a constant) in the code. This should only be accomplished with the concurrence of the author, however.

As previously stated, the HTGR core has several types of elements. Each type has a different force system (see Figs. 5, 6, 7, 9 and 10). On the other hand, all elements behave according to the following three generalized equations of motion:

Figure 13. Plenum and Boundary Constraints

$$m\ddot{u} = \Sigma F_x \quad (\text{horizontal equilibrium}) \quad (50)$$

$$m\ddot{w} = \Sigma F_z \quad (\text{vertical equilibrium}) \quad (51)$$

$$I\ddot{\theta} = \Sigma M_{cg} \quad (\text{rotational equilibrium}) \quad (52)$$

Accelerations may be computed for an element of interest if corresponding values of m , I , ΣF_x , ΣF_z and ΣM_{cg} are utilized.

The variety of force systems within the core results in the right hand sides of Eqs. (50) through (52) being functions of the element for which the equations of motion are to be derived. Only equations for the following two systems will be developed in this report, however:

- 1) Fuel element surrounded by non-staggered elements
(Element ik in Fig. 5).
- 2) Fuel column support floor element
(Element m in Fig. 7).

Mathematical descriptions of systems other than the two above may easily be developed with the aid of Figs. 4, 6, 7, 9 and 10 and the generalized equations of motion.

First, for the fuel element, Eqs. (50) through (52) are expanded as follows:

$$m_{ik} \ddot{u}_{ik} = FF_{i+1,j} + FF_{i+1,j+1} + FCH_{i,k+1} - FF_{ij} - FF_{i,j+1} - FCH_{ik} + D_u \quad (53)$$

$$m_{ik} \ddot{w}_{ik} = FVL_{ik} + FVC_{ik} + FVR_{ik} - FVL_{i,k+1} - FVC_{i,k+1} - FVR_{i,k+1} - W_{ik} + D_w \quad (54)$$

$$\begin{aligned}
I_{ik} \ddot{\theta}_{ik} = & FVR_{i,k+1} (b_{i,k+1} \cos \theta_{ik} + h_{ik} \sin \theta_{ik}) \\
& + FVC_{i,k+1} (h_{ik} \sin \theta_{ik}) \\
& - FVL_{i,k+1} (b_{i,k+1} \cos \theta_{ik} - h_{ik} \sin \theta_{ik}) \\
& + FF_{i+1,j+1} (b_{i,k+1} \sin \theta_{ik} + h_{ik} \cos \theta_{ik}) \\
& - FF_{i+1,j} (h_{ik} \cos \theta_{ik} - b_{ik} \sin \theta_{ik}) \\
& + FVL_{ik} (b_{ik} \cos \theta_{ik} + h_{ik} \sin \theta_{ik}) \\
& + FVC_{ik} (h_{ik} \sin \theta_{ik}) \\
& - FVR_{ik} (b_{ik} \cos \theta_{ik} - h_{ik} \sin \theta_{ik}) \\
& + FF_{ij} (b_{ik} \sin \theta_{ik} + h_{ik} \cos \theta_{ik}) \\
& - FF_{i,j+1} (h_{ik} \cos \theta_{ik} - b_{i,k+1} \sin \theta_{ik}) \\
& + FCH_{ik} (h_{ik} \cos \theta_{ik}) \\
& - FCH_{i,k+1} (h_{ik} \cos \theta_{ik}) + D_{\theta}
\end{aligned} \tag{55}$$

Plenum elements represented by Fig. 5 have $FVL_{i,k+1}$, $FCH_{i,k+1}$ and $FVR_{i,k+1}$ set to zero. $FVC_{i,k+1}$ in the plenum row is equated to the preload. F_k , F_R and M_{θ} from Section 2.7) are applied to certain plenum elements (see Fig. 13), and are, therefore, added to the right hand side of Eqs. (53) through (55), where appropriate.

Next, for the fuel column support floor element, Eqs. (50) through (52) are rewritten, with the aid of Fig. 7, as follows:

$$m_{FL_m} \ddot{u}_{FL_m} = FIMPX_{m+1,1} + FIMPX_{m+1,2} - FPOSTX_{m,2} - FPOSTX_{m,1} \\ - FIMPX_{m,2} - FIMPX_{m,1} + FCH_{n+2,1} + FCH_{n+1,1} + FCH_{n,1} \quad (56)$$

$$m_{FL_m} \ddot{w}_{FL_m} = FPOSTZ_{m,2} + FPOSTZ_{m,1} - FVL_{n+2,1} - FVC_{n+2,1} - FVR_{n+2,1} \\ - FVL_{n+1,1} - FVC_{n+1,1} - FVR_{n+1,1} - FVL_{n,1} - FVC_{n,1} \\ - FVR_{n,1} - W_{FL_m} \quad (57)$$

$$I_{FL_m} \ddot{\theta}_{FL_m} = FCH_{n,1} (HFL_m \cos \theta_{FL_m} - UARM_{m,1} BFL_m \sin \theta_{FL_m}) \\ + FCH_{n+1,1} (HFL_m \cos \theta_{FL_m} - UARM_{m,2} BFL_m \sin \theta_{FL_m}) \\ + FCH_{n+2,1} (HFL_m \cos \theta_{FL_m} - UARM_{m,3} BFL_m \sin \theta_{FL_m}) \\ + FPOSTX_{m,1} (HFL_m \cos \theta_{FL_m} + BPOST_m BFL_m \sin \theta_{FL_m}) \\ + FPOSTX_{m,2} (HFL_m \cos \theta_{FL_m} - BPOST_m BFL_m \sin \theta_{FL_m}) \\ - FVR_{n,1} (- WARM_{m,1} BFL_m \cos \theta_{FL_m} - HFL_m \sin \theta_{FL_m}) \\ - FVC_{n,1} \left[\frac{ - (WARM_{m,1} + WARM_{m,2}) }{2} BFL_m \cos \theta_{FL_m} \right. \\ \left. - HFL_m \sin \theta_{FL_m} \right] \\ - FVL_{n,1} (- WARM_{m,2} BFL_m \cos \theta_{FL_m} - HFL_m \sin \theta_{FL_m}) \\ - FVR_{n+1,1} (- WARM_{m,3} BFL_m \cos \theta_{FL_m} - HFL_m \sin \theta_{FL_m}) \\ \text{(continued)}$$

$$\begin{aligned}
& - FVC_{n+1,1} \left[\frac{-(WARM_{m,3} + WARM_{m,4})}{2} BFL_m \cos \theta_{FL_m} \right. \\
& \quad \left. - HFL_m \sin \theta_{FL_m} \right] \\
& - FVL_{n+1,1} (-WARM_{m,4} BFL_m \cos \theta_{FL_m} - HFL_m \sin \theta_{FL_m}) \\
& - FVR_{n+2,1} (-WARM_{m,5} BFL_m \cos \theta_{FL_m} - HFL_m \sin \theta_{FL_m}) \\
& - FVC_{n+2,1} \left[\frac{-(WARM_{m,5} + WARM_{m,6})}{2} BFL_m \cos \theta_{FL_m} \right. \\
& \quad \left. - HFL_m \sin \theta_{FL_m} \right] \\
& - FVL_{n+2,1} (-WARM_{m,6} BFL_m \cos \theta_{FL_m} - HFL_m \sin \theta_{FL_m}) \\
& - FPOSTZ_{m,1} (BFL_m BPOST_m \cos \theta_{FL_m} - HFL_m \sin \theta_{FL_m}) \\
& + FPOSTZ_{m,2} (BFL_m BPOST_m \cos \theta_{FL_m} + HFL_m \sin \theta_{FL_m}) \\
& - FIMPX_{m,1} (HFL_m \cos \theta_{FL_m} - BFL_m \sin \theta_{FL_m}) \\
& + FIMPX_{m,2} (HFL_m \cos \theta_{FL_m} + BFL_m \sin \theta_{FL_m}) \\
& + FIMPX_{m+1,1} (HFL_m \cos \theta_{FL_m} + BFL_m \sin \theta_{FL_m}) \\
& - FIMPX_{m+1,2} (HFL_m \cos \theta_{FL_m} - BFL_m \sin \theta_{FL_m}) \tag{58}
\end{aligned}$$

2.9 BOUNDARY MOTION

The PCRV is represented in MCOCO by a rigid boundary which may only translate in the horizontal and vertical directions (no rotation is allowed). Motion of the PCRV may be either sinusoidal dwells or acceleration time histories of seismic disturbances. Single or double axis excitation may be provided for either time histories or dwells. Mixing, however, is not permitted (e.g., vertical dwells may not be simultaneously provided as input with horizontal time histories).

2.9.1 Sinusoidal Dwells

Sinusoidal dwells are input as boundary motion by specifying peak g-level and frequency. At present, initial phase shift between horizontal and vertical motion cannot be provided. However, independent frequencies and g-levels for each degree of freedom is acceptable. Boundary motion for sinusoidal dwells is defined by the following four expressions:

$$u_o = - \frac{g}{(2\pi)^2} \frac{a_x}{\omega_x^2} \sin \omega_x t \quad (59)$$

$$\dot{u}_o = - \frac{g}{2\pi} \frac{a_x}{\omega_x} \cos \omega_x t \quad (60)$$

$$w_o = - \frac{g}{(2\pi)^2} \frac{a_z}{\omega_z^2} \sin \omega_z t \quad (61)$$

$$\dot{w}_o = - \frac{g}{2\pi} \frac{a_z}{\omega_z} \cos \omega_z t \quad (62)$$

In Eqs. (59) through (62), a_x and a_z are maximum boundary g-level along horizontal and vertical axes, respectively.

2.9.2 Acceleration Time Histories

Boundary motion corresponding to time histories of seismic disturbances is provided as excitation by specifying equally spaced acceleration data as a function of time. The code automatically interpolates accelerations between data points for any time t . Boundary velocities and displacements are then computed from input accelerations according to the following second-order Runge-Kutta integration equations:

$$u_o = u_{o,t-h} + h \dot{u}_{o,t-h} + \frac{h^2}{6} (2 \ddot{u}_o + \ddot{u}_{o,t-h}) \quad (63)$$

$$\dot{u}_o = \dot{u}_{o,t-h} + \frac{h}{2} (\ddot{u}_o + \ddot{u}_{o,t-h}) \quad (64)$$

$$w_o = w_{o_{t-h}} + h \dot{w}_{o_{t-h}} + \frac{h^2}{6} (2 \ddot{w}_o + \ddot{w}_{o_{t-h}}) \quad (65)$$

$$\dot{w}_o = \dot{w}_o + \frac{h}{2} (\ddot{w}_o + \ddot{w}_{o_{t-h}}) \quad (66)$$

2.10 Approximations of Angles

In order to reduce computational effort, series approximations of the trigonometric sine and cosine functions, which are updated at each integration, are employed. These approximations are used in lieu of the FORTRAN SIN and COS functions. The first two terms of the series expansions are utilized as approximations. Therefore,

$$\sin \theta_{ik} \approx \theta_{ik} - \frac{\theta_{ik}^3}{6} \quad (67)$$

$$\cos \theta_{ik} \approx 1 - \frac{\theta_{ik}^2}{2} \quad (68)$$

It follows then, that

$$1 - \cos \theta_{ik} \approx \frac{\theta_{ik}^2}{2} \quad (69)$$

and

$$\cos \theta_{ik} - \cos \theta_{i,k-1} \approx \frac{1}{2} (\theta_{i,k-1}^2 - \theta_{ik}^2) \quad (70)$$

Above expressions are used for approximating rotational displacements of all elements in the core, including those in the floor.

