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ANALYSIS OF DNA IMPACT TEST DATA

Gregory H. Canavan

Experiments conducted by the Defense Nuclear Agency provide an adequate basis for describing the fragment distribution and number from hypersonic collisions.

Experiments conducted by the Defense Nuclear Agency (DNA) provide a basis for describing the number and distribution of fragments and from hypersonic collisions. The tests were performed under a variety of conditions by a number of organizations. The full set of data is recorded in a summary report, which is reviewed below. The data are then analyzed for trends and significance, and the adequacy of various representations is discussed.

Test data taken from the DNA summary report¹ are summarized in Table I, which gives the name and number of each test, a brief description of the target, and the main experimental parameters, which are the projectile velocity and mass, target mass, and fraction of mass collected. It also gives the main derived quantities, which are the ratio of target to projectile mass, projectile kinetic energy, and the ratio of kinetic energy to target mass, which is a rough measure of the specific energy available for fragmentation.

Figure 1 plots the test parameters as a function of test name and number. The line identified by solid squares is for the velocity in km/s, which averages about 6 km/s, limited by the rail guns used. They are somewhat below average orbital collision velocities²—with the exception of the German FRGITS 1, 2, 3, and D (the developmental shot), which were at 10 km/s. The Battelle tests are part of a test of scaling at below average orbital velocities.

Target masses vary from a few tens of grams to almost a ton for the on-orbit ASAT test P 78. Most of the satellite mock ups in the Satellite Orbital Debris Characterization Impact Test (SOCIT) used masses of a few tens of grams, but the early GRC 381 and 385 used a few tens of grams and the Battelle tests used a few hundred grams. The projectile masses varied accordingly. The average was on the order of 100 grams, excluding the 16 kg P 78 projectile, but the GRC 381 and 385 projectiles were only two grams, the Battelle projectiles about four, and the FRGITS projectiles about 10 grams.

The average collection fraction is about 50%, with the exception of GRC 385, CU 5272, and the Battelle tests, which approached 100%. With them, the average is about 66%. If there is any correlation, it appears to be that the experiments with the smallest projectiles and targets give the highest fraction of fragment mass recovered, which is counterintuitive.

Figure 2 shows the derived parameters as functions of test name and number. The top line, the ratio of target to projectile mass, has an average of about 300. If the small-projectile FRGITS experiments are omitted, the average is about 100. However, the FRGITS experiments are useful, in that their mass ratio of about 2,000 is roughly the average ratio for all fragment collisions on orbit.³ The GRC tests are also useful in that they explore fragmentation at the mass ratio of 30-40 characteristic of catastrophic collisions on orbit.

The kinetic energy of the projectile varies primarily with its mass, although the high velocity of the FRGITS experiments compensates for their small projectile masses. The lower velocities used in the Battelle decrease the kinetic energy available. The ratio of kinetic energy to target plus projectile mass is about 0.1 MJ/kg for the satellite mock ups, as well as for the PSI, AFA, and first Battelle test. The GRC spherical tank experiments had a value of about 1 MJ/kg, which is an order of magnitude larger. FRGITS 1, 2, and 3 had a ratio about of about 0.1 MJ/kg, which is an order of magnitude smaller. The FRGITS development test D had a value of about 1 MJ/kg, which makes it a useful contact with the lower velocity GRC experiments. The Battelle experiments had a ratio that varied systematically from 0.1 to 0.01 MJ/kg.

Scaling parameters. Two important products of these tests are A and B, the parameters used to represent the cumulative number of fragments with mass greater than m, which is

$$C = A(M_t/m)^B, \quad (1)$$

where M_t is the target mass, which is approximately the total mass of fragments. The values of B can be inferred for each experiment of known target and projectile masses from the slope of the plot of $\ln C$ versus $\ln m$; A is determined by the intercept. The values inferred from each experiment are shown in Table II and displayed in Fig. 3. The solid bars are the values of A, which show a great deal of scatter; the open bars are the values of B, which show much less scatter about their mean value of 0.62.

