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Joel G. Bennett
Richard C. Dove

MASTER

los alamos
scientific laboratory
of the University of California
LOS ALAMOS, NEW MEXICO 87544

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PROPOSAL FOR ANALYSIS OF HTGR
CORE RESPONSE TO SEISMIC INPUT

by

Joel G. Bennett and Richard C. Dove

ABSTRACT

The scaling laws that govern the physical modeling of a high temperature gas-cooled reactor (HTGR) core are formulated and methods for step-by-step development and verification of both physical and analytical models are discussed. The analytical method is shown to be feasible and some one-dimensional results for a simple parameter study in problems involving impacting blocks are given.

I. INTRODUCTION

An important requirement of HTGR safety research is to assure the integrity of an HTGR core during seismic excitation. To meet this objective it is necessary to be able to predict the forces and motions of the various core elements under potential upset conditions. Due to a number of factors, it is not possible to do this using current state-of-the-art methods. These factors include the nature of the core structure itself, the large number of elements involved, the materials of construction, and the variability of the imposed loadings.

The approach being taken is to apply an analytical prediction method to determine the forces and motion experienced by the core blocks. This prediction method will be developed through mathematical modeling of all significant parameters and verified by the comparison of the results obtained with tests of physical models.

The system of loosely stacked graphite blocks which makes up the core of the HTGR presents a unique structural problem. Each one of the several thousand blocks has the kinematic capability of undergoing three translations and three rotations, therefore requiring six independent coordinates for a complete description of the motion. Resulting deformations and stresses are dependent upon graphite material properties which are known to vary with

time, temperature, radiation level, and loading history. It is apparent from the complexity of both material properties and geometries that any analysis (numerical or experimental) of this system will require a number of simplifications; hence, it is especially important that any analysis be designed to allow as complete validation as is possible of simplifications made and methods used. Assumptions regarding the general motion of the system, the mechanism of energy loss, the properties that govern system behavior, etc., should not be made intuitively. Rather, analytical and experimental models should be first designed for the specific purpose of determining permissible assumptions and the validity of methods which can later be applied to the analysis of the HTGR core.

General Atomic Corporation (G.A.) has been engaged in both analytical and scale modeling of the HTGR core for some time and its work in the area scale modeling must be considered as current state of the art. Therefore, a brief statement of G.A.'s program, as determined from available literature and conversations, will allow comparison of the program proposed in this document and the state of the art.

G.A. has constructed and tested a 1/5-scale core model using graphite blocks. In addition to photographic coverage, core blocks and spring packs

were instrumented to measure forces and motions. This is an impressive model in many ways and additional tests are planned. These include: (1) tests to measure dowel forces, (2) core support structure tests, (3) biaxial motion tests, (4) control rod insertion tests. It is not apparent, however, that all important parameters have been properly scaled and, if not, whether the effect of failure to scale is well understood. Parameters which may not be properly scaled include block density and stiffness, frictional forces, and energy loss mechanisms.

G.A. has conducted tests using full-size core blocks to determine the coefficient of restitution (e), and they have found it to be velocity dependent. It is known that, in general, coefficient of restitution is also shape and size dependent. Therefore, the use of a value of (e) determined from full size blocks for scale model analysis has no obvious basis. The scale model blocks are, by definition, of different size and since the hole pattern has been altered between the full size and the model block the shape factor has also been changed. The use of coefficient of restitution (e) as the principal parameter governing core block behavior seems questionable. Energy losses due to Coulomb friction may be more important and block stiffness might be more appropriately accounted for by use of material modulus.

For the above reasons, and because it will undoubtedly be desirable to use scale-model techniques to investigate a number of future HTGR core designs, we believe that more fundamental research in the use of scale models for the HTGR core is essential before model tests are used to investigate and verify a particular HTGR core design.

Physical model test results should be cross checked and possibly extended by means of analytical model solutions. Although G.A. has developed a number of analytical models and computer codes for their solution, it does not appear that comparison of results from the physical and analytical models has been possible to date.

