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HTGR FUEL ELEMENT COLLISION DYNAMICS TEST PROGRAM

by

S. M. RODKIN and B. E. OLSEN

**Prepared under
Contract EY-76-C-03-0167
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for the San Francisco Operations Office
Department of Energy**

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ABSTRACT

This report presents the results of a test program which investigated the collision dynamics phenomena of HTGR graphite fuel elements of 1/5-, 1/2-, and full-scale. It established the coefficient of restitution and contact time for these elements as a function of impact velocity.

The application of the scaling laws to the collision dynamics parameters of these elements was also investigated.

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1. INTRODUCTION

Earlier tests with a pendulum test rig (Ref. 1), established the coefficient of restitution (e) for a standard full-scale LHTGR fuel element (0.625 in. fuel hole, 0.828 in. coolant hole) of H-327 graphite as 0.3. This value of e was quoted at 50 in./sec; although e was observed to vary with the impact velocity (increasing with increasing velocities), 50 in./sec represents a maximum expected value of fuel element impact velocity for an Operating Basis Earthquake (O.B.E.).

The subject tests were conducted to verify the 1/5- and 1/2-scale element designs, which are used in the HTGR core seismic test models. Furthermore, this test program provides parameter input and correlation points for the analytical models used to calculate core seismic design loads (Ref. 2). Since the fuel element graphite in future HTGRs is likely to be of type H-451, repeated full-scale element tests were also performed with this material to establish any differences in the collision dynamics parameters.

2. OBJECTIVES

The specific objectives of this test program were as follows:

1. Verify the value of e for the $1/5$ - and $1/2$ -scale elements previously designed and determine the functional relationship of e to the element impact velocity.
2. Provide additional $1/5$ - and $1/2$ -scale test data in terms of contact time (ct) for two element collisions and post-impact velocity distribution for multiple element collisions and boundary collisions.
3. Obtain similar data for full-scale prototype fuel elements made of H-451 graphite.
4. Evaluate the application of the employed scaling laws to the parameters of collision dynamics.

3. SUMMARY

The objectives were achieved through pendulum tests and linear track tests on 1/5-scale elements and through linear track tests on 1/2- and full-scale elements. All collisions were nominally flat-on collisions involving the long side of each element. The pendulum tests consisted of impacts of two elements moving toward each other with approximately equal velocity just prior to impact. Similar tests of two elements moving toward each other were performed on the linear tracks. In addition, impact tests on the linear tracks were performed with one element moving and one element stationary prior to impact, one moving and two stationary, etc., and also with one or more moving elements impacting nearly rigid boundaries. The velocities just prior to impact ranged from 8 to 50 in./sec.

The results of all testing are presented as plots of the various parameters versus impact velocity. A linear regression (least squares) line (Appendix A) was drawn on most plots so that trends can be clearly observed and compared. The standard deviation of the data points about the regression line is shown in some figures. Each parameter is shown separately for the 1/5-, 1/2-, and full-scale results. In some instances, normalized composite plots comparing 1/5-, 1/2-, and full-scale results are shown.

4. OBSERVATIONS AND CONCLUSIONS

The following observations and conclusions were made from the analyzed test data:

1. The values of e tend to increase with impact velocity in the range tested.
2. The mean values of e at impact velocities of 50 in./sec for the 1/5-, 1/2-, and full-scale element of H-327 graphite are 0.33, 0.45, and 0.30 respectively.
3. A composite plot of all H-327 e data from the 1/5-, 1/2-, and full-scale tests indicates good correlation of 1/5- and 1/2-scale data with full-scale, although considerable data scatter exists.
4. The mean e value for H-451 graphite at 50 in./sec is 0.52 (full scale LHTGR standard element), which is higher than e for H-327 graphite.
5. The ct tends to decrease with increasing impact velocities.
6. For 1/5-, 1/2-, and full-scale elements of H-327 graphite, the ct at 50 in./sec are approximately 0.20, 0.75, and 2.00 msec respectively.
7. The 1/5- and 1/2-scale ct are lower than normalized full-scale values, indicating that the model fuel elements are stiffer than the scaling laws would predict.

8. The ct minimum for H-451 graphite (full-scale LHTGR standard element) was lower than the ct for H-327 graphite. This was expected since H-451 has a higher elastic modulus.
9. For the case of one moving element impacting a series of stationary elements, the post-impact momentum distribution among the elements as a function of impact velocity was similar for all scales tested. The post-impact momentum ratio of the extreme element in each series increases with increasing impact velocity, whereas the post-impact momentum of the impacting element decreases with increasing impact velocity. The post-impact momentum distribution of intermediate elements in the series ranges from a decrease with increasing impact velocity for those nearest the initial impact site to an increase for those farthest away (nearest the extreme element).
10. Momentum distribution trends similar to those described in paragraph 7 were observed for collisions of two or more elements with the boundaries.
11. The full-scale H-451 graphite elements withstood impact accelerations of 293 g without apparent damage.
12. The internally mounted strain gages, calibrated for static loads, yielded inconclusive data. This was probably caused by the varying nature of the stress wave propagation from the dynamic loading, which was not always flat-on.

5. TEST PROGRAM

5.1. TEST ITEM SCALING

A set of scaling laws was produced for the tests representing the fuel element model design parameters and the response parameters of importance. These parameters and their basic variables are given in Table 5-1.

The variables were reduced to a set of nondimensional relationships which represent the model similitude requirements. These are given in Table 5-2.