Figure 4 more clearly indicates an important feature of the frequency of occurrence of various values of B: it is bimodal. There are roughly equal numbers of occurrences of values below the mean and above it. That is, there are three tests with values of B between 0.4 and 0.45 (labeled by 0.4), three tests with values between 0.45 and 0.5 (labeled by 0.45, etc.), two at 0.5, and 1 at 0.55, for a total of nine below $B = 0.6$; 14 from 0.65 to 0.8; and none in the 0.6 to 0.65 interval in which the mean lies. This significance of this bimodality is discussed after that of the correlations in the data.

Correlations. In evaluating these tests, it is useful to look for correlations of the parameters with the test and derived parameters. As B is more important in determining the distribution and number of fragments, the discussion below concentrates on it. Figure 5 shows B as a function of V for the various tests, which can be identified by V on Table I. B increases roughly as the square root of V up to about 6 km/s, after which the values fall. The FRGIT 1, 2,

and 3 values of 4.3-4.6 are much lower, although that is in part due to the correlation with target to projectile mass ratio discussed below. However, the FRGIT D developmental test, which has a mass ratio of 41 typical of the GRC tests, has a value of $B = 0.67$, as does the P 78 ASAT test, which has the largest masses at orbital velocities.

Figure 6 for B versus the ratio of kinetic energy to target mass shows a similar increase at ratios below 0.1 Mj/kg, and a saturation at about 0.7 for larger values. The outlying point of $B = 0.79$ at a ratio of 0.015 Mj/kg is CU 5271, which was re-tested at CU 5272 for the same values, giving a value of $B = 0.45$.

Figure 7 shows B versus the ratio of target to projectile mass. Many of the points lie around a value of 0.7. The five points at a mass ratio of 75 are the Battelle experiments at below orbital velocities, which reflect the velocity correlation exhibited in Fig. 5. The value of 0.45 at a ratio of 380 is the re test CU 5272 discussed above. The three points at about 0.45 at mass ratios of about 2,000 are FRGITS 1, 2, and 3, which are at roughly the average mass ratio of all debris collisions.

Figure 8 shows the histogram of the number of occurrences of various values of the collection efficiency for the full set of tests. The seven full collections are for the GRC spherical tank, the CU 5272 re test, and the Battelle velocity study. The two at 0.8 are FRGITS 1 and SOCIT 3. The three at 0.6 are SOCIT 4, GRC 6385, and PSI 5268. The five at 0.5 are MOCK 1, SOCIT 3, GRC 6380, PSI, 5192, and P 78. The four at 0.45 are FRGITS 1, 2, 3 and the spherical tank GRC 6385. The one at 0.3 is CU 5271, which was also gave $B = 0.79$. The one at 0.15 is the AFA defense suppression target, which gave a nominal value of $B = 0.63$.

It is difficult to see any direct correlation between test conditions and collection, except that, as noted above, the smaller experiments reported larger collection fractions. The correlation of collection efficiency with B is shown in Fig. 9, which indicates that the majority of the tests with high collection efficiency gave B smaller than the mean of 0.62 and that the majority of the tests that gave values larger than the mean had collection efficiencies of 0.45 to 0.5. The only significant statistic is that B varies inversely with collection efficiency, the reason for which is not obvious.

Analysis. Several attempts have been made to produce models for the variation of A and B with experimental parameters for use in subsequent analyses. The Air Force Scientific Advisory Board simply used the average value of $B = 0.62$ from above and determined A by conservation of mass.⁴ DNA⁵ and NASA-Kaman⁶ efforts attempted to predict the variation of B from a combined empirical-theoretical model and determine A by conservation, producing the Fragmentation Algorithms for Strategic and Theater Targets (FASTT) Empirical Breakup Model. NASA JSC EVOLVE calculations assume $C = 0.4478[(M_t + M_p)/m]^{-0.7496}$, for which B is

rounded to 0.75 without loss of accuracy below, as the experiments are not reported to better accuracy.⁷

The accuracy of the SAB representation is implicit in the discussion above: it agrees precisely with the mean value of B, but does not attempt to capture all of the variances. Calculations are, however, performed in a manner that reflects the reduction in the value of B at large ratios of target to projectile mass.