It is recognized that the analysis of a system of blocks as large as that contained in the HTGR core must be restricted to a size that current generation computers can handle economically. Furthermore, since this system is inherently geometrically nonlinear, the current state-of-the-art methods require that a time history method of analysis be

used and such methods are computationally expensive. Because of these considerations it is tempting to assume that the impact phenomena and the resulting energy loss are the dominant features and to use an integrated form of Newton's Law, i.e., the impulse-momentum method.

As applied to this system, one possible method of approach is to express energy losses through the coefficient of restitution. Such an approach is subject to the following criticism. (1) Clearly, adjustment of the coefficient of restitution data to account for frictional losses is a necessary step if this is the only method used to account for energy loss. (The other alternative is to use an equivalent viscous damping term.) Because this system is not continuous but contains gaps between blocks, it may be that a static coefficient of friction or some equivalent break-away representation is an important parameter in the proper description of this system motion. Thus, it is not clear that either adjustment of coefficient of restitution data or an equivalent viscous representation of energy loss is a valid physical representation of the system. An accurate representation using static and kinetic frictional forces requires beginning the analysis with Newton's second law and performing two integrations to obtain displacement-time history. (2) The coefficient of restitution is not strictly a property of the material, but rather a function of material, the geometry and velocity of the colliding bodies. Geometry (external shape and internal hole pattern) and velocity dependent data for this value (e) must be available for central impact, oblique central impact, and eccentric impact. Also, the duration time of contact, which is a function of the wave speeds and geometry (external and internal) of the colliding bodies, must be an input to an impulse-momentum analysis. Thus, it is clear that an extensive experimental program to measure these parameters would have to be initiated for any proposed material or geometric design changes since an analysis based on this approach is invalid without such data.

In the sections which follow, scale modeling is analyzed and discussed and a suggested analytical program is formulated. A program is suggested which will allow step-by-step verification of scaling laws and methods of analysis. The proposed models, both analytical and physical, will initially involve

fewer and geometrically simpler elements than are actually present in the core structure but will permit selection of the parameters which control the core response to seismic excitation. These parameters, the relative effects of which must be well understood before an actual core model is constructed, include spring forces, block clearances, block locating techniques, block properties (stiffness, hysteresis loss), friction, etc. An especially important feature of the proposed approach is the simultaneous development of analytical and physical models of the identical system with progressive extension of both models to more complicated systems.

II. SCALE MODEL TESTING

It can be shown that the simple system in Fig. 1 is governed by the same parameters as is the more complicated HTGR core structure. For this system we may write:

$$X = \phi(\bar{X}, t, d, c, K, M, Q, E_1, E_n, \sigma_1, \sigma_n, D, \mu, g) \quad (1)$$

where the terms are defined as:

X = response motion of any point, a function of time (t)

$\bar{X}$ = input motion, a function of time (t)

d = block dimension

c = clearance

M = block mass

K = spring modulus

t = time

Q = any external force applied to a block (including friction)

$E_1 - E_n$ = moduli of elasticity of the block

$\sigma_1 - \sigma_n$ = stress levels used to define the stress vs strain characteristics of the block material

D = unloading modulus

μ = Poisson's ratio of the block material

g = gravitational constant

The terms E_1 , E_n , σ_1 , σ_n , and D are further defined in Fig. 2 where as many values of E and σ may be used as are required to define the shape of the stress-strain relationship. Internal energy loss is accommodated since the unloading curve is allowed to differ from the loading curve.

The input ($\bar{X}$) could, of course, be in terms of velocity ($\dot{\bar{X}}$), acceleration ($\ddot{\bar{X}}$) or force ($\bar{F}$) without affecting the analysis that follows; likewise, the response (X) of the system could just as well be in terms of velocity, acceleration or force.