The scale factors for element lengths (λ) were chosen as 1/5 and 1/2 for the two models. Graphite was chosen as the element material, specifically H-327 graphite for the 1/5- and 1/2-scale elements and H-451 graphite for the full-scale elements. The choice of graphite meant that the following restrictions were imposed:

$$\rho_m = \rho$$

and

$$E_m = E$$

Using these relations in similitude requirements No. 3, 4, 5, and 6 of Table 5-2, the relationships of time, velocity, acceleration, and force between each model and the full scale can be readily expressed (see Table 5-3). The relationships in Table 5-3 hold true for horizontal motion along a plane if similitude requirements No. 1 and 2 of Table 5-2 are met. The requirement for similarity of shape (No. 1 of Table 5-2) was met only with regard to the outer surfaces of the 1/5- and 1/2-scale

TABLE 5-1
LIST OF VARIABLES

	Basic Variable	Dimension
Model length	l	L
Shape factor	s	--
Time, contact time	t	T
Element velocity	$\dot{d}$	LT^{-1}
Element acceleration	$\ddot{d}$	LT^{-2}
Element density	ρ	$FL^{-4}T^2$
Young's modulus	E	FL^{-2}
Coefficient of restitution	e	--
Impact force	f	F

TABLE 5-2
MODEL SIMILITUDE REQUIREMENTS

1. $s_m = S$
2. $e_m = e$
3. $\rho_m \dot{d}_m l_m / E_m = \rho \dot{d} l / E$
4. $\ddot{d}_m t_m^2 / l_m = \ddot{d} t^2 / l$
5. $\dot{d}_m t_m / l_m = \dot{d} t / l$
6. $f_m / E_m l_m^2 = f / E l^2$

Note: subscript m = model.

TABLE 5-3
SUMMARY OF MODEL SCALING LAWS

$$l_m = \lambda l$$

$$\dot{d}_m = \dot{d}$$

$$\ddot{d}_m = \frac{1}{\lambda} \ddot{d}$$

$$t_m = \lambda t$$

$$e_m = e$$

$$f_m = \lambda^2 f$$

elements, since the geometry of some 208 internal fuel and coolant holes was ignored.

It was attempted to achieve the correct coefficient of restitution with 1/5- and 1/2-scale elements (No. 2 of Table 5-2) by employing alternate internal hole patterns. The correct element weights were achieved within the constraints of similitude requirement No. 2 by means of metal inserts.

The design of the model elements was carried out on the basis described. The test results obtained in terms of coefficient of restitution and contact times are included in Section 6 as a comparison of 1/5-, 1/2-, and full-scale values.

The element dimensions, weights, and hole configurations are given in Table 5-4.

5.2. TEST CONTRACTORS

The 1/5- and full-scale H-327 element pendulum tests were performed by the Norco, California Division of Wyle Laboratories.

The 1/5- and 1/2-scale H-327 element linear track tests were performed by the students of the Harvey Mudd College Engineering Clinic under the direction of the Professors of Engineering at Harvey Mudd College, Claremont, California.

The full-scale H-451 element linear track tests were performed by the Ogden Division of Approved Engineering Test Laboratories of Fullerton, California. Similar test equipment and test methods were used for all linear track tests.

TABLE 5-4
TEST ITEMS

Scale	Weight (lb)	Height (in.)	Dimension Across Flats (in.)	Configuration (Number, Location, and Diameter of Holes)
1/5	2.29 ^(a)	6.24	2.84	One central through hole 1-3/4 in.
1/2	32.4 ^(a)	15.6	7.1	One central through hole 1.95 in., 6 through holes 1.92 in. diameter on 2.38 in. radius. 6 aluminum plugs 3.96 in. long x 1.92 in. diameter centered at mid-height. Light press fit. ^(b)
Full	260 ^(a)	31.2	14.2	Prototype fuel and coolant holes with loose-fitting steel rods, simulating the fuel rods, added to obtain the weight shown.

(a) Includes test fixture weight.

(b) This configuration was arrived at following numerous tests of various combinations of hole size and arrangement. The correct (scaled) weight and desired coefficient of restitution are obtained.

5.3. TEST EQUIPMENT

5.3.1. Pendulum Test Rig

The pendulum test rig is shown in Fig. 5-1. The framework supporting the graphite elements was made of small-diameter, thin-wall aluminum tubing; consequently, its weight and rotary inertia were small compared with that of the graphite elements. Bearings were used at the pivot points. Tests confirmed that friction and windage losses were negligible.

5.3.2. Test Track

The full-scale test track is shown in Fig. 5-2. Figure 5-3 shows the method of attaching the graphite elements to the track. Similar test equipment was used for the 1/5- and 1/2-scale tests except that the roller bearings, the brackets, and the track were reduced in size, and the rods tying the brackets together ran outside the elements (Fig. 5-4) rather than through coolant holes as for the full scale.

In all cases adequate track supports were provided to prevent sag under load from exceeding acceptable values. All test tracks were level and all horizontal and vertical alignment was carefully checked.

Acceleration of all elements to the desired pre-impact velocity was performed manually.

5.3.3. Boundary

A nearly rigid bumper simulating the HTGR core boundary was provided for each of the 1/5-, 1/2-, and full-scale multi-element boundary collision tests.

The 1/5- and 1/2-scale boundary stiffness values were scaled according to the scaling relation $K_m = \lambda^2 K_p$, where K_m is the model stiffness, K_p is

Fig. 5-1. One-fifth-scale pendulum collision test fixture

Fig. 5-2. Over-all view of full-scale test set-up for multi-element collision with boundary

Fig. 5-3. Typical attachment fixture arrangement

Fig. 5-4. One-fifth-scale boundary

the prototype stiffness, and λ is the scale factor. The actual boundary stiffness values obtained are indicated in Table 5-5. The 1/5-, 1/2-, and full-scale boundary test rigs are shown in Figs. 5-4, 5-5, and 5-6, respectively.

TABLE 5-5
BOUNDARY STIFFNESS

Scale	Stiffness (lb/in.)
1/5	468,000
1/2	1,560,000
Full	6,000,000

Figure 5-4 shows construction details of the 1/5-scale boundary test rig. The 1/2-scale boundary test rig was scaled up to provide the required higher stiffness.

5.4. INSTRUMENTATION

The instrumentation for all tests is listed in Table 5-6 and described below.

5.4.1. 1/5-Scale Pendulum Test

One rotary potentiometer was used on each of the two pendulum arms. Each produced a signal proportional to angular displacement. These signals were recorded on oscillograph paper, providing traces proportional to angular displacement versus time. Impact and rebound velocities were obtained using the relation

$$V = r\omega$$

TABLE 5-6
INSTRUMENTATION

Test	Transducer Type
Pendulum Test	Rotary potentiometer
Linear Track Tests	
1/5-scale inter-element	Velocity sensors, contact time circuit
1/5-scale boundary	Velocity sensors, boundary load
1/2-scale inter-element	Velocity sensors, contact time circuit, element strain gages
1/2-scale boundary	Velocity sensors, boundary load
Full-scale inter-element	Velocity sensors, strain gages, acceler- ometers, contact time circuit
Full-scale boundary	Velocity sensors, element strain gages accelerometers, contact time circuit, boundary load

Fig. 5-5. One-half-scale test rig

Fig. 5-6. Full-scale boundary test rig

where V is linear velocity, r is the mean radius to the center of each element and ω is the angular velocity in radians per second obtained by differentiating each displacement versus time trace.