3. NUMERICAL INTEGRATION ALGORITHMS

Two types of integration methods are available in MCOCO: second-order Runge-Kutta and central difference. Studies were conducted with the COCO computer program (Ref. 3) to determine the most efficient of the two. Results are reported in Ref. 4 and indicate that the central difference operator is the most economical for COCO. Also, solutions using central difference were essentially the same as those obtained from Runge-Kutta (for the same time step). Similar conclusions were drawn from preliminary studies performed with MCOCO.

The central difference integration procedure in MCOCO is identical with that described in Ref. 3, whereas the Runge-Kutta algorithm differs slightly.

3.1 CENTRAL DIFFERENCE INTEGRATION METHOD

The central difference integration method employed in MCOCO was taken from Ref. 3. This scheme is based on the procedure outlined in Ref. 5. Velocities and displacements are computed from the expressions

$$\dot{x}_{n+1/2} = \dot{x}_{n-1/2} + h \ddot{x}_n \quad (71)$$

$$x_{n+1} = x_n + h \dot{x}_{n+1/2} \quad (72)$$

In Eq. (71),

$$\ddot{x}_n = f(x_n, \dot{x}_{n-1/2}, t_n) \quad (73)$$

Since $\dot{x}_{n-1/2}$ is not available for initial computations, the algorithm is not self-starting. Therefore, the following equation, based on Euler's method (Ref. 3), is utilized in lieu of (71) at integration start:

$$\dot{x}_{n+1/2} = \dot{x}_n + \frac{h}{2} \ddot{x}_n \quad (74)$$

3.2 SECOND ORDER RUNGE-KUTTA INTEGRATION ALGORITHM

The Runge-Kutta method used in the code was taken from Eq. (3.12) of Ref. 6. Constants taken from the reference are

$$\gamma_1 = \gamma_2 = 1/2$$

$$\alpha_1 = \alpha_2 = 2/3$$

$$\alpha_3 = 4/3$$

$$\sigma_1 = 1/2$$

$$\sigma_2 = 1/2$$

Velocities and displacements are computed at $t = t_0$ and $t = t_0 + h$. This differs slightly from the Runge-Kutta method employed in Ref. 3. In the reference, accelerations at $t = t_0$ and $t_0 + 2/3 h$ are used to evaluate velocities and displacements at $t = t_0 + h$. The above constants are substituted into Eq. (3.12) (Ref. 6) to produce

$$\ddot{x}_n = f(t_n, x_n, \dot{x}_n) \quad (75)$$

$$x_{n+2/3} = x_n + 2/3 h \dot{x}_n + 1/3 h^2 \ddot{x}_n \quad (76)$$

$$\dot{x}_{n+2/3} = \dot{x}_n + 2/3 h \ddot{x}_n \quad (77)$$

$$t_n = t_0 \quad (78)$$

$$\ddot{x}_{n+2/3} = f(t_n, x_{n+2/3}, \dot{x}_{n+2/3}) \quad (79)$$

$$t_{n+1} = t_n + h \quad (80)$$

$$x_{n+1} = \dot{x}_n + h \dot{x}_n + \frac{h^2}{4} (\ddot{x}_n + \ddot{x}_{n+2/3}) \quad (81)$$

$$\ddot{x}_{n+1} = \dot{x}_n + \frac{h}{4} (\ddot{x}_n + 3 \ddot{x}_{n+2/3}) \quad (82)$$

The Runge-Kutta algorithm is self-starting. It should be noted that this method requires two function evaluations per time step whereas central difference requires only one. This is primarily the reason for the economy of the central difference procedure.

The Runge-Kutta method in MCOCO consists of Eqs. (75) through (82). Equations (78) and (79) differ slightly from those employed in Ref. 3 which uses $t_{n+2/3} = t_n + 2/3h$ for (78) and $\ddot{x}_{n+2/3} = f(t_{n+2/3}, x_{n+2/3}, \dot{x}_{n+2/3})$ for (79).

4. INPUT DESCRIPTION

Forms and abbreviated descriptions of data required to provide input to the code are contained in Appendix 1. This section contains a detailed definition, by individual card, of input requirements to operate the program. FORTRAN A, E, F and I formats are utilized. As is standard practice, data requiring an I format must be right justified, E formats must have exponents right justified, and F (numeric) and A (alphanumeric) formats may have data entered anywhere in the field. Also, data cards requiring E formats may use F and vice-versa. Formats on the data cards override those in the program.

Card 1

TITLE - Any alphanumeric data for a run title.

Card 2

- NCOL - Number of vertical columns (including core barrel plates, if applicable) in the core to be simulated ($5 \leq \text{NCOL} \leq 29$).
For core barrel plates NCOL = 7, 10, 13, 16, 19, 22, 25 or 28.
No core barrel plates NCOL = 5, 8, 11, 14, 17, 20, 23 or 26.
- NPRT - Print interval. The code will print output every NPRT integration steps ($\text{NPRT} \geq 1$).
- NPLOTS - Number of plots desired of boundary and core displacements.
 $\text{NPLOTS} \leq 30$ per run.
- NREPCH - Restart deck punch option.
IF NREPCH = 0, do not punch restart deck.
IF NRGPCCH = 1, punch restart deck.
- NRESTA - Restart deck input option
If NRESTA = 0, do not input restart deck.
If NRESTA = 1, input restart deck.

Card 3

NBL(I) - Number of elements above floor in column I . I = 1,2,3,...NCOL

Card 4

- TO - Time (sec) at which the core dynamic analysis is to be initiated. This value is not modified for a restart run (e.g., User wishes to simulate 1.0 second of real time by making two 0.5 second runs: the first one punches a restart deck; the second run uses the deck. The simulation starts at $t_0 = 2.0$ seconds. Therefore, $t_0 = 2.0$ for run 1 and run 2).
- TMAX - The time (sec) at which the run is to be terminated. If it is desired to stop a simulation at $t = 2.5$ seconds, say, it is recommended that $TMAX = 2.49999$ be utilized.
- HH - Integration time step (sec).
- METHOD - Integration method to be employed
IF METHOD = 0, central difference integration is used.
IF METHOD = 1, 2nd order Runge-Kutta is used.

Card 5

- SPH - Horizontal corner spring constant for a full height fuel element (lb/in.).
- CH - Horizontal corner impact mechanism damping coefficient for a full height fuel element (lb-sec/in.).
- SPV - Vertical corner spring constant for a full height fuel element (lb/in.).
- CV - Vertical corner impact mechanism damping coefficient for a full height fuel element (lb-sec/in.).

Card 6

- SPB1 - Initial stiffness of spring pack. See Appendix 2 (lb/in.).
- SPB2 - Final stiffness of spring pack (lb/in.).

Card 6 (continued)

- TRAVL - Distance for which SPB1 is effective. After compressing TRAVL inches, SPB2 is spring pack spring rate (in.).
- CSP - Spring pack damping coefficient used with SPB1 (lb-sec/in.).
- ISPGAP - Spring pack gap indicator.
If ISPGAP = 0, gap at interfaces 1 and NCOL+1, Figure 2, are not set to zero and Cards 6A and 6B are omitted.
If ISPGAP = 1, spring pack gaps (at interfaces 1 and 29) are read on Cards 6A and 6B.

Card 6A (Optional Card)

- GAP(1,K) - Gap between spring packs 2 through 7 (Figure 2) and core barrel plates (or reflector blocks) for right hand side of core (in.).

Card 6B (Optional Card)

- GAP(NCOL+1,K) - Gap between spring packs 2 through 7 (Figure 2) and core barrel plates (or reflector blocks) for left hand side of core (in.).

Card 7

- CSPRV - Vertical center spring constant for a full height fuel element (lb/in.).
- CCV - Vertical center impact mechanism damping coefficient for a full height fuel element (lb-sec/in.).

Card 8

- SROT - Plenum element rotational spring constant (lb-in./rad)
- SKEY - Keyway constraint spring constant (lb/in.).
- SREFL - Spring constant between the boundary and either the PRB or core barrel plate (if present) (lb/in.).

Card 9

- NETYPE - Number of element types above floor level (e.g., full height, 3/4 height and 1/2 height fuel elements plus PRBs and core barrel plates would mean NETYPE = 5). Maximum NETYPE = 15.
- NGTYPE - Number of gap types above floor level. If $NGTYPE \cdot GT \cdot NCOL$, it is indicative that user wishes to input independent lateral gaps for each impact point. Also, if $NGTYPE \cdot GT \cdot NCOL$, optional cards 9A and 9B are unnecessary. If $NGTYPE \cdot LE \cdot NCOL$, maximum NGTYPE = 15, If $NGTYPE \cdot GT \cdot NCOL$, maximum NGTYPE = 999.

Card 9A (Optional Card)

VALU1(I) - Numerical value of gap for each ITYPE given on Card 9B. There are NGTYPE total gaps provided as input on Card(s) 9A (in.).

Card 9B (Optional Card - However, if 9A is input, 9B must also)

ITYPE(I) - Gap type between columns 1 and 2, 3 and 4, ..., NCOL-1 and NCOL. ITYPE(I), where $I = 2, 3, 4, \dots, NCOL$, corresponds to VALU1(I), etc.

Card 10

I - Element type identifier. There must be NETYPE I's and data that follows.

VALU1(I) - Total width of element I (in.).

VALU2(I) - Total height of element I (in.).

VALU3(I) - Weight of element I (lb).

There should be one Card 10 for each type of element (i.e., if NETYPE = 5, there must be 5 card 10's). Maximum I = 15.

Card 11

MTYPE(I,K) - Element type for column I, Element K. I here corresponds to I on Card 10. There should be one Card 11 for each column. In MTYPE(I,K), $K = 1, 2, 3, \dots, NBL(I)$, $I = 1, 2, 3, \dots, NCOL$.

Card 12

PRELD - Vertical preload on the top center of each element in the plenum row (lb).

Card 13

SK - Dowel spring constant (lb/in.).
CDW - Dowel damping coefficient (lb-sec/in.).
GAPR - Right hand dowel gap (in.).
GAPL - Left hand dowel gap (in.).
COF - Coefficient of friction between element horizontal interfaces.
SLP - Slope of the friction force versus velocity between element interfaces (Defined as S on Fig. 11) (lb-sec/in.).

Values on Card 13 are applied to every element in the core.