The FASTT model is trained on a subset of the full set of the test data related to the SOCIT tests proper. If applied to this subset, the SAB process would produce the average value of $B = 0.69$ shown. The FASTT model predictions are compared with the experimental data in Table III.A, where they are indicated by A_f and B_f . The former shows much less variation than the experimental A; its mean value is about 20% below that of the data. B also shows less variation; its mean is about 1.5% below that of the SOCIT data. However, Fig. 10 shows that this modest error in B_f averages over variations from +6% in SOCIT 3 (MOCK 2 Oscar) to -13% in SOCIT 4 (Oscar). That range of 19% in primary experiments is almost as large as the full variance at issue in model comparisons.

The NASA JSC EVOLVE calculations value of $B \approx 0.75$ gives a relative error of $0.75/B - 1$, which is shown in the right column of Table III.A and displayed in Fig. 11. The EVOLVE value systematically overestimates B for tests with B less than 0.75, culminating in a 67% overestimate of the value for CU 5272, which results in an average overestimate for the SOCIT subset of about 8.3%.

The tests excluded from the full set to form the SOCIT subset are shown in Table III. There are twelve tests, including the FRGITS higher than orbital velocity, Battelle lower than average velocity, one each of the GRC and CU tests, and the AFA test. For this subset the SAB procedure gives an average value of about 0.56. The FASTT predictions for this case were not given, although having been trained on the SOCIT subset, it would be useful to have its predictions for the excluded subset.

The EVOLVE relative errors are shown in the right column of Table II. B and displayed in Fig. 12. They systematically overestimate B below for all but the one point above 0.75 by fractions ranging up to 60-80% for $B = 0.4$ to 0.5 , the most likely values in this subset. The overall average error is about 42%, as shown.

When the 8% error for the SOCIT subset and the 42% error for the excluded data set are averaged, the overall average EXCEL error in B is about 26%. The mean of the SOCIT subset in turn overestimates the average B for the full test sample by about $0.69/0.62 \approx 11\%$. Thus, there are two issues in using the EXCEL constant $B = 0.75$ to represent the full test data set: 1. It overestimates B for the SOCIT subset for which the FASTT mean is reasonably accurate, and 2. the SOCIT subset is not representative of the full data set. Figure 13 shows the histogram of

occurrences of various values of B versus the experimental B, indicating by solid bars the test data included in the SOCIT training set for FASTT and by open bars the data excluded. Consistent with the observations above, the selection process has included primarily those tests with large values of B and excluded those with values smaller than the average of the full test set. That may be useful for training for some purposes, but the exclusion of all tests with values much above and below the average collision speed produces a value of B that is not appropriate for averaging over debris distributions to produce fragment production.

Summary and conclusions. Experiments conducted by the DNA provide a basis for describing the number and distribution of fragments and from hypersonic collisions. The full set of data recorded in a summary report is reviewed, analyzed for trends and significance, and the adequacy of various representations is discussed. The test data can be characterized by the parameters A and B. The former has greater variance, but is less sensitive in predictions of debris. The latter has less variance but greater sensitivity. The distribution of B is shown to be bimodal, to have saturating variation with V and specific kinetic energy, and little systematic variation with the ratio of target to projectile mass below about 1,000. Collection efficiency varies widely, averages about 50%, and shows little correlation with B. The FASTT model reproduces the SOCIT data for which it is trained; the NASA JSC EVOLVE prescription overestimates it by about 8%. For the remainder of the test data, the EVOLVE prediction of B is about 42% high, for an overall average of about 26%.

The two issues in using the EXCEL $B = 0.75$ to represent the full test data set are that it overestimates B for the SOCIT subset and that the SOCIT subset is not representative of the full data set. The selection process for the SOCIT test set includes primarily those tests with large values of B and excludes those with values smaller than the average of the full test set. The exclusion of all tests with values much above and below the average collision speed produces a value of B that is not appropriate for averaging over debris distributions to produce fragment production.