5.4.2. Linear Track Tests

5.4.2.1. 1/5-Scale Linear Track Test. This test employed spark generators and paper tape to produce records of displacement versus time from which velocity was obtained by differentiation. Two spark electrodes were fixed to each element and connected to the spark generator by thin trailing wires. Two spark electrodes and two strips of paper were used to provide separate, distinct records of forward (+) and backward (-) displacement. A switching device was used to switch the voltage from one electrode to the other at the appropriate time.

Contact time was obtained in this test by passing current through the elements and using them as the contactors in a make-break circuit. The current traces were displayed on an oscilloscope and photographed for record purposes.

A signal proportional to boundary load versus time was obtained from strain gages mounted on the boundary structure as shown in Fig. 5-4. The boundary test rig was statically calibrated in a Riehle testing machine to obtain load magnitude from the strain gage signals. Dry cell batteries were used to insure constant excitation voltage to the strain gage circuit. Temperature-compensating strain gages were not used; however the circuit was balanced prior to each run.

5.4.2.2. 1/2-Scale Test. Element velocity and boundary load were obtained in the same manner as in the 1/5-scale tests. Contact time was obtained in a manner similar to that used in the 1/5-scale tests except that a 2-in. square thin brass strip insulated from the element was used as one side of

the contact switch. The brass strip was 0.001-in. thick and the insulating paper was 0.002-in. thick for a total of 0.003 in. Both strips were glued in place at the center of the contact face of one element. The lead wire was brought out through a 1/4-in. hole drilled perpendicular to the face and intersecting one of the large longitudinal holes. This arrangement provided greater safety than the 1/5-scale method in that voltage was applied to the graphite elements only during the short contact time rather than continuously.

To measure internal load, two strain gages were installed in one element. The gages were installed on the inner surface of one of the 1.92-in. diameter holes adjacent to one of the impact faces and were oriented to respond to strain in the direction of motion of the element. One gage was at each end of the element, 1.5-in. in from the edge.

Static compressive loads were incrementally applied in several across-the-flats orientations to obtain the relationship between applied load and strain gage signal. The calibration data were erratic. Reliable load measurement could not be obtained.

5.4.2.3. Full-Scale Test. Velocity data were obtained from the displacement indicator shown in Fig. 5-7. The device consisted of a linear gear with the inter-tooth spaces filled with potting compound. The tooth pitch was 0.196 in. A wiper arm attached to the element provided a make-break circuit depending upon whether it contacted a gear tooth or the nonconductive potting compound. The displacement data represented by the make-break information were recorded on oscillograph paper, which provided timing references. Velocity was then obtained by differentiation of the oscillograph trace. A wiper arm was attached to each element and the signal from each was recorded on a separate oscillograph trace.

Contact time was obtained by a method similar to that used for 1/2-scale tests. Four 0.001-in. thick contact strips were used, each

Fig. 5-7. Full-scale displacement sensing device

approximately 1/2 in. x 3/4 in. They were placed at the four corners of the impacting face of the element. A nonconducting adhesive was used to attach the strips.

Strain gages for load measurements were installed on the inner surface of the coolant holes in three of the elements. Two coolant holes were selected for application of strain gages. These were adjacent to the flat contact surfaces. One strain gage was installed near one end of each coolant hole. The strain gages were calibrated for load in the direction of element motion by applying incremental static compressive loads in this direction only and obtaining plots of applied load versus strain gage signal. Two accelerometers were installed on each of the same three elements, in the same coolant holes as the strain gages but at opposite ends. Thus each of the two selected coolant holes had a strain gage near one end and an accelerometer near the other end. The sensitive axis of each accelerometer was oriented in the direction of motion of the elements.

Boundary load was obtained from the load cell in the same manner as in the 1/2- and 1/5-scale tests, except that a calibration test to obtain signal output as a function of load was not performed, since a static calibration record was already in existence. A load versus deflection test was performed on the load cell to determine its spring rate (Table 5-5). A hydraulic testing machine was used to apply the load and dial gages were used to measure the deflection of the sensing element.

5.5. TEST PROCEDURE

The track test procedures for the 1/5-, 1/2-, and full-scale elements were similar. Each consisted of manually accelerating one or more elements to approximately the desired velocity and releasing them to continue at essentially constant velocity until impact with either one or more stationary or moving elements. Similar tests were also performed impacting against an approaching element or against a boundary support. The appropriate transducer signals were recorded for each trial.

Prior to each trial the elements were realigned as necessary to insure flat-on collisions. This precautionary measure was observed during all tests including the pendulum tests.

The pendulum tests consisted of drawing both 1/5-scale elements back an equal angular distance, simultaneously releasing them, and recording the transducer signals indicating impact and rebound velocity.

The test conditions are tabulated as shown below.

Linear Track Tests

One-fifth-scale inter-element tests	Table 5-7
One-fifth-scale boundary tests	Table 5-8
One-half-scale inter-element tests	Table 5-9
One-half-scale boundary tests	Table 5-10
Full-scale inter-element tests	Table 5-11
Full-scale boundary tests	Table 5-12

Pendulum Tests

One-fifth-scale	Table 5-13
-----------------	------------

TABLE 5-7
ONE-FIFTH-SCALE INTER-ELEMENT TEST CONDITIONS

Sequence Number (a)	Pre-Impact Element Configuration (b)	Impact Velocity (in./sec)
1	() ()	9.4 to 49.25
2	() () ()	16.3 to 59.3
3	() () () ()	25.1 to 55.6
4	() () () () ()	16.8
5	() () () ()	26.4 to 57.2

(a) Each sequence consisted of 6 to 15 trials.

(b) Each set of parentheses represents one element. The left-hand element or group of elements was in motion and the right-hand group was stationary prior to impact.