These 15 terms can be arranged into 12 dimensionless groups which give

$$\frac{X}{d} = \psi \left(\frac{c}{d}, \frac{\bar{X}}{d}, \frac{Kd}{Q}, \frac{M}{t^2 K}, \frac{E_1 d^2}{Q}, \frac{g t^2}{d}, \frac{E_n}{E_1}, \frac{\sigma_n}{E_1}, \frac{\sigma_n}{\sigma_1}, \frac{D}{E_1}, \mu \right) \quad (2)$$

as the governing equation for both model and prototype. From this the following scale factors which relate the model (subscript 'M') to the prototype (subscript 'p') can be determined.

$$\text{Time scale: } N_t = \frac{t_p}{t_M} = \sqrt{N_d} \quad (\text{compute})$$

$$\text{Length scale: } N_d = \frac{d_p}{d_M} = \sqrt{\frac{N_M}{N_E}} \quad (\text{compute})$$

$$\text{or in terms of density } N_d = \frac{N_E}{N_\rho}$$

$$\text{Force scale: } N_Q = \frac{Q_p}{Q_M} = N_E N_d^2 \quad (\text{compute})$$

Spring modulus scale:

$$N_K = \frac{K_p}{K_M} = N_E N_d \quad (\text{compute})$$

$$\text{Mass scale: } N_M = \frac{M_p}{M_M} = N_\rho N_d^3 \quad (\text{select})$$

$$\text{Modulus scale: } N_E = \frac{E_p}{E_M} \quad (\text{select})$$

In addition, the four terms $\left(\frac{E_n}{E_1}, \frac{\sigma_n}{E_1}, \frac{\sigma_n}{\sigma_1}, \frac{D}{E_1} \right)$ indicate that the material used for the model must have stress-strain characteristics similar to the prototype material. Poisson's ratio (μ) should be the same for model and prototype material.

It is apparent that these scales and design conditions are very restrictive. For example, the simplest way to insure that model and prototype materials have the required similarity would be to

use the same material for both. However, this gives a value of unity for both density scale and modulus scale ($N_E = 1$, $N_\rho = 1$) which in turn dictates that the length scale be unity. Hence, a scale model is not possible unless some way is found to adjust the mass independent of material density. In many model tests this has been accomplished by adding lumped masses to structural members. However, calculations show that if 1/5-scale graphite blocks were used to model full-size graphite blocks, the model blocks would have to contain 70% (by volume) of lead. Clearly, such a modification could be expected to violate the requirement for similarity of other material properties.

If a different material is used for the model it must have a relatively smaller ratio of modulus (E) to density (ρ) than the prototype material (graphite). At first glance, this does not seem to be a difficult condition to fulfill--indeed a number of plastics have ratios of E to ρ which would result in length scales of between 5 and 10, i.e., the plastic model would be between 1/5 and 1/10 the size of the graphite prototype. However, if stresses in either the model or the prototype exceed a value beyond which the material behavior can be described in terms of a single modulus value (E_1 , see Fig. 2) there is no immediate assurance that the model and prototype will exhibit the required similarity.

If the gravitational constant (g) is omitted from the governing variables in Eq. (1) the term ($\frac{gt^2}{d}$) does not appear in Eq. (2). For this case the length scale ($N_d = \frac{d_p}{d_m}$) can be selected as any desired value since it is independent of the density scale (N_ρ) and the modulus scale (N_E). For this case (g, omitted) if the same material is used for the model and prototype, the time scale (N_t) is equal to the length scale (N_d). Now the question is: What is the effect of omitting "g"? Or: Does the behavior of the system depend upon "g"? The force of gravity does, of course, affect this system since frictional forces are proportional to normal forces which are dependent on the weight (hence, "g") of the blocks and any vertical acceleration resulting from coupling of horizontal inputs or from vertical inputs. To omit "g" is to distort all frictional damping effects. Furthermore, in the HTGR core there are stacks of blocks and if vertical

excitation (the vertical component of the ground motion) produces vertical motion, response as depicted in Fig. 3 is possible. In Fig. 3 the dotted lines represent possible response motions which must be influenced by a vertical restoring force, i.e., gravity.

For these reasons a "true" scale model will probably not be feasible.* However, physical model testing offers two other possibilities. First, a physical system can be designed as the system to be mathematically modeled. This will allow verification of the mathematical model and its solution and it, in turn, can be extended. Second, an "adequate" scale model may be possible.** This will require tests specifically designed to determine the effect of failure to faithfully scale one or more of the variables discussed above. Results from these tests (for example, a test to determine the effect of failure to exactly model gravitational effects) should make it possible to use an adequate scale model to make valid predictions for the prototype.