Card 14

IBM - Indicator for type of boundary motion to be provided as input.
If IBM = 1, a sine dwell is required.
If IBM = 2, a horizontal acceleration time history is required.
If IBM = 3, a vertical acceleration time history is required.
If IBM = 4, a combined horizontal and vertical time history is required.

The following four parameters are omitted if IBM = 2, 3, or 4 (Fields are left blank).

AMPLU - Maximum horizontal g-level for a sinusoidal dwell forcing function.
FREQU - Frequency associated with AMPLU (Hz).
AMPLW - Maximum vertical g-level for a sinusoidal dwell forcing function.
FREQW - Frequency associated with AMPLW (Hz).

Card 15

- CSQU - Fluid dynamics damping coefficient in the x-direction. CSQU will be multiplied by $\dot{u}|\dot{u}|$ for each element above floor level (lb-sec²/in.²).
- CSQW - Fluid dynamic damping coefficient in the z-direction. CSQW will be multiplied by $\dot{w}|\dot{w}|$ for each element above floor level (lb-sec²/in.²).
- CSQT - Fluid dynamic rotary damping coefficient about the center of gravity. CSQT will be multiplied by $\dot{\theta}|\dot{\theta}|$ for each element above floor level (in-lb-sec²/rad²).

Card 16

- NUMSL(I) - Number of contact points on left hand side of gap I (or vertical column interface I) where $I = 2, 3, 4, \dots, \text{NCOL}$. Maximum NUMSL(I) = 40. See Fig. 14.
- NUMSR(I) - Number of contact points on right hand side of gap I where $I = 2, 3, 4, \dots, \text{NCOL}$. Maximum NUMSR(I) = 40. See Figure 14.
- The following four cards (17-20) are repeated in sequence for each vertical column interface (gap).

Card 17

- NEL(I,J) - Element number for Jth contact point on left side of gap I where $I=2, 3, 4, \dots, \text{NCOL}$, $J=1, 2, 3, \dots, \text{NUMSL}(I)$. There are NUMSL(I) total values (per gap) to be provided as input.

Card 18

- NER(I,J) - Element number for Jth contact point on right side of gap I where $I=2, 3, 4, \dots, \text{NCOL}$, $J=1, 2, 3, \dots, \text{NUMSR}(I)$. NUMSR(I) total values (per gap) are required for input.

Card 19

- YL(I,J) - Normalized vertical distance from element cg to Jth contact point on left side of gap I. $YL(I,J) = \frac{+Z_{Lij}}{H_{ij}/2}$. NUMSL(I) total values per gap are required (in.).

Figure 14. NUMSL, NUMSR, KSL and KSR Defined

Card 20

YR(I,J) - Normalized vertical distance from element c_g to Jth contact point on right side of gap I. $YR(I,J) = \pm \frac{Z_{Rij}}{H_{ij}/2} \cdot NUMSR(I)$
total values per gap are required (in.).

Card 21

NUMIF(I) - Total number of impact forces (total contact points, left and right) at vertical column interface (gap) I. $I = 2,3,4,\dots,NCOL$.
Maximum NUMIF(I) = 52. See Figure 15.

Card 22

KSL(I,J) - Contact point number for impact force J on the left hand side of gap I. $I = 2,3,4,\dots,NCOL$, $J = 1,2,3,\dots,NUMIF(I)$.
See Figure 15.

KSR(I,J) - Contact point number for impact force J on the right hand side of gap I. $I = 2,3,4,\dots,NCOL$, $J = 1,2,3,\dots,NUMIF(I)$.
See Figure 15.

Card 22A (Optional Card)

This card is omitted if $NGTYPE \cdot LE \cdot NCOL$

GAP(I,J) - Gap (in.) at Jth contact point number at Interface I.
 $I = 2,3,4,\dots,NCOL$, $J = 1,2,3,\dots,NUMIF(I)$. If this method is chosen to read gaps ($NGTYPE \cdot GT \cdot NCOL$), a value must be provided at each impact force location. Input all gaps, using Card(s) 22A prior to going to Card 23.

Cards 23 through 28 are repeated, in sequence, for each column (and interface), except for $I = NCOL$. See instructions for Cards 27 and 28.

Card 23

VSF(I,J) - Ratio of vertical element corner spring constant at Column I, element J to SPV. $I = 1,2,3,\dots,NCOL$, $J = 1,2,3,\dots,NBL(I)$.

Card 24

VDF(I,J) - Ratio of vertical element corner damping coefficient at Column I, element J to CV. $I = 1,2,3,\dots,NCOL$, $J = 1,2,3,\dots,NBL(I)$.

Figure 15. NUMIF Defined

Card 25

VSFC(I,J) - Ratio of vertical element center spring constant at Column I, element J to CSPRV. I = 1,2,3,...NCOL, J = 1,2,3,...NBL(I).

Card 26

VDFC(I,J) - Ratio of vertical element center spring constant at column I, element J to CCV. I = 1,2,3,...NCOL, J = 1,2,3,...NBL(I).

Cards 23 through 28 are provided as input for NCOL-1 cycles. For last cycle (I=NCOL), cards 27 and 28 are omitted (23 through 26 only are input).

Card 27

HSK(I,J) - Ratio of horizontal element spring rate to SPH at interface I, impact force number J. I = 2,3,4,...NCOL, J = 1,2,3,...NUMIF(I).

Card 28

HDF(I,J) - Ratio of horizontal element damping coefficient to CH at interface I, impact force number J. I = 2,3,4,...NCOL, J = 1,2,3,...NUMIF(I).

Card 29

BFL(I) - Width (in.) of core support element I where I = 1,2,3,...NFLLOOR. NFLLOOR is computed in the code as follows:

$$\text{NFLLOOR} = \frac{\text{NCOL}+4}{3} \quad (\text{no core barrel plates})$$

or

$$\text{NFLLOOR} = \frac{\text{NCOL}+2}{3} \quad (\text{core barrel plates})$$

Card 30

HFL(I) - Height of core support element I where I = 1,2,3,...NFLLOOR. See Card 29 for definition of NFLLOOR (in.).

Card 31

BPOST(I) - The horizontal distance from element I centerline to support post location divided by the half width (see Figure 7). I = 1,2,3,...NFLLOOR. See Card 29 for definition of NFLLOOR.

Card 32

AMFLR(I) - Weight of support floor element I. $I = 1, 2, 3, \dots, \text{NFLOOR}$.
See Card 29 for NFLOOR definition (1b).

Card 33

SPOSTZ - Core support post vertical spring constant (lb/in.).
CPOSTZ - Core support post vertical damping coefficient (lb-sec/in.)
SPOSTX - Core support post horizontal spring constant (lb/in.)
CPOSTX - Core support post horizontal damping coefficient (lb-sec/in.)

Card 34

MGAP - Number of gaps between horizontal interfaces of floor elements or elements and spring packs ($\text{MGAP} = \text{NFLOOR} + 1$).
GAPFU(I) - $I = 1, 2, 3, \dots, \text{MGAP}$. If $I = 1$, GAPFU(I) is gap between upper right corner of floor element I and right spring pack.
If $I = 2, 3, 4, \dots, \text{MGAP} - 1$, GAPFU(I) is gap between upper corners of floor elements I and I-1. If $I = \text{MGAP}$, GAPFU(I) is gap between upper left corner of floor element I-1 and left spring pack (in.).

Card 35

GAPFL(I) - $I = 1, 2, 3, \dots, \text{MGAP}$. If $I = 1$, GAPFL(I) is gap between lower right corner of floor element and fictitious right spring pack* at the same horizontal level. If $I = 2, 3, 4, \dots, \text{MGAP} - 1$, GAPFL(I) is gap between lower corners of floor elements I and I-1. If $I = \text{MGAP}$, GAPFL(I) is gap between lower left corner of floor element I-1 and fictitious left spring pack.*

Cards 35A and 35E are required only if plots of core response are desired ($\text{NPLOTS} \neq 0$).

*

Spring packs do not exist at this level. Consequently, no forces are calculated here. However, WARM (Figure 7) and certain plot parameters currently require GAPFL(1) and GAPFL(MGAP). It is therefore recommended that GAPFL(I) be set to GAPFU(I), for input, at $I = 1$ and MGAP.

Card 35A (Optional Card)

- CONTR(1) - XMAX or maximum plotting frame coordinate in the horizontal direction. This value should be slightly larger than maximum core width (width of all elements plus gaps) plus $2 \times \text{GAPLAT}$ (last parameter on this card) plus maximum positive horizontal boundary displacement. XMAX is measured from the lower left corner of the boundary at simulation start (in.).
- CONTR(2) - XMIN or minimum plotting frame coordinate in the horizontal direction. This value should be a slightly more negative than the maximum negative (minimum) horizontal boundary displacement. (e.g., $u_{0\min} = -9.0$ in., let $\text{XMIN} = -10.0$ in., $u_{0\min} = 0.0$ in., let $\text{XMIN} = -1.0$ in.)(in.).
- CONTR(3) - YMAX or maximum plotting frame coordinate in the vertical direction. This value should be slightly larger than maximum core height plus $1.25 \times \text{HFL(I)}$ plus maximum positive vertical boundary displacement. YMAX is measured from the lower left corner of the boundary at simulation start (in.).
- GAPLAT - Distance, which will be scaled in plots, between outer core elements (either reflector blocks or core barrel plates) and the boundary for plotting purposes. This parameter is only used in the plot routines (in.).

Caution should be used in setting XMAX, XMIN, YMAX, YMIN if a time history forcing function is to be utilized and the simulation is to be started at some time other than zero. The code automatically sets all acceleration points prior to t_0 (start time, not time equals zero) to zero. This can result in rather large final displacements which may put part or all of the graph off the plot page. It is suggested that the portion of the acceleration time history of interest be integrated twice (to produce displacements) in order to properly set XMAX, XMIN, YMAX and YMIN.

Card 35B (Optional Card)

- PLTYTL - Plot title. Any alphanumeric data in columns 1-80 of this card.

Card 35C (Optional Card)

ICACOM - CALCOMP plot indicator.

If ICACOM = 0, use SC-4020 plotter.

If ICACOM $\neq$ 0, use CALCOMP plotter.

Card 35D (Optional Card)

SS - Plot size for CALCOMP plotter (omit SS if SC-4020 plotter is used) (in.).

XMAGNI - Magnification factor for plotting. If XMAGNI > 1.0, horizontal and vertical displacements of each element in the core will be multiplied by XMAGNI prior to plotting. This produces core motion amplification. Boundary motion, however, is not amplified. Caution should be exercised in selecting this parameter, since, if it is too large, elements may be plotted outside the boundary. XMAGNI = 2.0 has been successfully utilized.

HGAP - Gap inserted between horizontal interfaces of all elements in the core for plotting purposes only (in.).

Card 35E (Optional Card)

NTIMES(I)-Number of integration steps at which Ith plot of the core response is desired. I = 1,2,3,...NPLOTS.