TABLE 5-8
ONE-FIFTH-SCALE BOUNDARY TESTS

Sequence Number (a)	Number of Grouped Elements Impacting Bumper	Impact Velocity (in./sec)
1	()	9 to 43.5
2	() ()	10.2 to 34.5
3	() () ()	15 to 36.5
4	() () () ()	12 to 42.5
5	() () () () ()	15.6 to 39.5

(a) Each sequence consisted of 14 to 51 trials.

TABLE 5-9
ONE-HALF-SCALE INTER-ELEMENT TEST CONDITIONS

Sequence Number (a)	Pre-Impact Element Configuration (b)	Impact Velocity (in./sec)
1	() ()	8.5 to 46.9
2	() () ()	10.7 to 39.4
3	() () () ()	12.5 to 39.7
4	() () () ()	8.2 to 47.3
5	() () () () ()	13.5 to 47.8

(a) For sequence 1, the elements were in motion toward each other with approximately equal velocity. For sequences 2 through 5 the left hand element or group of elements was in motion prior to impact and the right hand group was stationary. Each sequence consisted of approximately 20 trials.

(b) Each set of parentheses represents one element.

TABLE 5-10
ONE-HALF-SCALE BOUNDARY TESTS

Sequence Number (a)	Number of Grouped Elements Impacting Bumper	Impact Velocity (in./sec)
1	()	7.9 to 42.9
2	() ()	33.1 to 42

(a) Each sequence consisted of approximately 15 trials.

TABLE 5-11
FULL-SCALE INTER-ELEMENT TEST CONDITIONS

Sequence Number (a)	Pre-Impact Element Configuration (b)	Impact Velocity (in./sec)
1	() ()	9 to 50.25
2	() () ()	13.3 to 58.8
3	() () () ()	12.9 to 58
4	() () () () ()	12.6 to 53.9
5	() () () () () ()	9.8 to 52.5
6	() () ()	11.8 to 49.4
7	() () () ()	10.3 to 45.2
8	() () () () ()	9.3 to 50.7
9	() () () () () ()	11.2 to 52
10	() () () ()	12 to 47.4
11	() () () () ()	10.9 to 47
12	() () () () () ()	11.5 to 53
13	() () () () ()	9.8 to 45.2
14	() () () () () ()	9.7 to 50.3
15	() () () () () () ()	9.5 to 48
16	() () () () () () () ()	11.2 to 47.9

(a) For sequences 1 through 15 the left-hand element or group of elements was in motion prior to impact and the right-hand group was stationary. For sequence 16 the elements were in motion toward each other with approximately equal velocity. Each sequence consisted of five to eight trials.

(b) Each set of parentheses represents one element.

TABLE 5-12
FULL-SCALE BOUNDARY TESTS

Sequence Number ^(a)	Number of Grouped Elements Impacting Bumper	Impact Velocity (in./sec)
1	()	9.1 to 50.3
2	() ()	10.9 to 48.2
3	() () ()	9 to 50.3
4	() () () ()	10.4 to 50.7
5	() () () () ()	13 to 52.5
6	() () () () () ()	9.4 to 50.7

(a) Each sequence consisted of five trials.

TABLE 5-13
ONE-FIFTH-SCALE PENDULUM TEST CONDITIONS

Sequence Number (a)	Pre-Impact Element Configuration	Impact Velocity (in./sec)
1	() ()	10.7
2	() ()	16.5
3	() ()	21.5
4	() ()	26.8

(a) Sequence 1 consisted of one trial. Sequences 2, 3, and 4 each consisted of three trials.

6. RESULTS AND DISCUSSION

The test data were used to generate the following collision characteristics as functions of impact velocity for the 1/5-, 1/2-, and full-scale elements except as noted:

1. Coefficient of restitution.
2. Contact time.
3. Ratio of post- and pre-impact velocities for collisions which involved more than two elements.
4. Ratio of post- and pre-impact velocities for boundary collisions involving two or more elements.
5. Boundary forces.
6. Impact acceleration (full-scale only).

6.1. COEFFICIENT OF RESTITUTION

The coefficient of restitution test results as functions of impact velocity for the two element collision tests are shown in the following figures.

Full-scale	H-327 graphite	Fig. 6-1
One-fifth-scale		Fig. 6-2
One-half-scale		Fig. 6-3
Composite (1/5-, 1/2-, and full-scale)		Fig. 6-4
Full-scale	H-451 graphite	Fig. 6-5

Fig. 6-1. Full-scale coefficient of restitution versus impact velocity (pendulum tests)

Fig. 6-2. One-fifth-scale coefficient of restitution versus impact velocity.

Fig. 6-3. One-half-scale coefficient of restitution versus impact velocity

Fig. 6-4. Composite coefficient of restitution versus impact velocity

Fig. 6-5. Full-scale coefficient of restitution versus impact velocity (linear track test)

Figure 6-1 shows full-scale data for H-327 obtained from pendulum tests. These represent the design data for the 1/5- and 1/2-scale elements. It is observed that e increases with impact velocity.

The 1/5-scale test data are shown in Fig. 6-2. The linear least square line characterizes the data points well, with the exception of a few points so widely scattered that they clearly represent unusual test errors.

The 1/2-scale data shown in Fig. 6-3 indicate that the mean e value achieved by the design is slightly higher than that of the 1/5-scale design. The trend toward increasing e with impact velocity is stronger. With the exception of one data point, the spread of the data is small. Some overlapping of the data obtained by the two modes of impact shown is evident.

All the e values from 1/5-, 1/2-, and full-scale tests on H-327 graphite are shown in Fig. 6-4 for comparison. Good agreement is obtained between the different scale tests. The spread of data is moderate, especially when the points which clearly represent unusual errors are ignored. These tests therefore show that the design of the 1/5- and 1/2-scale elements provides adequate coefficient of restitution values.

The full-scale data for H-451 graphite were obtained from linear track tests, Fig. 6-5. Good overlap of data by the two impact modes is obtained and the data spread is small. The median values of e are much higher than H-327 graphite.

The reasons are both the difference between H-327 and H-451 graphite material properties and their methods of testing. Probably the pendulum method caused lower than actual values of e , since impact vibrations in the test rig could have contributed to energy loss. These losses were incorporated into the estimate of e . Thus, material properties, alone, do not change e as much as tests results would indicate.