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DNA table I

Table I. Defense Nuclear Agency Impact Test Results												
	Test name and number	Notes	V	M tgt	M proj	Mt/Mp	KE	KE/Mt	collec			
1	Socit 4, GRC 6789, Oscar	full Oscar with circuit boards	6	34	0.15	226.7	2.7	0.079	0.6			
2	MOCK 1, KSC 6766, Oscar rep	Oscar replica with circuit boards	6	27	0.15	180	2.7	0.1	0.5			
3	SOCIT 3, GRC 6787, MOCK 2, Oscar rep	full Oscar with circuit boards	6	29.5	0.15	196.7	2.7	0.092	0.5			
4	MBB49367, FRGITS 1	1/4 scale generic satellite, 12 E boxes	10	19.3	0.01	1930	0.5	0.026	0.8			
5	GRC 381	spherical Al tank at 50 torr	6.4	0.03	0.002	15	0.041	1.365	0.8			
6	GRC 385	spherical Al tank at 600 psi	6.4	0.03	0.002	15	0.041	1.365	1			
7	GRC 6380	spherical Al tank, 183 fragments	5.5	2.1	0.08	26.25	1.21	0.576	0.5			
8	GRC 6385	spherical Al tank, 179 fragments	5.5	2.1	0.08	26.25	1.21	0.576	0.6			
9	PSI 5192	ASAT, Al tube with electronics boards	6	26	0.24	108.3	4.32	0.166	0.5			
10	PSI 5268	ASAT, Al tube with electronics boards	3.7	26	0.24	108.3	1.607	0.062	0.6			
11	CU 5272	Al tube with 36 electronics boards	3.4	31	0.08	387.5	0.462	0.015	1			
12	P 78	impact of on-orbit satellite	7	865	15	57.67	367.5	0.425	0.5			
13	MBB 49366, FRGITS devel	rectangular E box with 10 circuit boards	10	0.33	0.008	41.25	0.4	1.212	0.45			
14	MBB 49368, FRGITS 2	Al 1/4 scale generic sat with 12 E boxes	10	19.3	0.01	1934	0.5	0.026	0.45			
15	MBB 49369, FRGITS 3	Al 1/4 scale generic sat with 12 E boxes	10	17.3	0.01	1730	0.5	0.029	0.46			
16	GRC 6386	spherical Al tank	5.5	2.1	0.081	25.93	1.225	0.583	0.49			
17	CU 5271	18 cm tube filled with electronics	3.4	31	0.08	387.5	0.462	0.015	0.3			
18	AFA 6472	1/4 scale defense suppression target	5.6	7.3	0.084	86.9	1.317	0.18	0.19			
19	Battelle LGG 50	steel cylinder filled with TEP liquid	3	0.31	0.004	77.5	0.018	0.058	1			
20	Battelle LGG 51	steel cylinder filled with TEP liquid	2.5	0.31	0.004	77.5	0.013	0.04	1			
21	Battelle LGG 53	steel cylinder filled with TEP liquid	2	0.31	0.004	77.5	0.008	0.026	1			
22	Battelle LGG 59	steel cylinder filled with TEP liquid	1.5	0.31	0.004	77.5	0.005	0.015	1			
23	Battelle LGG 60	steel cylinder filled with TEP liquid	2.2	0.31	0.004	77.5	0.01	0.031	1			