Restart deck is inserted at this point in card sequence (After Card 35 if no core response plots are desired or 35E if there are to be plots.).

Cards 35F and 35G are required only for seismic time history simulations.

Card 35F (Optional Card)

ITH - FORMAT for time history acceleration data points to be provided as input. IF ITH = 0, data points must be in 8E9.3 FORMAT. If ITH = 1, data points must be in 8E10.5 FORMAT.

NINPU - Total number of acceleration input data points for horizontal
or MINPU (NINPU) or vertical (MINPU) time history.

Card 35F (continued)

- FACTOR - Conversion factor for acceleration data points if units are other than in./sec².
- SCALE - Input g-level for time history simulation, if GG(I,J) is for 1.0 g ground motion.
- DELT - Time step between input time history data points. DELT for horizontal and vertical time histories must be the same (sec).

Card 35G (Optional Card)

- GG(I,J) - Acceleration time history data points (table). I = 1 (horizontal) or 4 (vertical). J = 1,2,3,...NINPU (horizontal) or MINPU (vertical) (in./sec²).

For double axis time history, input horizontal first (i.e., Card 35F with NINPU, Card 35G with horizontal time history then Card 35F (again) with MINPU, and Card 35G (again) with vertical time history).

5. OUTPUT

MCOCO has the capability of producing six distinct types of output; namely:

- 1) Input repeat
- 2) Initial condition printout
- 3) Printout as a function of time
- 4) Termination printout
- 5) Restart deck printout (optional)
- 6) Graph of core response (optional)

The first four types of output are automatic and are generated by the normal execution of a data deck.

Input repeat produces a duplicate of card images utilized to input the program. It aids in rapidly checking a data deck, especially for initial runs. It is also valuable for verification of the proper number of data cards. Initial condition printout consists of input card data and values computed prior to the start of a simulation. It is useful for checking input FORMAT, column staggering, computations of initial conditions, etc.

Printout as a function of time is produced at each NPRT integration step. It consists of the printout heading, current time and number of integration steps (INTERVAL or print page) and the following data for each element:

COL-B - Column and element location in the core.
THETA, THETAD - Angular displacement (deg) and velocity (deg/sec)
U, UD - Horizontal displacement (in.) and velocity (in./sec).
W, WD - Vertical displacement (in.) and velocity (in./sec).
FVL, FVC, FVR - Left, center and right vertical impact force at lower face (lb).

FBL, FBR - Left and right total lateral impact force at a horizontal interface (1b).

FRI - Friction force (1b).

FDS - Dowel shear force (1b).

Velocities and displacements for this type output are instantaneous, whereas forces are maximum values between print intervals. Only the stiffness portion of dowel and collision forces are printed. If core response is to be plotted, container and element corner coordinates are also printed.

Termination printout consists of maximum and minimum values and corresponding time of occurrence of U, W, THETA, UD, WD and THETAD for each element. Also, maximum values and corresponding times for the following data are printed:

FVL, FVC, FVR, FBL, FBR, FRI, FDS

Spring pack loads

Core support post loads (vertical and horizontal)

Core support floor lateral impact loads

Relative displacement between floor elements and PCRV

Restart card images are printed in the same format as the punched restart deck. This is done automatically, if the restart option is selected. The printout provides a means of verifying restart cards prior to initiating a continuation of a simulation. Punch errors may also be detected.

If the plot option is selected, graphs of element and boundary displacement are produced. Plots may prove useful for model verification (i.e., correct alignment, fuel columns supported by proper floor element, etc.). Core motion characteristics are also vividly displayed if this option is chosen.

6. SYMBOLS

- $a_{D_L}(\text{GAPL})^*$ - left hand dowel gap (in.).
 $a_{D_R}(\text{GAPR})$ - right hand dowel gap (in.).
 $a_{FL_m}(\text{GAPFU}_m \text{ and } \text{GAPFL}_m)$ - lateral gap between core floor elements m and $m+1$ (GAPFU and GAPFL refer to upper and lower corners) (in.).
 $a_{ij}(\text{GAP}_{ij})$ - lateral gap at interface (gap) i , impact force number j (in.).
 $a_x(\text{AMPLW})$ - g-level for sinusoidal dwell in vertical direction.
 $a_z(\text{AMPLU})$ - g-level for sinusoidal dwell in horizontal direction.
 BFL_m - half width of element m in core support floor (in.).
 b_{ik} - half width of core element k in column i (in.).
 $BPOST_m$ - horizontal distance from floor element center of gravity to support post center, divided by element half width.
 c_{ik} - horizontal distance from an element corner to a point on a dowel (in.).
 $C_T(\text{CSQT})$ - fluid dynamic rotary damping coefficient about the center of gravity (in.-lb-sec²/rad²).
 $C_U(\text{CSQU})$ - fluid dynamic damping coefficient in the horizontal direction (lb-sec²/in.²).
 $C_W(\text{CSQW})$ - fluid dynamic damping coefficient in the vertical direction (lb-sec²/in.²).
 D_{ik} - static spring compression of vertical springs in element k , row i due to preload and dead weight (in.).

* symbols in parentheses are used for input, others for equation development

- D_{θ} - rotational fluid dynamic damping (in.-lb).
- D_u - horizontal fluid dynamic damping (lb).
- D_w - vertical fluid dynamic damping (lb).
- F_C - collision force (sum of spring and damping forces) (lb).
- FC_m - total load (dead weight and preload) above floor element m (lb).
- FCH_{ik} - sum of dowel and friction forces at the lower horizontal interface of element k, column i (lb).
- F_D - damping force (lb).
- FDS_{ik} - dowel shear force on lower horizontal interface of element k, column i (lb).
- FF_{ij} - lateral collision force for impact force number j, interface i (lb).
- $FIMPX_{m,1}$ - horizontal collision force at top of vertical interface between floor element m and m-1 (lb).
- $FIMPX_{m,2}$ - horizontal collision force at bottom of vertical interface between floor element m and m-1 (lb).
- F_K - force due to plenum key constraint (lb).
- $F_{N_{ik}}$ - total vertical force at bottom of element k, column i (lb).
- $FPOSTX_{m,1}$ - horizontal collision force at top of right support post (lb).
- $FPOSTX_{m,2}$ - horizontal collision force at top of left support post (lb).
- $FPOSTZ_{m,1}$ - vertical force at top of right support post (lb).
- $FPOSTZ_{m,2}$ - vertical force at top of left support post (lb).
- F_R - force due reflector plenum constraint (lb).
- FRI_{ik} - friction force at lower horizontal interface of element k, column i (lb).
- F_S - spring force (lb).
- FVC_{ik} - center vertical force at lower horizontal interface of element k, column i (lb).
- FVL_{ik} - left vertical force at lower horizontal interface of element k, column i (lb).

- F_S - spring force (lb).
- FVR_{ik} - right vertical force at lower horizontal interface of element k, column i (lb).
- g - acceleration of gravity (386.4 in./sec²).
- $h(HH)^*$ - integration time step (sec).
- H - height of an element.
- HDF_{ij} - ratio of horizontal damping coefficient to CH for impact force k, interface i.
- HFL_m - half height of element m in support floor (in.).
- h_{ik} - half height of element k in column i (in.).
- HSK_{ij} - ratio of horizontal spring constant to SPH for impact force k, interface i.
- I_{ik} - mass moment inertia of element k, column i (lb-in./sec²).

$$I_{ik} = \frac{W_{ik}}{3g} (b_{ik}^2 + h_{ik}^2)$$
- I_{FLm} - mass moment inertia of floor element m (lb-in-sec²).

$$I_{FLm} = \frac{W_{FLm}}{3g} (B_{FLm}^2 + H_{FLm}^2).$$
- k - spring constant (lb/in.).
- k_K - plenum keyway constraint spring constant (lb/in.).
- k_R - plenum reflector constraint spring constant (lb/in.).
- k_θ - plenum rotational constraint spring constant (lb/in.).
- m_{ik} - mass element k, column i (lb-sec²/in.).
- m_{FLm} - mass of floor element m (lb-sec²/in.).
- M_θ - moment due to plenum rotational constraint (in.-lb).
- $NCOL$ - number of columns.
- NE - number of elements.
- NFL - number of floor elements.

* symbols in parentheses are used for input, others for equation development

- PL - vertical preload on center of plenum element (lb).
- RW_{ik} - sum of preload and column weight above and including element k, column i (lb).
- S(SLP) - slope of friction force versus velocity between element interfaces (lb-sec/in.).
- SPOSTZ - vertical spring rate of core support post (lb/in.).
- t - time (sec).
- TOWT_i - total weight of all elements in column i (lb).
- UARM_{m,i} - normalized horizontal distance from floor element cg to point i (see Fig. 7).
- u_{FLm} - absolute horizontal displacement of floor element m center of gravity (in.).
- u_{FLm}^p - absolute horizontal displacement of point p on floor element m (in.).
- $\dot{u}_{FLm}$ - horizontal velocity of floor element m cg (in./sec).
- $\dot{u}_{FLm}^p$ - horizontal velocity of point p on floor element m (in./sec).
- $\ddot{u}_{FLm}$ - horizontal acceleration of floor element m cg (in./sec²).
- u_{ik} - absolute horizontal displacement of cg of element k, column i (in.).
- u_{ik}^p - absolute horizontal displacement of point p on element k, column i (in.).
- $\dot{u}_{ik}$ - horizontal velocity of cg of element k, column i (in./sec).
- $\dot{u}_{ik}^p$ - horizontal velocity of point p on element k, column i (in./sec).
- u_o - absolute horizontal displacement of boundary (PCRV) (in.).
- $\dot{u}_o$ - horizontal boundary velocity (in./sec).
- $\ddot{u}_o$ - horizontal boundary acceleration (in./sec²).
- $u_{o,t-h}$ - absolute horizontal boundary displacement at one integration step preceding time t (in.).
- $\dot{u}_{o,t-h}$ - horizontal boundary velocity at an integration step preceding time t (in./sec).

- $\ddot{u}_{0,t-h}$ - horizontal boundary acceleration at an integration step preceding time t (in./sec).
- VDF_{ik} - ratio of vertical corner damping coefficient to CV for element k , column i .
- $VDFC_{ik}$ - ratio of vertical center damping coefficient to CCV for element k , column i .
- VSF_{ik} - ratio of vertical corner spring constant to SPV for element k , column i .
- $VSFC_{ik}$ - ratio of vertical center spring constant to CSPRV for element k , column i .
- $WARM_{m,i}$ - normalized horizontal distance from floor element m to point i (see Fig. 7).
- w_{FL_m} - absolute vertical displacement of floor element m center of gravity (in.).
- $w_{FL_m}^p$ - absolute vertical displacement of point p on floor element m (in.).
- $\dot{w}_{FL_m}$ - vertical velocity of floor element m cg (in./sec).
- $\dot{w}_{FL_m}^p$ - vertical velocity of point p on floor element m (in./sec).
- $\ddot{w}_{FL_m}$ - vertical acceleration of floor element m cg (in./sec²).
- w_{ik} - absolute vertical displacement of cg of element k , column i (in.).
- w_{ik}^p - absolute vertical displacement of point p on element k , column i (in.).
- $\dot{w}_{ik}$ - vertical velocity of cg of element k , column i (in./sec).
- $\dot{w}_{ik}^p$ - vertical velocity of point p on element k , column i (in./sec).
- w_0 - absolute vertical displacement of boundary (PCRV) (in.).
- $\dot{w}_0$ - vertical boundary velocity (in./sec).
- $\ddot{w}_0$ - vertical boundary acceleration (in./sec²).
- $w_{0,t-h}$ - absolute vertical boundary displacement at one time step preceding time t (in./sec).