6.2. CONTACT TIME

The ct test results as functions of impact velocity are shown in the following figures:

Full-scale	} H-327 graphite	Fig. 6-6
One-fifth-scale		Fig. 6-7
One-half-scale		Fig. 6-8
Composite (1/5-, 1/2-, and full-scale)		Fig. 6-9
Full-scale	H-451 graphite	Fig. 6-10

The full-scale ct data, obtained from pendulum tests on H-327 graphite, shows a decreasing trend with increasing values of impact velocity. This is represented by the median curve in Fig. 6-6.

The 1/5-scale ct data obtained from both pendulum tests and linear track tests are widely scattered and the trend is not obvious. The scatter is due to the difficulty in achieving flat-on impacts in both methods of testing. A reasonable correlation between the two methods is obtained, however, despite the scatter. (See Fig. 6-7.)

The 1/2-scale data in Fig. 6-8, obtained from the linear track tests, show far less scatter and the trend is more visible.

In Fig. 6-9, comparing the 1/5-, 1/2-, and full-scale ct data, the 1/2- and full-scale ct data are normalized to 1/5-scale according to the relations

$$t_m = \lambda t_p, \quad v_m = v_p$$

(from the scaling analysis outlined in Section 5.1).

Fig. 6-6. Full-scale elements contact time versus impact velocity (pendulum tests)

Fig. 6-7. One-fifth-scale contact time versus impact velocity

Fig. 6-8. One-half-scale contact time versus impact velocity

Fig. 6-9. Composite contact time versus impact velocity (normalized to 1/5-scale)

Fig. 6-10. Full-scale contact time versus impact velocity (linear track test)

The full-scale ct were therefore multiplied by $1/5$ for comparison with the $1/5$ -scale data, and the $1/2$ -scale ct multiplied by $2/5$. The curves show that the $1/5$ - and $1/2$ -scale elements, in general, have smaller contact times than the full-scale elements. This means that these element designs were too stiff according to the scaling laws of Section 5.1. Apparently, the decision not to incorporate fuel and coolant holes in the $1/5$ - and $1/2$ -scale designs violated the similitude requirements in scaling and effected the element stiffness.

The ct for H-451 full-scale elements, as obtained from the linear track tests, are shown in Fig. 6-10. From the analysis of the test data, there was a large difference between the minimum contact time of the four contact gages and the average contact time. The lower curve with minimum contact time is probably a more realistic measurement of flat-to-flat impact contact time and is recommended for analytical use.

6.3. MULTIPLE ELEMENT COLLISIONS

Samples of test results from multiple element collisions are shown in Figs. 6-11 through 6-13 for the $1/5$ -, $1/2$ -, and full-scale elements, respectively. The balance is included in Appendix B. All stationary elements were in contact (within the limitations discussed elsewhere) prior to impact by the moving element or elements.

The results are presented as plots of the final velocity of a given element versus the initial velocity of the impacting element. The final velocity is given in percent of initial velocity and is corrected to 100% conservation of initial momentum. This method of presentation was adopted so that test results could better be correlated with analytical results, which represent 100% conservation of momentum.

Fig. 6-11. One-fifth-scale post-impact velocity distribution versus impact velocity

Fig. 6-12. One-half-scale post-impact velocity distribution versus impact velocity

Fig. 6-13. Full-scale post-impact velocity distribution versus impact velocity

Consider the expression

$$\sum (miVi)_i = \sum (miVi)_f \quad (6-1)$$

where $miVi$ is the momentum of the i^{th} element and the i and f outside the parentheses indicate initial and final momenta. Because of friction and other losses, the equality of Eq. 6-1 does not hold true when the expression is applied to the test results. The right side of the expression is typically 0.975 times the left side. Equation 6-1 was modified as follows for application to the test results:

$$\sum (miVi)_i = I/F \sum (miVi)_f$$

where I and F are initial and final momenta, respectively. Since the mass remained constant, the final velocity of each element was increased by the ratio of I to F for each test condition. Tables B-1 through B-12 of Appendix B list values of I/F for numerous full-scale multiple element collisions (i.e., two elements colliding with two elements, two colliding with three, three colliding with two, etc.). The mean of all the values tabulated in these tables is 97.46%.

Figures 6-11 through 6-13, representing one element colliding with two stationary elements, all exhibit the same trend. The impactor element, called element No. 1, loses momentum as a function of increasing impact velocity, and the extreme element in the series (farthest from the impactor) gains momentum. The momentum change of the intermediate elements in each series remains nearly constant with impact velocity.

Similar trends are seen in collisions of one moving element with up to five stationary elements. Figures B-1 through B-6, Appendix B, give examples of the trends. Tables B-1 through B-11, Appendix B, list the raw data in terms of initial and final velocity of full-scale elements involved in collisions of one-on-five, two-on-two up to two-on-four, three-on-one up to three-on-three, four-on-one, four-on-two, and five-on-one.

6.4. BOUNDARY COLLISIONS

Figures 6-14, 6-15, and 6-16 present boundary loads as functions of element impact velocity for 1/5-, 1/2-, and full-scale elements, respectively. A single element impacting the boundary was used to generate the data for Fig. 6-14. The boundary load is strongly dependent on element impact velocity, as is expected. In Figs. 6-15 and 6-16, single element and two element impacts with the boundary are shown. The trend toward increasing load with increasing impact velocity is evident for both one and two element configurations.

For single and multiple element collisions with the boundaries, test results are presented in terms of final to initial momentum ratios versus impact velocity (Figs. 6-17 through 6-22). The ordinates for these figures were generated by dividing the right side of Eq. 6-1 by the left side. For two element collisions with the boundaries, trends in momentum change similar to those discussed in Section 6.3 are displayed for 1/5- and 1/2-scale; i.e., the element nearest the initial impact site loses momentum increasingly with increasing impact velocity, and the element farthest from the site loses momentum decreasingly with increasing impact velocity (Figs. 6-17 and 6-18). The trend is less pronounced for the full-scale (Fig. 6-19).

For single element boundary collisions the momentum ratio as a function of impact velocity is nearly constant for 1/5- and 1/2-scale (Figs. 6-20 and 6-21). For the full-scale (Fig. 6-22), an increasing trend is evident.