It should be pointed out that in this analysis internal energy loss has been included by allowing for a hysteresis loop in the stress-strain diagram rather than by inclusion of a coefficient of restitution (e) as a governing variable. The reason for this is that coefficient of restitution (e) is difficult to isolate as a material property since test system parameters such as size, shape and velocity of impact influence the numerical value obtained for "e". Furthermore, energy loss during a collision process is not uniquely related to a given value of "e"; rather, for any given "e" the energy loss depends on the relative masses and relative velocities involved.

III. ANALYTICAL PROGRAM

A. Formulation

The current analytical method under development for this study involves the use of the so-called

*Murphy (Similitude in Engineering) defines a true scale model as follows: "True models are models in which all significant characteristics of the prototype are faithfully reproduced to scale."

**Murphy defines an adequate scale model as follows: "Adequate models are models from which accurate predictions of one (or more) characteristics of the prototype may be made, but which will not necessarily yield accurate predictions of other characteristics."

component element method combined with an equilibrium iteration procedure.

Figure 4 illustrates a flowchart of the equilibrium iteration scheme currently being used. The philosophy of the scheme is basically to trace the time history of each block through a succession of equilibrium states, each new state being based on the previous configuration.

The first step for this procedure is to determine the initial acceleration of each block from equilibrium considerations ($\Sigma F = Ma$). This step assumes that the temporal history of the displacement of the boundary is known. The initial forces are found from force-displacement curves.

The accelerations from this step are extended forward in time by predicting the acceleration that will exist at the end of a small time increment. This predicted acceleration is then integrated twice using any reasonable time integration scheme, such as the Newmark β or Wilson θ or other methods. The current program makes use of the Newmark method with $\beta = 0.25$ for which it is well known that the expressions for velocity and displacement are simple finite difference expressions of the truncated Adams type [1]. Using these displacements, the corresponding forces on all blocks must be determined from known force-displacement information. A typical force-displacement curve for block contact forces is shown in Figure 5. Figure 5a represents the block as a linear force-displacement element with stiffness equal to AE/ℓ , where A is cross-sectional area, ℓ is block thickness, and E is modulus of elasticity. It should be recognized that the method described can be used equally well for more sophisticated (nonlinear) force displacement elements. See Fig. 5b as an example. In general, however, the more sophisticated the force-displacement information, the more costly the time history analysis will be.

All forces, as determined from computed displacements, are now applied to the blocks and their corresponding accelerations are determined from equilibrium considerations. These new accelerations are compared to the ones which were predicted and if they agree to within a given percentage tolerance, an equilibrium state has been attained.

In this case, time is incremented and the equilibrium state is recorded as the time history of the system.

For the case where agreement is not obtained with predicted values, the accelerations found from applying the force-displacement information are used as a new prediction, and the integration step is repeated. This iteration process is continued until agreement is obtained.

In order to illustrate the various effects that may be included, consider the free body diagram (FBD) of a given block shown in Figure 6. The effects of friction, normal contact, dowel pin forces, and clearances between blocks and between pins can be represented using this FBD and the proper force-displacement information.

B. Preliminary Investigations and Results

The purpose of this section is to give a "Proof of Method" illustration and to show the flexibility of this formulation for small-scale parameter studies. The advantage of such studies is obvious. A good "feel" for the relative importance of the various physical parameters can be obtained at a minimum of cost. This can be used to some advantage in analytical studies, but more importantly it can eliminate the necessity of considering certain physical model parameters, as will be illustrated.

Figure 7 shows the four-block representation of the sample problem studies. It is in no way meant to be representative of a slice from an HTGR core. However, it is used here to represent some of the various effects believed to be of importance in the response of such a core.