- $\dot{w}_{0t-h}$ - vertical boundary velocity at an integration step preceding time t (in./sec).
- $\ddot{w}_{0t-h}$ - vertical boundary acceleration at an integration step preceding time t (in./sec²).
- w_{FLm} - weight of floor element m (lb).
- w_{ik} - weight of element k , column i (lb).
- x - horizontal impact mechanism (spring) deflection (in.).
- $\dot{x}$ - horizontal impact mechanism (damper) velocity (in./sec).
- x_D - deformation of dowel (in.).
- $\dot{x}_D$ - relative velocity between dowel and socket (in./sec).
- $\dot{x}_{FL}$ - floor horizontal impact mechanism velocity (in./sec).
- x_n - displacement at time t (in.).
- $x_{n+2/3}$ - displacement 2/3 of a time step above time t (in.).
- x_{n+1} - displacement one time step above time t (in.).
- $\dot{x}_{n-1/2}$ - velocity 1/2 time step below time t (in./sec).
- $\dot{x}_n$ - velocity at time t (in.).
- $\dot{x}_{n+1/2}$ - velocity 1/2 time step above time t (in./sec).
- $\dot{x}_{n+2/3}$ - velocity 2/3 time step above time t (in./sec).
- $\dot{x}_{n+1}$ - velocity one time step above time t (in./sec).
- $\ddot{x}_n$ - acceleration at time t (in./sec²).
- $\ddot{x}_{n+2/3}$ - acceleration 2/3 time step above time t (in./sec²).
- $\bar{x}_{ik}$ - horizontal coordinate of point p on element k , column i (in.).
- z - vertical impact mechanism (spring) deflection (in.).
- $\dot{z}$ - vertical impact mechanism (damper) velocity (in./sec).
- z_{FL} - floor vertical impact mechanism deflection (in.).
- $\dot{z}_{FL}$ - floor vertical impact mechanism velocity (in.).

- $\bar{z}_{ik}$ - vertical coordinate of point p on element k, column i (in.).
- $\alpha_1, \alpha_2, \alpha_3$ - constants used in Runge-Kutta integration method.
- γ_1, γ_2 - constants used in Runge-Kutta integration method.
- μ - friction coefficient.
- θ_{FL_m} - floor element m rotational angle (rad).*
- $\dot{\theta}_{FL_m}$ - floor element m rotational velocity (rad/sec).*
- $\ddot{\theta}_{FL_m}$ - floor element m rotational acceleration (rad/sec²).*
- θ_{ik} - rotational angle of element k, column i (rad).*
- $\dot{\theta}_{ik}$ - rotational velocity of element k, column i (rad/sec).*
- $\ddot{\theta}_{ik}$ - rotational acceleration of element k, column i (rad/sec²).*
- σ_1, σ_2 - constants used in Runge-Kutta integration method.
- ω_x - frequency of sinusoidal dwell boundary motion in horizontal direction (Hz).
- ω_z - frequency of sinusoidal dwell boundary motion in vertical direction (Hz).

*radian or degrees

7. SAMPLE PROBLEM

The sample problem consists of ten columns of a 1/5 scale core (see Fig. 16). This particular model, rather than the full array core, was selected for demonstration because of cost considerations.

The reflector element thickness at an outside diameter is 7.226 inches. See Fig. A2-3, Appendix 2. "Effective" width of a 1/5 scale element is equal to the area of the hexagon element divided by across the flat width or

$$\frac{A_{\text{HEX}}}{b} = \frac{6.985}{2.83} = 2.468 \text{ in. } \{2.434 \text{ for } b = 2.81 \text{ in}^*\}$$

Therefore, the number of hexagonal fuel elements associated with one reflector element thickness is

$$\frac{7.226}{2.468} = 2.93 \quad \{2.97 \text{ for } b = 2.81 \text{ in.}\}$$

Current modeling techniques utilize this factor of 2.97 to multiply spring rates, masses, etc., of fuel elements. Results are then provided as code input. Computed fuel element forces must then be divided by 2.97 to obtain loads on a single element. It should be noted that the 2.97 factor applies to fuel elements only and not to reflector blocks, core barrel plates or the support floor. The eight types of elements present in the sample problem are depicted in Figs. 17 through 19. Dimensions and weights are also given on the figures.

Vertical center springs are not utilized (Ref. 7). Spring rates for the basic full scale fuel element were obtained from Ref. 8. Horizontal spring rates were obtained directly from the reference, whereas, vertically,

* Drawing dimensions for element width and shown on Fig. A2-3; 2.83 was used in sample problem.

Figure 16. MCOCO Ten Column 1/5 Scale Model

FULL HEIGHT FUEL ELEMENT

THREE-QUARTER HEIGHT FUEL ELEMENT

HALF HEIGHT FUEL ELEMENT

* WEIGHTS HERE ARE 2.97 TIMES ACTUAL ELEMENT WEIGHT (e.g., $2.97 W = 2.97 (2.07) = 6.15 \text{ LB}$)

Figure 17. 1/5 Scale Fuel Element Properties

Figure 18. 1/5 Scale Plenum Element, Reflector Block and Core Barrel Plate Properties

REFLECTOR SUPPORT FLOOR ELEMENT

FUEL COLUMN SUPPORT FLOOR ELEMENTS

Figure 19. 1/5 Scale Floor Element Properties

two times reference values were used (i.e., a spring resting on a spring produces a series system, hence, individual vertical rates must be doubled; horizontal springs are assumed independent).

Computation of vertical corner impact mechanism spring rate and damping for the full height fuel element are as follows (see Ref. 9):

$$k_V = \frac{200,000}{2} = 100,000 \text{ lb/in.}$$

$$k_H = \frac{166,000}{2} = 83,000 \text{ lb/in.}$$

$$CR = 0.36$$

$$\xi = \frac{\sqrt{[\ln(CR)]^2}}{\pi^2 + [\ln(CR)]^2} = 0.309$$

For interelement impact, from Appendix 3,

$$c = \xi \sqrt{mk}$$

where

$$m = 2.97 \frac{W}{g}$$

and

$$k = 2.97 k_V = 2.97 (100,000) = 297,000 \text{ lb/in.}$$

or

$$k = 2.97 k_H = 2.97 (83,000) = 246,500 \text{ lb/in.}$$

Therefore,

$$c_V = 2.97 \xi \sqrt{\frac{W}{g} k_V} = 21.25 \text{ lb-sec/in.}$$

$$c_H = 2.97 \xi \sqrt{\frac{W}{g} k_H} = 19.36 \text{ lb-sec/in.}$$

The full height fuel element impact mechanism spring constants and damping coefficients are summarized in Table 2. For elements other than full height, additional factors are presented below and also summarized in the table.

(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

$$(\text{and vice versa}) = 2 \left[\frac{2(4/3)}{2 + 4/3} \right] = 1.6$$

Vertical spring factor--half-height to full-height

$$(\text{and vice versa}) = 2 \left[\frac{2(1)}{2+1} \right] = 1.3333$$

Vertical damping factor = 1.0

(2) Three-quarter height elements

Horizontal spring and damping factor = 0.75

Vertical spring factor--three-quarter height to three-quarter

$$\text{height} = 2 \left[\frac{(4/3)(4/3)}{4/3 + 4/3} \right] = 1.3333$$

Vertical damping factor = 1.0

There are three dowels per element. Each dowel has a stiffness of 4000 lb/in. Two dowels are assumed to act simultaneously. This produces a spring rate of 8000 lb/in. Dowel stiffness for code input is, therefore

$$k_D = 2.97 (8000) = 23,760 \text{ lb/in.}$$

Dowel damping is computed assuming the ratio of dowel spring rate to damping is the same as that for the lateral impact mechanism. Hence,

$$c_D = \frac{23,760}{246,500} (19.36) = 1.866 \text{ lb-sec/in.}$$

The top row of hexagonal elements are half-height and differ from other half-height elements in mass only. The factor is

$$\frac{2.63}{3.07} = \frac{6}{7}$$

Table 2

PROPERTIES OF IMPACT MECHANISMS FOR FUEL ELEMENTS

Impact Mechanism	Stiffness (lb/in.)	Damping (lb-sec/in.)
Vertical Corner, 1-1*	246,500 (k_V)	21.25 (c_V)
Horizontal Corner, 1*	297,000 (k_H)	19.36 (c_H)
Vertical Corner, $1-\frac{1}{2}$ or $\frac{1}{2}-1$	1.3333 k_V	1.0 c_V
Horizontal Corner, $\frac{1}{2}$	0.5 k_H	0.5 c_H
Vertical Corner, $\frac{3}{4}-\frac{1}{2}$ or $\frac{1}{2}-\frac{3}{4}$	1.6 k_V	1.0 c_V
Horizontal Corner, $\frac{3}{4}$	0.75 k_H	0.75 c_H
Vertical Corner, $\frac{3}{4}-\frac{3}{4}$	1.333 k_V	1.0 c_V

*Vertically, springs are in series, hence, 1-1 refers to full height fuel element atop full height element, etc. Horizontally, springs are independent. Therefore, 1 refers to full height fuel elements, $\frac{1}{2}$ to half-height, etc.

Table 3

PROPERTIES OF IMPACT MECHANISMS FOR PLENUM ELEMENTS

Impact Mechanism	Stiffness (lb/in.)	Damping (lb-sec/in.)
Vertical Corner, $\frac{1}{2}-1$	1.263 k_V	0.923 c_V
Horizontal Corner, $\frac{1}{2}$	0.429 k_H	0.429 c_H
Vertical Corner, $\frac{1}{2}-\frac{1}{2}$	1.846 k_V	0.923 c_V

Plenum element spring and damping factors are, therefore (see Table 3),

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

$$\text{Vertical spring factor--half-height to half-height} =$$

$$2 \left[\frac{2(6/7) 2}{2(6/7) + 2} \right] = 1.846$$

$$\text{Vertical spring factor--full height to half-height} =$$

$$2 \left[\frac{2(6/7) 1}{2(6/7) + 1} \right] = 1.263$$

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

Reflector element impact mechanism spring constants and damping coefficients are computed, as before, by means of mass ratios. Therefore,

$$k_{V_{PRB}} = k_V \frac{W_{PRB}}{W(2.97)} = 297,000 \left[\frac{26.2}{2.07 (2.97)} \right] = 1,265,700 \text{ lb/in.}$$

$$c_{V_{PRB}} = c_V \frac{W_{PRB}}{W(2.97)} = 21.25 \left[\frac{26.2}{2.07 (2.97)} \right] = 90.56 \text{ lb-sec/in.}$$

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 are:

$$\text{Spring} = \frac{1,265,700}{297,000} = 4.26$$

$$\text{Damper} = \frac{90.56}{21.25} = 4.26$$

The horizontal factors for reflector blocks are taken at 1.0 for springs and dampers (Table 4).