6.5. IMPACT ACCELERATION

Figure 6-23 presents impact accelerations obtained from collisions of one moving full-scale element with one stationary element in which accelerometers were mounted in each element. The data from each accelerometer are in close agreement, as expected, indicating validity of the measurements. Similar data were not obtained for the 1/5- or 1/2-scale elements.

Fig. 6-14. One-fifth-scale boundary force versus impact velocity

Fig. 6-15. One-half-scale boundary force versus impact velocity

Fig. 6-16. Full-scale boundary force versus impact velocity

Fig. 6-17. Post-impact momentum ratio versus impact velocity.
Two 1/5-scale elements impacting the boundary

Fig. 6-18. Post-impact momentum ratio versus impact velocity.
Two 1/2-scale elements impacting the boundary

Fig. 6-19. Post-impact momentum ratio versus impact velocity.
Two full-scale elements impacting the boundary

Fig. 6-20. Post-impact momentum ratio versus impact velocity.
One 1/5-scale element impacting the boundary

Fig. 6-21. Post-impact momentum ratio versus impact velocity.
One 1/2-scale element impacting the boundary

Fig. 6-22. Post-impact momentum ratio versus impact velocity.
One full-scale element impacting the boundary

Fig. 6-23. Impact acceleration versus impact velocity (full scale).
One moving element impacting one stationary element

Figure 6-24 presents data from collisions of one moving element with two stationary elements. The full-scale element withstood impact accelerations to 293 g without apparent failure.

Fig. 6-24. Impact acceleration versus impact velocity (full scale).
 One moving element impacting two stationary elements

7. ERROR ANALYSIS

7.1. GENERAL

All the test values are based on numerous repetitive tests (see Tables 5-7 through 5-13). In some cases, as many as 51 repetitions were performed. This provided a broad statistical base from which a random error analysis was made.

The random error in percent is represented by the fractional standard deviation ($\hat{S}$) and

$$S = \frac{S}{\bar{y}},$$

where S is one standard deviation (1σ) on either side of the regression line and $\bar{y}$ is the mean value of the ordinate.

Some systematic or nonrandom error sources were also present. The errors from these sources were small in comparison to the random errors.

Table 7-1 presents the random error in each test series and the total error, which is obtained by adding the systematic error and the random error.

7.2. ERROR SOURCES

The primary source of systematic, or nonrandom, error was friction. The error magnitude due to friction is indicated by the momentum loss. The mean momentum loss in several hundred observations was 2.5%. This value was used throughout Table 7-1 as the systematic error magnitude.

TABLE 7-1
ERROR SUMMARY

	Coefficient of Restitution		Contact Time		Post-Impact Momentum Distribution			
					Inter-Element ^(a)		Boundary ^(a)	
	$\hat{S}$	Total	$\hat{S}$	Total	$\hat{S}$	Total	$\hat{S}$	Total
1/5-scale	0.20	0.225	0.20	0.225	0.12	0.145	0.18	0.205
1/2-scale	0.10	0.125	0.10	0.125	0.15	0.175	0.12	0.145
Full-scale	0.08	0.105	0.18	0.205	0.11	0.135	0.05	0.075

(a) The $\hat{S}$ values listed represent the arithmetic averages of $\hat{S}$ computed for each element involved in each of several inter-element and boundary collisions.

Velocity was determined by measurements of oscillogram trace deflection amplitudes for pendulum tests, spacing of spark holes in paper tape for 1/5- and 1/2-scale track tests, and spacing of oscillogram trace deflections for full-scale tests. Measurement inaccuracy resulted in random errors.

Small random errors may have been introduced by the rotary potentiometers and recorders used in the pendulum tests, by spark generator frequency variation in the 1/5- and 1/2-scale track tests, and by the recorder used in the full-scale tests.

Element contact surface irregularity contributed to the spread of the data. The elements were changed around frequently, resulting in different faces contacting each other. This prevented biasing of the data from the condition of a particular pair of contacting faces.

The contact time data was subject to random error due to any surface irregularity which was present or a less-than-perfect flat-on impact which caused premature circuit completion and erroneous contact time indication. Four contact strips, one near each corner of the impacting face, were used for full-scale tests. The data indicated variations in contact time for the four corners of the same element of up to 10.5 msec (13.3 msec versus 2.8 msec) at 11.07 ips impact velocity, diminishing to 2.55 msec (3.8 versus 1.25 msec) at 47.88 ips impact velocity. The average and the minimum of the four readings from each of the four contact strips were used in preparing Fig. 6-10.

Another possible source of data spread was the dynamic response of the test rig at impact, especially the responses of the roller bearing tie rods, roller bearings, and track.

8. REFERENCES

1. Hughes, P. T., and G. Jones, "DV&S Collision Test for Model Fuel Elements," General Atomic Company unpublished data, 1973.
2. Rickard, N. D., "CRUNCH 1D, A Computer Program for Seismic Analysis of the HTGR Core," ERDA Report GA-A14120, General Atomic Company, March 1977.

APPENDIX A
LINEAR LEAST SQUARES LINE, MEANS, AND STANDARD DEVIATION

In Eqs. A-1 and A-2, Y corresponds to the value of the ordinate at a particular abscissa (X) and n is the number of points:

$$A = \frac{\sum y \sum x^2 - \sum x \sum xy}{n \sum x^2 - (\sum x)^2} \quad (A-1)$$

and

$$B = \frac{n \sum xy - \sum x \sum y}{n \sum x^2 - (\sum x)^2} \quad (A-2)$$

Then

$$Y = A + BX \quad (A-3)$$

is the equation of the best fit straight line.

The means and standard deviation were generated using the following equations:

$$\bar{X} = \frac{1}{n} \sum_{i=1}^n X_i \quad (\text{Abcissa mean}) \quad , \quad (A-4)$$

$$\bar{Y} = \frac{1}{n} \sum_{i=1}^n Y_i \quad (\text{Ordinate mean}) \quad , \quad (A-5)$$

and

$$S = \sqrt{\frac{\Sigma(Y - A - BX)^2}{n}} \quad \text{(Standard deviation of the data points about the regression line)} \quad (A-6)$$

$$\hat{S} = \frac{S}{\bar{y}} \quad \text{(Fractional standard deviation)} \quad (A-7)$$

APPENDIX B
ADDITIONAL DATA

Samples of test results from multiple element collisions are shown in Figs. B-1 through B-9 for the 1/5-, 1/2, and full-scale elements. These figures give examples of trends seen in collisions of one moving element with up to five stationary elements.