Figure 8 illustrates the computer-produced time history of the four-block system undergoing frictionless impact. Note that the vertical scales are different. At time t_1 on Fig. 8 the wall impacts block 1 which immediately leaves the wall and moves ahead to impact block 2 at time t_2 . Having transferred all its momentum, block 1 is then at rest until time t_3 when it is struck by block 2 as the rebounding sequence of impacts occur. Using Fig. 8, the initial sequence of impacts may be traced to the fixed wall. Note that since the moving wall has moved to the left at time t_3 , the first block undergoes a corresponding negative displacement to "catch up" with the wall at t_3 and

rebound from it again. This behavior is a preliminary indication of the importance of forcing frequency to the system response.

Two further observations can be made concerning these curves. First, the time for which the first block is at rest after impacting the second and before the second rebounds to impact the first, t_2 until t_8 , is unexpectedly long. This is the case since the first block, having no frictional force to resist motion, is impacted by the wall but immediately separates from it with very little momentum transfer.

The second observation that can be made is that the displacement curves during "rest" periods for the blocks are not perfectly flat, indicating the block had some residual momentum after impact. This lack of flatness is indicative of the numerical error that occurs because impact and/or separation occurs during the small time increment that is used to approximate the continuum time. This error may be made as small as deemed necessary by the reduction of the time increment, but a corresponding increase in computational cost will result. In energy dissipative systems this residual momentum will quickly be lost.

Figure 9 illustrates the displacement-time history for the same system when friction is included. In this case the forcing function was given an amplitude of 1.27 cm (0.5 in) in order to insure that more than one impact occurs. Even so, the values of the static and kinetic friction coefficients are such that the third block does not move far enough to strike the fourth one.

The friction model used here is believed to be more representative of the actual case than that of the so-called local stiffness representation which has been suggested by Levy [2]. In the present model, if relative velocity exists between two surfaces, the friction force is the kinetic value. If no relative velocity exists, then the friction force computed is that value necessary for equilibrium. This computed force is compared with the "break-away" value of $\mu_s N$ where μ_s is the static coefficient of friction and N is the normal force between the surfaces, and if this force is greater than the break-away value, then the break-away value is applied for this time step. Just how effective such a representation is may be seen by

examining the curve for block 1 in Fig. 9. The "waviness" that occurs is the block being "chattered" along by the wall as it is forced to move in an alternating break-away/impact sequence. The kinetic friction coefficient is high enough such that the wall just "pushes" the blocks along.

To illustrate that this is indeed the interpretation of these curves (i.e., someone might question if this waviness is numerical error or instability) the exact same case is illustrated in Fig. 10 but with the kinetic coefficient of friction reduced from 0.2 to 0.01. A quite different behavior of the system may be seen to occur as the first block is observed to break away from the wall, impact the second block, be hit by the wall and break away again, etc. Note the bouncing around of the fourth block as it alternately bounces off the fixed end wall and the third block.

It is obvious from the results presented thus far that the mechanism of Coulomb frictional energy dissipation is a very important parameter in the proper modeling of this system. It is also obvious that if we let the normal force between the block's bottom surface and the floor vary from zero to, say, W (the weight of a block) as it would if the blocks were given a vertical acceleration, then the behavior of the system would vary between that of Fig. 9 and Fig. 10. This point also illustrates the potential error in neglecting g in the scale model tests for the vertical or combination vertical/horizontal excitation cases.

As a final illustration of the ability of this analytical model to be of value when coupled with an experimental study, the importance of the variation of stiffness may be seen by examining Fig. 11 and Fig. 12. These figures, plotted to the same vertical scale, represent a variation in block stiffness of two orders of magnitude. Although the curves appear to be identical, these results do not indicate that stiffness is negligible in obtaining the stresses that exist or the accelerations that will occur over very short time spans, but rather that stiffness has less effect on the displacement and velocity of the individual blocks than do other parameters such as friction and/or gap size. This means that in the physical model, block-to-block variation in stiffness might be neglected. It may also be an indication that

reasonably small nonlinearities in material properties may not be a strong consideration in predicting displacements and velocities.

A computer-generated movie, which very clearly shows the total pattern of block motion, has been produced for sample problems similar to those just discussed. This method of presentation will be continued as progressively more complex systems are studied because the movie is an especially useful method for showing overall displacement patterns and for comparison to physical test results which can easily be recorded photographically.