Core barrel plates are affixed directly to the spring packs (see Appendix 2). They are approximately the same height and thickness as the reflector elements, 0.5 inches wide and made of steel. Stiffness and damping factors developed for the reflector blocks were also utilized for the core barrel plates.

Table 4

PROPERTIES OF IMPACT MECHANISMS FOR PERMANENT REFLECTOR BLOCKS

Impact Mechanism	Stiffness (lb/in.)	Damping (lb-sec/in.)
Vertical Corner	$4.26 k_V^*$	$4.26 c_V$
Horizontal Corner	$1.0 k_H$	$1.0 c_H$

*Table 2 defines k_V , c_V , k_H and c_H

Table 5

OTHER PROPERTIES USED IN SAMPLE PROBLEM

Dowel	$k = 23,760 \text{ lb/in.}$	$c = 1.866 \text{ lb-sec/in.}$
Core Support Post	$k_V = 612,000 \text{ lb/in.}$ $k_H = 0$	$c_V = 61.9 \text{ lb-sec/in.}$ $c_H = 0$
Spring Pack	$k = 800 \text{ lb/in. (initial)}$ $= 580,000 \text{ lb/in. (final)}$	$c = 1.31$ (bottom out distance = 0.2")
Floor Gaps	$= 0.011 \text{ in. (between elements 1-2, 2-3 and 3-4)}$ $= 0.0 \text{ in. (between elements 1 and 4 and spring packs)}$	
Column Gaps	$= 0.011 \text{ in. (at interfaces 3, 6 and 9)}$ $= 0.068 \text{ in. (at interfaces 4, 5, 7 and 8)}$ $= 0.0 \text{ in. (at interfaces 2 and 10)}$ $= 0.0 \text{ in. (at interfaces 1 and 11)}$	
Dowel Gap	$= 0.0 \text{ in.}$	
Friction Coefficient	$= 0.2$	
Slope of friction force versus velocity	$= 40 \text{ lb-sec/in.}$	

Properties for the core support post and spring packs, in addition to gaps and friction factors, are listed in Table 5. The integration time step utilized was 0.00002 seconds.

Plenum element rotational spring rate, keyway constraint spring rate, clamped reflector spring rate and fluid dynamic damping coefficients were all set to zero.

The run was initiated at $t = 1.0$ seconds and continued for 0.2 seconds of real time. The central difference integration method was used.

A 0.24 g horizontal time history of a General Atomic Soil 3 (Shock 4) seismic disturbance was utilized to produce boundary motion.

Control cards required to execute the MCOCO code with core barrel plates are listed below:

▽ASG,AX	RWT*MCOCOB
▽XQT	RWT*MCOCOB.A

Input is placed subsequent to the ▽XQT card. In order to execute the sample problem from $t = 1.0$ to $t = 1.03$, add the following card:

▽ADD, P	RWT*MCOCOB.TEST
---------	-----------------

The element named TEST of the catalogued file RWT*MCOCO contains card images of input data required for the sample problem. ▽ADD appends this data.

Three other versions of the code exist on catalogued files. Control Cards required to utilize and functions of each version are listed below:

▽ASG,AX	RWT*MCOCO
▽XQT	RWT*MCOCO.A

These cards will execute the basic code which will analyze, at most, nine fuel columns and two reflector columns.

▽ASG,AX	RWT*MCOCOF
▽XQT	RWT*MCOCOF.A

RWT*MCOCOF is an expanded version of the program which will accept as many as 24 fuel columns and two reflector columns.

▽ASG,AX	RWT*MCOCOF CB
▽XQT	RWT*MCOCOF CB.A

This version was developed to simulate the full array core. Input may be provided for up to 24 fuel columns, two reflector columns, and two core barrel plate columns.

The expanded codes could also be used to analyze less than full array models. Storage requirements, however, for RWT*MCOCOF CB is 114 K words of memory. This precludes rapid turnaround. Because of this, it is anticipated that at least two versions of the code will be maintained.

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3. Rickard, N. D., "COCO - A Computer Program for Seismic Analysis of a Single Column of the HTGR Core," GA-A14600, General Atomic Company, February 1978.
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5. Beltschko, T., "Comparative Evaluation of Numerical Methods for Dynamic Structural Analysis," Methods for Dynamic Structural Analysis, Berlin, Paper No. T1/1, September 1975.
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7. Thompson, R. W., "Documentation of Current COCO Model," unpublished data, General Atomic Company, 18 August 1976.
8. Thompson, R. W., "Revised COCO Model," unpublished data, General Atomic Company, 13 September 1976.
9. Shatoff, H. D., et al., "Core Seismic Methods Verification: Status Report," GA-A14812, General Atomic Company, to be published.

APPENDIX 1

FORMS FOR INPUT DATA CARDS

WORD	
COLUMN	1-80
FORMAT	A
CARD 1	TITLE
SYMBOL	TITLE

WORD	1	2	3	4	5
COLUMN	1-6	7-12	13-18	19-24	25-30
FORMAT	I6	I6	I6	I6	I6
CARD 2	Number of vertical columns $5 \leq \text{NCOL} \leq 29$	Print interval $\text{NPRT} \geq 1$	Number of plots	Punch Restart Deck 0 = No 1 = Yes	Read Restart Deck 0 = No 1 = Yes
SYMBOL	NCOL	NPRT	NPLOTS	NREPC	NRESTA

Note: If restart deck is to be read, insert subsequent to Card 35 or 35E

WORD	1	2...NCOL
COLUMN	1-6	7-12...
FORMAT	12I6	
CARD 3	Number of elements in Column 1	NCOL Total values
SYMBOL	NBL(1)	NBL(2)...NBL(NCOL)

Number of
elements
excludes core
support block

WORD	1	2	3	4	
COLUMN	1-12	13-24	25-36	42	
FORMAT	E12.5	E12.5	E12.5	I6	
CARD 4	Simulation start time	Maximum run time	Integration time step	Integration method 0 = Central diff. 1 = 2nd order Runge-Kutta	
SYMBOL	T0	TMAX	HH	METHOD	

WORD	1	2	3	4	
COLUMN	1-12	13-24	25-36	37-48	
FORMAT	E12.5	E12.5	E12.5	E12.5	
CARD 5	Horizontal corner spring stiffness	Horizontal corner spring damping	Vertical corner spring stiffness	Vertical corner spring damping	
SYMBOL	SPH	CH	SPV	CV	

WORD	1	2	3	4	5
COLUMN	1-12	13-24	25-36	37-48	54
FORMAT	E12.5	E12.5	E12.5	E12.5	I6
CARD 6	Initial stiffness of bilinear spring	Final stiffness of bilinear spring	Spring travel before SPB2 is effective	Spring pack damping	Spring pack gap indicator 0 = zero spring pack gap 1 = read spring pack gap
SYMBOL	SPB1	SPB2	TRAVL	CSP	ISPGAP

Note: If ISPGAP.
EQ. 0, omit cards
6A & B. If
ISPGAP.EQ. 1,
provide spring
pack gaps on 6A
and B.

WORD	1	2....NBL(1)
COLUMN	1-12	13-24....
FORMAT	6F12.5	
CARD 6A	Gap for right hand spring pack number 2	Gap for right hand spring pack number 3... Note: NE = NBL(1)
SYMBOL	GAP(1,1)	GAP(1,2)....GAP(1,NE)

Optional Card

WORD	1	2....NBL(NCØL)
COLUMN	1-12	13-24....
FORMAT	6F12.5	
CARD 6B	Gap for left hand spring pack number 2	Gap for left hand spring pack number 3 ... Note: NINT = NCØL+1 NE = NBL(NCØL)
SYMBOL	GAP(NINT,1)	GAP(NINT,2)....GAP(NINT,NE)

Optional Card

WORD	1	2	
COLUMN	1-12	13-24	
FORMAT	E12.5	E12.5	
CARD 7	Vertical center spring stiffness	Vertical center spring damping	
SYMBOL	CSPRV	CCV	

WORD	1	2	3	
COLUMN	1-12	13-24	25-36	
FORMAT	E12.5	E12.5	E12.5	
CARD 8	Top element rotational spring rate	Keyway constraint spring rate	Clamped reflector spring rate	
SYMBOL	SROT	SKEY	SREFL	

WORD	1	2	
COLUMN	1-6	7-12	
FORMAT	I6	I6	
CARD 9	Number of element types to be defined	Number of gap types to be defined	If NGTYPE·GT·NCOL, it is indicative that user wishes to input independent lateral gaps for each impact point
SYMBOL	NETYPE	NGTYPE	

Note: If NGTYPE·
GT·NCOL, Omit
cards 9A & 9B

WORD	1	2...NGTYPE
COLUMN	1-12	13-24...
FORMAT	6F12.5	
CARD 9A	Value of gap for each ITYPE	NGTYPE total gaps
SYMBOL	VALU1(1)	VALU1(2)...VALU1(NGTYPE)

Optional card

WORD	1	2...NCØL
COLUMN	1-5	6-10...
FORMAT	I4I5	
CARD 9B	Gap type between Columns 1 & 2	NCØL-1 Total Values
SYMBOL	ITYPE(2)	ITYPE(3)....ITYPE(NCØL)

Optional card

WORD	1	BLANK	2	3	4
COLUMN	1-6	7-12	13-24	25-36	37-48
FORMAT	I6	6X	E12.5	E12.5	E12.5
CARD 10	Element Type Ident.		Width of Element I	Height of Element I	Weight of Element I
SYMBOL	I	---	VALU1(I)	VALU2(I)	VALU3(I)

One card for each
element type

WORD	1	2...NBL(1)
COLUMN	1-5	6-10...
FORMAT	I4I5	
CARD 11	Element type for Col. 1, Element 1	Element type for Col. 1, Element 2
SYMBOL	MTYPE(1,1)	MTYPE(1,2)...MTYPE(NCOL,NBL)

One card for
each column.
In MTYPE(I,J)
J=1,...NBL
I=1,...NCØL

WORD	1	
COLUMN	1-12	
FORMAT	E12.5	
CARD 12	Vertical preload on top element of each column	
SYMBOL	PRELD	