Tables B-1 through B-17 list the raw data in terms of initial and final velocity of full-scale elements involved in collisions of one-on-five, two-on-two up to two-on-four, three-on-one up to three-on-three, four-on-one, four-on-two, and five-on-one.

The following nomenclature is used for the tables found in this appendix:

Subscript i indicates initial velocity (in./sec).

Subscript f indicates post-impact velocity (in./sec).

I/F represents the ratio of initial to final momentum (%).

Fig. B-1. One-fifth scale H-327 1 → 2 3 4

Fig. B-2. One-fifth scale H-327 1 → 2 3 4 5

Fig. B-3. One-half scale H-327 1 → 2 3 4

Fig. B-4. One-half scale H-327 1 → 2 3 4 5

Fig. B-5. Full-scale H-451

Fig. B-6. Full-scale H-451 1 → 2 3 4 5

Fig. B-7. One-fifth scale H-451

Fig. B-8. One-fifth scale H-451

Fig. B-9. One-fifth scale H-451

TABLE B-1
ONE ELEMENT COLLIDING WITH FIVE ELEMENTS, FULL-SCALE H-451

$V1_i$	$V1_f$	V2	V3	V4	V5	V6	I/F
30.95	1.38	2.8	3.32	4.4	7.0	9.14	90.6
2.6	4.94	4.57	5.78	6.85	8.12	11.18	97.2
52.5	2.88	4.29	5.68	6.99	9.97	14.48	85.2

TABLE B-2
TWO ELEMENTS COLLIDING WITH ONE ELEMENT, FULL-SCALE H-451

$V1_i$	$V2_i$	$V1_f$	$V2_f$	V3	I/F
11.76	11.76	6.19	7.17	9.20	95.9
18.61	18.61	7.97	12.4	15.64	96.7
28	28	12.2	19.6	23.15	103.8
36.75	36.75	15.76	26.73	30.15	98.8
42.0	42.0	17.82	29.4	37.93	101.4
49.41	49.41	21.15	35.64	40.83	98.8

TABLE B-3
TWO ELEMENTS COLLIDING WITH TWO ELEMENTS, FULL-SCALE H-451

$V1_i$	$V2_i$	$V1_f$	$V2_f$	V3	V4	I/F
10.33	10.33	3.59	4.13	5.61	7.21	99.4
19.53	19.53	3.59	8.07	10.54	14.81	94.7
27.6	27.6	6.43	12.78	14.77	18.67	95.4
34.19	34.19	5.62	15.89	19.15	26.25	97.8
36.75	36.75	6.11	17.29	21	28.68	99.4
41.12	41.12	6.55	19.03	24.5	32.66	100.6
39.46	39.46	6.36	17.82	22.79	31.44	99.3
45.23	45.23	5.84	19.41	26.97	37.69	99.4

TABLE B-4
TWO ELEMENTS COLLIDING WITH THREE ELEMENTS, FULL-SCALE H-451

$V1_i$	$V2_i$	$V1_f$	$V2_f$	V3	V4	V5	I/F
18.97	18.97	3.04	4.23	6.46	9.41	12.81	99.7
19.6	19.6	3.29	4.63	6.52	8.78	13.33	93.2
29.85	29.85	4.62	7.1	9.64	14.7	22.97	88.8
37.21	37.21	5.51	8.12	12.35	19.6	28.27	99.2
50.69	50.69	7.73	8.63	18.43	27.61	37.45	98.5

TABLE B-5
TWO ELEMENTS COLLIDING WITH FOUR ELEMENTS, FULL-SCALE H-451

$V1_i$	$V2_i$	$V1_f$	$V2_f$	V3	V4	V5	V6	I/F
19.22	19.22	2.83	2.98	3.84	5.85	8.22	11.98	92.9
28.68	28.68	3.46	4.67	5.41	9.35	12.84	17.98	93.6
37.21	37.21	4.81	5.23	6.62	13.07	18.49	24.10	97.2
0.03	52.03	9.27	9.67	10.33	19.6	25.13	31.44	101.3

TABLE B-6
THREE ELEMENTS COLLIDING WITH ONE ELEMENT, FULL-SCALE H-451

$V1_i$	$V2_i$	$V3_i$	$V1_f$	$V2_f$	$V3_f$	V4	I/F
11.95	11.95	11.95	7.0	7.54	9.09	8.34	89.2
23.71	23.71	23.71	14.52	16.9	18.97	18.2	96.4
32.31	32.31	32.31	19.8	24.81	24.30	27.87	99.8
37.21	37.21	37.21	20.63	24.6	30.63	33.97	98.4
47.42	47.42	47.42	26.03	33.22	40.0	44.54	101.2

TABLE B-7
THREE ELEMENTS COLLIDING WITH TWO ELEMENTS, FULL-SCALE H-451

$V1_i$	$V2_i$	$V3_i$	$V1_f$	$V2_f$	$V3_f$	V4	V5	I/F
10.89	10.89	10.89	3.55	4.71	6.13	6.55	7.42	86.8
20.92	20.92	20.92	6.28	9.92	12.0	14.7	15.6	93.2
28.82	28.82	28.82	8.06	12.17	16.26	26.61	27.10	99.7
36.07	36.07	36.07	9.51	17.29	21.0	28.27	31.96	98.8
49.0	49.0	49.0	14.1	24.5	30.47	37.69	42.0	101.2

TABLE B-8
THREE ELEMENTS COLLIDING WITH THREE ELEMENTS, FULL-SCALE H-451

V1 _i	V2 _i	V3 _i	V1 _f	V2 _f	V3 _f	V4	V5	V6	I/F
11.53	11.53	11.53	1.99	3.35	4.68	5.60	7.21	7.35	87.2
22.27	22.27	22.27	4.17	5.62	7.98	12.38	15.23	16.24	92.2
30.95	30.95	30.95	6.67	9.09	12.51	18.26	20.28	24.91	98.8
40.0	40.0	40.0	7.48	12.51	18.04	22.97	27.10	27.74	96.5
52.50	52.50	52.50	9.42	12.84	18.55	33.6	41.12	--	104.2