DNA Table II

Table II. Average parameters from DNA impact tests.			
	Test name and number	A	B
1	Socit 4, GRC 6789, Oscar	0.32	0.78
2	MOCK 1, KSC 6766, Oscar rep	0.42	0.71
3	SOCIT 3, GRC 6787, MOCK 2, Oscar rep	0.53	0.65
4	MBB49367, FRGITS 1	1.75	0.46
5	GRC 381	0.38	0.75
6	GRC 385	1.22	0.73
7	GRC 6380	0.7	0.75
8	GRC 6385	0.71	0.76
9	PSI 5192	0.9	0.68
10	PSI 5268	0.49	0.69
11	CU 5272	0.41	0.45
12	P 78	0.82	0.67
13	MBB 49366, FRGITS devel	0.51	0.67
14	MBB 49368, FRGITS 2	1.59	0.43
15	MBB 49369, FRGITS 3	1.17	0.45
16	GRC 6386	0.77	0.74
17	CU 5271	0.16	0.79
18	AFA 6472	0.63	0.71
19	Battelle LGG 50	1.01	0.54
20	Battelle LGG 51	0.82	0.51
21	Battelle LGG 53	0.91	0.42
22	Battelle LGG 59	1.1	0.41
23	Battelle LGG 60	0.99	0.56
	Averages	0.796	0.62217

DNA Table II/

Table II. Averages for partitioned test sets.							
<i>A included</i>							
	DATA	A	B	Af	Bf	Bf/B-1	.75/B-1
1	GRC 381	0.38	0.75	0.37	0.76	0.01333	0
2	GRC 385	1.22	0.73	0.37	0.76	0.0411	0.0274
3	GRC 6380	0.7	0.75	0.38	0.75	0	0
4	GRC 6385	0.71	0.76	0.38	0.75	-0.0132	-0.0132
5	PSI 5192	0.9	0.68	0.51	0.67	-0.0147	0.10294
6	PSI 5268	0.49	0.69	0.58	0.63	-0.087	0.08696
7	CU 5272	0.41	0.45	0.92	0.43	-0.0444	0.66667
8	P 78	0.82	0.67	0.49	0.68	0.01493	0.1194
9	MOCK 1, KSC 6766, Oscar rep	0.42	0.71	0.47	0.7	-0.0141	0.05634
10	SOCIT 3, GRC 6787, MOCK 2, Oscar rep	0.53	0.65	0.47	0.69	0.06154	0.15385
11	Socit 4, GRC 6789, Oscar	0.32	0.78	0.49	0.68	-0.1282	-0.0385
	Averages	0.627	0.69273	0.494	0.682	-0.0155	0.08268
<i>B excluded</i>							
							.75/B-1
1	MBB49367, FRGITS 1	1.75	0.46				0.63043
2	MBB 49366, FRGITS devel	0.51	0.67				0.1194
3	MBB 49368, FRGITS 2	1.59	0.43				0.74419
4	MBB 49369, FRGITS 3	1.17	0.45				0.66667
5	GRC 6386	0.77	0.74				0.01351
6	CU 5271	0.16	0.79				-0.0506
7	AFA 6472	0.63	0.71				0.05634
8	Battelle LGG 50	1.01	0.54				0.38889
9	Battelle LGG 51	0.82	0.51				0.47059
10	Battelle LGG 53	0.91	0.42				0.78571
11	Battelle LGG 59	1.1	0.41				0.82927
12	Battelle LGG 60	0.99	0.56				0.33929
	Averages	0.951	0.5575				0.41614

Table I

Fig. 1. Test parameters for DNA impact tests.

Fig 2 Table I

Fig. 2. Derived parameters for DNA impact tests.

A & B vs test

Fig. 3. A coefficient and B fragmentation exponent versus test name and number.

hist all

Fig. 4. Frequency of occurrence of values of fragmentation exponent.

B vs V

V (km/s)

Fig. 5. Fragmentation exponent B versus projectile speed V.

B vs KE/Mt

B vs Mt/Mp

ratio of target to projectile mas
Fig. 7. Fragmentation B exponent versus ratio of target to projectile mass.

collect hist

Fig. 8. Number of occurrences of various values of collection efficiency.

B vs collect

Fig. 9. Fragmentation B exponent versus collection fraction.

Bf/Bt-1 vs Bt

Experimental E

Fig. 10. relative error in FASTT B versus experimental B.

Bevolve/B - 1 vs B

Experimental B.

Fig. 11. Relative error in EVOLVE B versus experimental B.

Chart8

Experimental B

Fig. 12. Relative error in EVOLVE B vs experimental B for excluded test data.

hist combined

Fig. . Number of occurrences of various values of fragmentation exponent B