WORD	1	2	3	4	5
COLUMN	1-12	13-24	25-36	37-48	49-60
FORMAT	E12.5	E12.5	E12.5	E12.5	E12.5
CARD 13	Dowel spring constant	Dowel damping coefficient	Right hand dowel gap	Left hand dowel gap	Coefficient of friction between element horizontal interfaces
SYMBOL	SK	CDW	GAPR	GAPL	CØF

WORD	6	
COLUMN	61-72	
FORMAT	E12.5	
CARD 13 (cont'd)	Slope of friction force function	
SYMBOL	SLP	

WORD	1	2	3	4	5
COLUMN	1-6	13-24	25-36	37-48	49-60
FORMAT	I6	E12.5	E12.5	E12.5	E12.5
CARD 14	Input boundary motion	Horizontal g-level (if SINE dwell)	Horizontal frequency (If SINE dwell)	Vertical g-level (If SINE dwell)	Vertical frequency (If SINE dwell)
SYMBOL	IBM	AMPLU	FREQU	AMPLW	FREQW

IBM=1(SINE dwell)
 =2(Hor.A.T.H.)
 =3(Ver.A.T.H.)
 =4(Hor. &
 Ver.A.T.H.)
 A.T.H=acceleration
 time
 history

Note: Columns 13-60 of Card 14 are blank for time-history simulations

WORD	1	2	3	
COLUMN	1-12	13-24	25-36	
FORMAT	E12.5	E12.5	E12.5	
CARD 15	Element aero damping coef- ficient in x- direction	Element aero. damping coef- ficient in z- direction	Element rotary aero. damping coefficient	
SYMBOL	CSQU	CSQW	CSQT	

WORD	1	2	3	4	5...NUMSR(NCØL)
COLUMN	1-5	6-10	11-15	16-20	21-25...
FORMAT	7(2I5)				
CARD 16	Number of contact points on left side of Gap 2	Number of contact points on right side of Gap 2	Number of contact points on left side of Gap 3	Number of contact points on right side of Gap 3	NCØL-1 total values
SYMBOL	NUMSL(2)	NUMSR(2)	NUMSL(3)	NUMSR(3)	NUMSL(4)....

Note: Cards 17 through 20 are repeated for each gap

WORD	1	2	3 ... NSL
COLUMN	1-2	3-4	5-6 ...
FORMAT	18 (I2,I2)		
CARD 17	Element number for 1st contact point on left side of Gap I	Element number for 2nd contact point on left side of Gap I	NSL total values per gap
SYMBOL	NEL(I,1)	NEL(I,2)	NEL(I,3) ... NEL(NCØL,NSL)

NSL=NUMSL(I)
I = 2,...NCOL

WORD	1	2	3 ... NSR
COLUMN	1-2	3-4	5-6 ...
FORMAT	18 (I2,I2)		
CARD 18	Element number for 1st contact point on right side of Gap I	Element number for 2nd contact point on right side of Gap I	NSR total values per gap
SYMBOL	NER(I,1)	NER(I,2)	NER(I,3) ... NER(NCØL,NSR)

NSR=NUMSR(I)
I = 2,...NCOL

WORD	1	2	3 ... NSL
COLUMN	1-5	6-10	11-15 ...
FORMAT	14F5.2		
CARD 19	Normalized distance from element cg to 1st contact point on left side of Gap I	Normalized distance from element cg to 2nd contact point on left side of Gap I	NSL total values per gap
SYMBOL	YL(I,1)	YL(I,2)	YL(I,3) ... YL(NCØL,NSL)

$YL(I,J) = \frac{\pm ZL}{H/2}$

ZL = Distance
above (below) cg
H/2= Element
half-height

WORD	1	2	3 ... NSR
COLUMN	1-5	6-10	11-15 ...
FORMAT	14F5.2		
CARD 20	Normalized distance from element cg to 1st contact point on right side of Gap I	Normalized distance from element cg to 2nd contact point on right side of Gap I	NSR total values per gap
SYMBOL	YR(I,1)	YR(I,2)	YR(I,3) ... YR(NCØL,NSR)

$$YR(I,J) = \frac{\pm ZL}{H/2}$$

WORD	1	2	3 ... NCØL
COLUMN	1-5	6-10	11-15 ...
FORMAT	7(2I5)		
CARD 21	Number of impact forces at Gap 2	Number of impact forces at Gap 3	NCØL-1 total values
SYMBOL	NUMIF(2)	NUMIF(3)	NUMIF(3) ... NUMIF(NCØL)

WORD	1	2	3	4	5 ... NCØL-1
COLUMN	1-2	3-4	5-6	7-8	9-10 ...
FORMAT	18 (I2,I2)				
CARD 22	Contact point no. for impact force 1 on left side of Gap I	Contact point no. for impact force 1 on right side of Gap I	Contact point no. for impact force 2 on left side of Gap I	Contact point no. for impact force 2 on right side of Gap I	NCØL-1 Total values
SYMBOL	KSL(I,1)	KSR(I,1)	KSL(I,2)	KSR(I,2)	KSL(I,3) ...

$$I = 2, \dots, NCØL$$

Note: Read all gaps, using Card(s) 22A, prior to reading 23

WORD	1	2	3 ... NUMIF(NCØL)
COLUMN	1-6	7-12	13-18 ...
FORMAT	12F6.2		
CARD 22A	Gap at 1st contact point in Column I	Gap at 2nd contact point in Column I	I = 2, ... NCØL
SYMBOL	GAP(I,1)	GAP(I,2)	GAP(I,3) ... GAP(NCØL,NUMIF(NCØL))

Note: If NGTYPE-
LE-NCØL, Omit
Card 22A

Note: Cards 23-28 are repeated for each column and interface except when I = NCØL

WORD	1	2	3 ... NBL(NCØL)
COLUMN	1-6	7-12	13-18 ...
FORMAT	12F6.2		
CARD 23	Ratio of vertical element corner spring rate at column 1, Elt. 1 to SPV	Ratio of vertical element corner spring rate at column 1, Elt. 2 to SPV	I = 1, ... NCØL
SYMBOL	VSF(I,1)	VSF(I,2)	VSF(I,3) ... VSF(NCØL,NBL(NCØL))

WORD	1	2	3 ... NBL(NCØL)
COLUMN	1-6	7-12	13-18 ...
FORMAT	12F6.2		
CARD 24	Ratio of vertical elt. corner damping coefficient to CV at column 1, Element 1	Ratio of vertical elt. corner damping coefficient to CV at column 1, Element 2	I = 1, ... NCØL
SYMBOL	VDF(I,1)	VDF(I,2)	VDF(I,3) ... VDF(NCØL,NBL(NCØL))

WORD	1	2	3 ... NBL(NCØL)
COLUMN	1-6	7-12	13-18 ...
FORMAT	12F6.2		
CARD 25	Ratio of vertical element center spring rate at Column 1, Element 1 to CSPRV	Ratio of vertical element center spring rate at Column 1, Element 2 to CSPRV	I = 1, ... NCØL
SYMBOL	VSFC(I,1)	VSFC(I,2)	VSFC(I,3) ... VSFC(NCØL, NBL(NCØL))

WORD	1	2	3 ... NBL(NCØL)
COLUMN	1-6	7-12	13-18 ...
FORMAT	12F6.2		
CARD 26	Ratio of vertical element center damping coefficient at Column 1, Element 1 to CCV	Ratio of vertical element damping coefficient at Column 1, Element 1 to CCV	I = 1, ... NCØL
SYMBOL	VDFC(I,1)	VDFC(I,2)	VDFC(I,3) ... VDFC(NCØL, NBL(NCØL))

Note: See Section 4 for elimination of Cards 27-28 when I = NCØL

WORD	1	2	3 ... NUMIF(NCØL)
COLUMN	1-6	7-12	13-18 ...
FORMAT	12F6.2		
CARD 27	Ratio of horizontal element spring rate to SPH at impact force No. 1, Interface I	Ratio of horizontal element spring rate to SPH at impact force No. 2, Interface I	I = 2, ... NCØL
SYMBOL	HSK(I,1)	HSK(I,2)	HSK(I,3) ... HSK(NCØL, NUMIF(NCØL))

WORD	1	2	3 ... NUMIF(NCØL)
COLUMN	1-6	7-12	13-18 ...
FORMAT	12F6.2		
CARD 28	Ratio of horizontal element damping coefficient to CH at impact force No. 1, Interface I	Ratio of horizontal element damping coefficient to CH at impact force No. 2 Interface I	I = 2, ... NCØL
SYMBOL	HDF(I,1)	HDF(I,2)	HDF(I,3)... HDF(NCØL,NUMIF(NCØL))

WORD	1	2	3 ... NFLØØR
COLUMN	1-12	13-24	25-36 ...
FORMAT	6E12.5		
CARD 29	Width of Block 1 of core support floor	Width of Block 2 of core support floor	NFLØØR total values
SYMBOL	BFL(1)	BFL(2)	BFL(3) ... BFL(NFLØØR)

WORD	1	2	3 ... NFLØØR
COLUMN	1-12	13-24	25-36 ...
FORMAT	6E12.5		
CARD 30	Height of Block 1 of core support floor	Height of Block 2 of core support floor	NFLØØR total values
SYMBOL	HFL(1)	HFL(2)	HFL(3) ... HFL(NFLØØR)

WORD	1	2	3 ... NFL00R
COLUMN	1-12	13-24	25-36
FORMAT	6E12.5		
CARD 31	Ratio of core support post location (from Q) to Element 1 half width	Ratio of core support post location (from Q) to Element 2 half width	NFL00R total values
SYMBOL	BP0ST(1)	BP0ST(2)	BPOST(3) ... BPOST(NFL00R)

WORD	1	2	3 ... NFL00R
COLUMN	1-12	13-24	25-36 ...
FORMAT	6E12.5		
CARD 32	Weight of support floor Element 1	Weight of support floor Element 2	NFL00R total values
SYMBOL	AMFLR(1)	AMFLR(2)	AMFLR(3) ... AMFLR(NFL00R)

WORD	1	2	3	4
COLUMN	1-12	13-24	25-36	37-48
FORMAT	E12.5	E12.5	E12.5	E12.5
CARD 33	Core support post vertical stiffness	Core support post vertical damping	Core support post horizontal stiff- ness	Core support post horizontal damping
SYMBOL	SP0STZ	CP0STZ	SP0STX	CP0STX

WORD	1	2	3	4	5	6
COLUMN	1-12	13-24	25-36	37-48	49-60	61-72
FORMAT	I12	E12.5	E12.5	E12.5	E12.5	E12.5
CARD 34	Number of support floor gaps	Gap between upper right corner of floor Element 1 and spring pack	Gap between upper corners of floor Elements 2 and 1	Gap between upper corners of floor Elements 3 and 2	Gap between upper corners of floor Elements 4 and 3	Gap between upper left corner of floor Element 4 and spring pack
SYMBOL	MGAP	GAPFU(1)	GAPFU(2)	GAPFU(3)	GAPFU(4)	GAPFU(5)

WORD	1	2	3	4	5	6
COLUMN	1-12	13-24	25-36	37-48	49-60	61-72
FORMAT	I2X	E12.5	E12.5	E12.5	E12.5	E12.5
CARD 35	Blank	Gap between lower right corner of floor Element 1 and boundary	Gap between lower corners of floor Elements 2 and 1	Gap between lower corners of floor Elements 3 and 2	Gap between lower corners of floor Elements 4 and 3	Gap between lower left corner of floor Element 4 and boundary
SYMBOL	--	GAPFL(1)	GAPFL(2)	GAPFL(3)	GAPFL(4)	GAPFL(5)

Note: Insert restart deck subsequent to Card 35 or 35E.
Cards 35A-35E are optional and used only if plots are desired.