TABLE B-9
FOUR ELEMENTS COLLIDING WITH ONE ELEMENT, FULL-SCALE H-451

V1 _i	V2 _i	V3 _i	V4 _i	V1 _f	V2 _f	V3 _f	V4 _f	V5	I/F
9.8	9.8	9.8	9.8	5.9	6.34	7.69	7.56	8.53	91.9
19.53	19.53	19.53	19.53	12.56	13.39	15.15	17.28	20	100.3
35.0	35.0	35.0	35.0	21.15	24.0	28.41	30.62	30.95	96.5
42.92	42.92	42.92	42.92	27.48	31.78	36.07	38.18	39.2	100.6
45.23	45.23	45.23	45.23	28.82	34.79	36.3	38.43	39.73	98.4

TABLE B-10
FOUR ELEMENTS COLLIDING WITH TWO ELEMENTS, FULL-SCALE H-451

V1 _i	V2 _i	V3 _i	V4 _i	V1 _f	V2 _f	V3 _f	V4 _f	V5	V6	I/F
9.73	9.73	9.73	9.73	3.89	5.33	5.34	5.73	7.34	11.26	99.9
23.61	23.61	23.61	23.61	10.23	10.35	14	18.37	22.53	24.30	105.6
27.74	27.74	27.74	27.74	9.29	14.24	17.29	20.63	23.61	25.56	99.7
41.12	41.12	41.12	41.12	15.51	18.15	25.34	27.48	37.93	39.73	99.8
50.26	50.26	50.26	50.26	16.24	25.24	32.13	36.30	44.54	45.94	99.7

TABLE B-11
FIVE ELEMENTS COLLIDING WITH ONE ELEMENT, FULL-SCALE H-451

V1 _i	V2 _i	V3 _i	V4 _i	V5 _i	V1 _f	V2 _f	V3 _f	V4 _f	V5 _f	V6	I/F
9.48	9.48	9.48	9.48	9.48	7.39	7.87	7.82	7.71	8.65	9.19	102.6
20.35	20.35	20.35	20.35	20.35	14.7	14.31	15.76	17.93	20.07	21.38	102.3
31.78	31.78	31.78	31.78	31.78	22.1	22.36	25.56	25.79	30.62	31.44	99.3
42.0	42.0	42.0	42.0	42.0	30.0	29.85	35.0	36.07	38.43	40.55	99.9
47.8	47.8	47.8	47.8	47.8	31.78	34.59	39.2	41.12	45.23	46.30	99.7

TABLE B-12
ONE ELEMENT COLLIDING WITH BOUNDARY, FULL-SCALE H-451

V_i	V_f
9.13	4.25
18.91	10.89
30.62	18.49
40	24.5
50.26	44.88

TABLE B-13
TWO ELEMENTS COLLIDING WITH BOUNDARY, FULL-SCALE H-451

$V1_i$	$V2_i$	$V1_f$	$V2_f$
10.89	10.89	3.24	7.55
21.85	21.85	8.99	18.09
29.4	29.4	15.04	24.6
38.43	38.43	21.78	31.11
48.2	48.2	29.11	39.2

TABLE B-14
THREE ELEMENTS COLLIDING WITH BOUNDARY, FULL-SCALE H-451

$V1_i$	$V2_i$	$V3_i$	$V1_f$	$V2_f$	$V3_f$
8.95	8.95	8.95	1.79	4.26	4.32
16.33	16.33	16.33	3.16	8.52	12.73
30.47	30.47	30.47	11.62	19.09	24.5
42.92	42.92	42.92	23.81	31.78	32.85
50.26	50.26	50.26	26.97	34.59	37.21

TABLE B-15
FOUR ELEMENTS COLLIDING WITH BOUNDARY, FULL-SCALE H-451

$V1_i$	$V2_i$	$V3_i$	$V4_i$	$V1_f$	$V2_f$	$V3_f$	$V4_f$
10.37	10.37	10.37	10.37	--	24.83	3.68	4.72
20.35	20.35	20.35	20.35	2.09	6.53	8.27	13.64
30.62	30.62	30.62	30.62	12.17	17.82	19.53	17.98
40.83	40.83	40.83	40.83	17.5	24.1	37.45	34.59
50.69	50.69	50.69	50.69	21.86	26.02	32.31	42.92

TABLE B-16
FIVE ELEMENTS COLLIDING WITH BOUNDARY, FULL-SCALE H-451

$V1_i$	$V2_i$	$V3_i$	$V4_i$	$V5_i$	$V1_f$	$V2_f$	$V3_f$	$V4_f$	$V5_f$
12.98	12.98	12.98	12.95	12.98	--	3.89	5.47	6.11	6.24
20.49	20.49	20.49	20.49	20.49	3.28	7.23	9.64	13.9	16.66
32.13	32.13	32.13	32.13	32.13	11.48	17.29	20.35	23.06	24.76
38.68	38.68	38.68	38.68	38.68	12.92	18.43	21.78	26.49	28.82
52.5	52.5	52.5	52.5	52.5	21	25.34	31.28	35.59	37.21

TABLE B-17
SIX ELEMENTS COLLIDING WITH BOUNDARY, FULL-SCALE H-451

$V1_i$	$V2_i$	$V3_i$	$V4_i$	$V5_i$	$V6_i$	$V1_f$	$V2_f$	$V3_f$	$V4_f$	$V5_f$	$V6_f$
9.35	9.35	9.35	9.35	9.35	9.35	--	1.94	2.16	4.11	4.58	6.11
20.7	20.7	20.7	20.7	20.7	20.7	--	4	6.8	10.26	10.95	13.18
29.7	29.7	29.7	29.7	29.7	29.7	5.6	10.32	14.38	18.97	20.35	23.52
40.83	40.83	40.83	40.83	40.83	40.83	14	18.97	23.24	27.1	30	30.95
50.69	50.69	50.69	50.69	50.69	50.69	22.19	29.11	31.96	38.43	41.41	45.23