One further point concerning the analytical model formulation given here may be mentioned. It is a relatively simple matter to include material hysteresis energy losses by having both loading and unloading information in the force-displacement curves. Such a model is representative of the actual material behavior.

An analytical study of this same problem (i.e., seismic response of a block type core), conducted by the Japan Atomic Energy Research Institute, has recently become available. (See Reference 3.) This study, based on a code titled "PRELUDE-2," presents several one-dimensional solutions for the displacements, forces, and accelerations experienced by a system of core blocks. This study uses the basic "Force-Mass-Acceleration" approach and includes dowel pin forces and Coulomb friction. However, it does not distinguish between static and kinetic coefficients of friction and, hence, the "break-away" phenomenon is not represented. The size and complexity of systems to be analyzed may be limited by the fact that the analysis has apparently been done on a FACOM 230-60 computer with a cycle time of 0.92×10^{-6} seconds and a memory size from 32K to 256K, 36-bit words with up to 4M words of slower extended core added [4].

This and any follow-on studies which may be conducted by the Japan Atomic Research Institute may be very useful for comparative purposes.

IV. RECOMMENDATIONS

Since the design conditions for a "true" scale model appear to be prohibitively restrictive, "adequate" models should be investigated. All scale models should be "verified" to guard against unknown and unintentional distortions (e.g., failure

to scale small dimensions, such as roughness; failure to include an important variable in the analysis) and models deliberately designed as "adequate" models must certainly be "verified." Verification can be accomplished by comparison of results of one model (say, a 1/5-scale model) to results obtained from a second model (say, a 1/2-scale model) and/or by comparison of model results to an analytical solution. We suggest the use of a simplified analytical model to guide the design of an appropriate "adequate" model. Following this, several simplified scale models should be constructed, tested, and verified. This verification must be completed before a scale model of the actual prototype is designed, constructed, or tested. Continuing analytical work should allow at least partial correlation with final model tests.

It is recommended that an analytical solution be used to determine the relative effect of the various parameters, such as friction, modulus of elasticity, boundary spring stiffness, etc. With this guidance several scale models can be constructed and tested to verify the adequacy of these models for predicting the desired system characteristics. As a second step, both the analytical and the scale models should be extended to more complicated geometries with more degrees of freedom (i.e., more blocks).

The analytical results that have been presented here for the geometrically simple problems being studied are useful in designing this actual physical model as well as illustrating the flexibility of the proposed analytical scheme. It is believed that at this stage of the investigation a fundamental approach is necessary and that the scheme presented here represents a more fundamental one than others currently in use.

The present one-dimensional model should be extended to add more element components. Pin forces and clearances and the capability of including a "column" effect should be added. These changes, which will require some additional programming effort, can be used in conjunction with a parameter study which would include variation in forcing function frequency, gap size, and hysteretic losses. The study should be conducted in preparation for the physical model design.

A longer range effort should involve adding side walls and supports which are spring-coupled to the current side walls and supports in order to simulate the proposed physical model. Extension to a vertical plane model four blocks high is considered to be a major step in predicting the physical model behavior. Once this is accomplished the extension to a three-dimensional model including block translation and rotation could begin. These steps should be taken simultaneously with the experimental program since the assumptions necessary for the analysis require that the physical behavior be clearly understood.

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Fig. 1. System analyzed.

Fig. 2. Definition of material properties.

Fig. 3. Model for vertical motion analysis.

Fig. 4. Equilibrium iteration scheme.

Fig. 5. Typical force displacement curves for simple linear and nonlinear models.

Fig. 6. FBD of physical model component

Fig. 7. Sample problem studied

Fig. 8. Displacement--time history of the sample problem undergoing frictionless impact

Fig. 9. Displacement--time history of sample problem with high static and kinetic friction.

Fig. 10. Displacement--time history of sample problem with high static and low kinetic friction.

Fig. 11. Displacement--time history of first three blocks for decreased stiffness.

Fig. 12. Displacement--time history of first three blocks for increased block stiffness.