WORD	1	2	3	4	5
COLUMN	1-12	13-24	25-36	37-48	49-60
FORMAT	E12.5	E12.5	E12.5	E12.5	E12.5
CARD 35A	Graph frame XMAX	Graph frame XMIN	Graph frame YMAX	Graph frame YMIN	Lateral distance from core to PCRV in graph of core model
SYMBOL	CONTR(1)	CONTR(2)	CONTR(3)	CONTR(4)	GAPLAT

Note: Max's and Min's (on Card 35A) should include boundary displacements

Note: Read Cards 35A-35E only if NPLOTS.
NE.0

WORD	1	
COLUMN	1-80	
FORMAT	13A6,A7	
CARD 35B	Plot title	
SYMBOL	PLTYTL	

Optional card

WORD	1	
COLUMN	1-6	
FORMAT	I6	
CARD 35C	CALCOMP indicator	ICACOM . EQ . 0, Do not use CALCOMP ICACOM . NE . 0, Use CALCOMP
SYMBOL	ICACOM	

Optional card

WORD	1	2	3	
COLUMN	1-12	13-24	25-36	
FORMAT	F12.4	F12.4	F12.4	
CARD 35D	CALCOMP Plot size	Magnification size for plotting	Gap for plotting	Note: Omit SS if CALCOMP is not used
SYMBOL	SS	XMAGNI	HGAP	

Optional card

Note: Insert restart deck subsequent to Card 35 or 35E

WORD	1	2	3 ... NPLØTS
COLUMN	1-6	7-12	13-18 ...
FORMAT	12I6		
CARD 35E	Number of integration steps at which 1st plot is desired	Number of integration steps at which 2nd plot is desired	
SYMBOL	NTIMES(1)	NTIMES(2)	NTIMES(3) NTIMES(NPLØTS)

Optional card

Note: Cards 35F and 35G are required only for time history forcing functions

WORD	1	2	3	4	5
COLUMN	1-6	7-12	13-24	25-36	37-48
FORMAT	I6	I6	E12.5	E12.5	E12.5
CARD 35F	ITH = 0: Read TH FORMAT 8E9.3 ITH = 1: Read TH FORMAT 8E10.5	Number of time history input points	Conversion factor for units	Scale factor for desired g-level	Time step between time history input points
SYMBOL	ITH	NINPU(HOR.)	FACTOR	SCALE	DELT

Optional card

Note: For double axis time history, input horizontal first
MINPU(VERT.)

WORD	1	2	3 ... NINPU (or MINPU)
COLUMN	1-9 or 10	10-18 or	19-27 or
FORMAT	8(E9.3) or	11-20	21-30 ...
CARD 35G	8(E10.5)		
SYMBOL	GG(1,1) GG(4,1)	GG(1,2) GG(4,2)	GG(1,3) ... GG(1,NINPU) GG(4,3) ... GG(4,MINPU)

Optional card

Note: GG(1,I) and GG(4,I) are horizontal and vertical points, respectively

APPENDIX 2

PCRv, REACTOR CORE AND COMPONENTS

In order to illustrate the relationship between the actual HTGR core and the MCOCO model, the figures of this Appendix are presented. Figure A2-1 shows the HTGR core, A2-2 depicts a section of the core and support structure, and A2-3 presents the 1/5 scale horizontal plan view and strip model. Figure A2-4 shows the arrangement of the spring pack and core barrel plate in the 1/5 scale model of the core. This arrangement is incorporated into the MCOCO code.

3000 MW(t) GENERAL ARRANGEMENT

Figure A2-1. PCRV and Core

Figure A2-2.
HTGR Reactor Core and Support Arrangement

$$\text{STRIP} = \frac{10}{360} \times \pi \times (82.8) = 7.226 \text{ IN.}$$

$$b = 2.81 \text{ IN.}$$

$$\text{EFFECTIVE BLOCK WIDTH} = \frac{\text{AREA OF HEXAGON}}{2.81} = 2.434 \text{ IN.}$$

Figure A2-3.
1/5 Scale HTGR Core Horizontal Plan View and Strip Model

Figure A2-4. Spring Pack and Core Barrel Plate Characteristics

1

2

3

4

APPENDIX 3

DERIVATION OF DAMPING COEFFICIENT FOR SINGLE AND DOUBLE MASS SYSTEM

The equation of motion for the single mass system in Fig. A3-1 (in the absence of boundary motion) is

$$m_1 \ddot{x}_1 + c \dot{x}_1 + kx = 0 \quad (\text{A3-1})$$

In Eq. (A3-1), let

$$x = e^{st} \quad (\text{A3-2})$$

Therefore, taking derivatives,

$$\dot{x} = se^{st} \quad (\text{A3-3})$$

$$\ddot{x} = s^2 e^{st} \quad (\text{A3-4})$$

Substitution of (A3-2) through (A3-4) into (A3-1) yields

$$(m_1 s^2 + cs + k) e^{st} = 0 \quad (\text{A3-5})$$

We are interested in obtaining the two roots of s in (A3-5), which are

$$s = -\frac{c}{2m_1} \pm \sqrt{\left(\frac{c}{2m_1}\right)^2 - \frac{k}{m_1}} \quad (\text{A3-6})$$

Figure A3-1
Single Mass Boundary Impact Model

$k_s = \frac{k}{2}$, $C_s = \frac{C}{2}$, SINCE k_s AND C_s ARE SERIES VALUES OF k AND C

Figure A3-2
Double Mass Interelement Impact Model

The value of critical damping (c_c) can be obtained from (A3-6) by setting the discriminant equal to zero. This is accomplished below.

$$\frac{c_c}{2m_1} = \sqrt{\frac{k}{m_1}} \quad (A3-7)$$

Recasting Eq. (A3-7) produces

$$c_c = 2\sqrt{m_1 k} \quad (A3-8)$$

By definition

$$c = \xi c_c \quad (A3-9)$$

Substitution of (A3-8) into (A3-9) results in

$$c = 2\xi \sqrt{m_1 k} \quad (A3-10)$$

Equation (A3-10) is the expression utilized to calculate damping for the single mass system in Fig. A3-1.

The equations of motion for the double mass model depicted on Fig. A3-2 are:

$$m_1 \ddot{x}_1 + c_s (\dot{x}_1 - \dot{x}_2) + k_s (x_1 - x_2) = 0 \quad (A3-11)$$

$$m_1 \ddot{x}_2 + c_s (\dot{x}_1 - \dot{x}_2) - k_s (x_1 - x_2) = 0 \quad (A3-12)$$

Multiply (A3-11) by m_2 and (A3-12) by m_1

$$m_1 m_2 \ddot{x}_1 + c_s m_2 (\dot{x}_1 - \dot{x}_2) + k_s m_2 (x_1 - x_2) = 0 \quad (A3-13)$$

$$m_1 m_2 \ddot{x}_2 + c_s m_1 (\dot{x}_1 - \dot{x}_2) + k_s m_1 (x_1 - x_2) = 0 \quad (A3-14)$$

Subtract (A3-13) from (A3-14)

$$m_1 m_2 (\ddot{x}_2 - \ddot{x}_1) - c_s (m_1 + m_2) (\dot{x}_1 - \dot{x}_2) - k_s (m_1 + m_2) (x_1 - x_2) = 0 \quad (A3-15)$$

In Eq. (A3-15), let

$$y = x_2 - x_1 \quad (A3-16)$$

Therefore, taking derivatives

$$\dot{y} = \dot{x}_2 - \dot{x}_1 \quad (A3-17)$$

$$\ddot{y} = \ddot{x}_2 - \ddot{x}_1 \quad (A3-18)$$

Substitution of (A3-16) through (A3-18) into (A3-15) yields

$$m_1 m_2 \ddot{y} + c_s (m_1 + m_2) \dot{y} + k_s (m_1 + m_2) y = 0 \quad (A3-19)$$

In (A3-19), let

$$y = e^{st} \quad (A3-20)$$

Hence,

$$\dot{y} = s e^{st} \quad (A3-21)$$

$$\ddot{y} = s^2 e^{st} \quad (A3-22)$$

Substitution of (A3-20) through (A3-22) into (A3-19) produces

$$[m_1 m_2 s^2 + c_s (m_1 + m_2) s + k_s (m_1 + m_2)] e^{st} = 0 \quad (A3-23)$$

As before, we are interested in obtaining the two roots of s , which are

$$s = -\frac{c_s (m_1 + m_2)}{2 m_1 m_2} \pm \sqrt{\left[\frac{c_s (m_1 + m_2)}{2 m_1 m_2}\right]^2 - \frac{k_s (m_1 + m_2)}{m_1 m_2}} \quad (A3-24)$$

Critical damping here can be obtained by setting the discriminant of (A3-24) equal to zero. Therefore,

$$\frac{c_s (m_1 + m_2)}{2 m_1 m_2} = \sqrt{\frac{k_s (m_1 + m_2)}{m_1 m_2}} \quad (A3-25)$$

Setting $m_1 = m_2$, $c_s = \frac{c_c}{2}$, $k_s = \frac{k}{2}$ and solving for c_c , we obtain

$$c_c = 2\sqrt{m_1 k} \quad (A3-26)$$

For elements in contact (through series springs)

$$c = \frac{\xi c_c}{2} \quad (A3-27)$$

Substitution of (A3-26) into (A3-27) yields

$$c = \xi\sqrt{m_1 k} \quad (A3-28)$$

It should be noted that (A3-28) differs from (A3-10) by 2. Models which employ corner springs (as in MCOCO) have the following arrangements:

From Eq. (A3-10),

$$c_{TOTAL} = 2\xi\sqrt{km_1} = 2\xi\sqrt{2k_cm_1} \quad (A3-29)$$

$$c_{CORNER} = \frac{c_{TOTAL}}{2} = \xi\sqrt{2k_cm_1} \quad (A3-30)$$

From Eq. (A3-28)

$$c_{TOTAL} = \xi \sqrt{km_1} = \xi \sqrt{2k_c m_1} \quad (A3-31)$$

$$c_{CORNER} = \frac{c_{TOTAL}}{2} = \xi \sqrt{\left(\frac{k_c}{2}\right) m_1} \quad (A3-32)$$

Equations (A3-30) and (A3-32) are utilized to calculate damping for single mass-boundary and double mass interelement systems, respectively.

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