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IMPACT TEST DATA

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ANALYSIS OF HYPERVELOCITY IMPACT TEST DATA

Gregory H. Canavan

Experiments conducted by the Department of Defense provide an adequate basis for the determination of the fragment distribution and number from hypervelocity collisions. Models trained on only a portion of the data are shown to bias samples too far from the population to be useful for averaging over debris distributions or estimating fragment production rates. The average fragment production exponent is more appropriate for those purposes.

Introduction. Department of Defense (DoD) experiments conducted by the Defense Nuclear Agency (DNA, now DSWA) provide a basis for the determination of the number and distribution of fragments 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 and analyzed for trends and significance below. Those results are used to assess the adequacy of various representations of the data. The data is characterized primarily by a fragment production exponent, which can be determined for each experiment. It is shown to have a bimodal distribution, to have saturating variation with projectile velocity and kinetic energy, and to have little systematic variation with the ratio of target to projectile mass.

The models used by NASA to interpret the data reproduces the subset on which they are trained, which is not representative, and greatly overestimates the remainder. The selection process includes those tests with large values of the exponent and excludes those with small values. This biases the sample so far from the population that the value of its fragment production is not appropriate for averaging over debris distributions or estimating fragment production rates. The average exponent is more appropriate for those purposes.

Test data 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: projectile velocity and mass, target mass, and fraction of fragment 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 Federal Republic of Germany Impact Tests (FRGITS) 1, 2, 3, and D (developmental) shots, 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 antisatellite (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. 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 included, the average is about 66%. If there is any correlation, it is 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, which shows 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 experiments 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 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 the coefficient A and exponent B parameters used to represent the cumulative number of fragments with mass greater than m, which can be written as

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

where M_t is the target mass, which is approximately the total fragments mass. 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 0.52.

Figure 4 clearly demonstrates an important feature of the distribution of 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 on the abscissa), 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, within which the mean value 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, where the various tests 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 values, 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 mass and is also at orbital velocities.

Figure 6 shows B versus the ratio of kinetic energy to target mass, which exhibits 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 test parameters, giving a value of $B = 0.45$.

Figure 7 shows B versus the ratio of target to projectile mass. Most of the points lie below 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 of CU 5272 discussed above. The three points at ≈ 0.45 at mass ratios of $\approx 2,000$ are FRGITS 1, 2, and 3, which have roughly the average mass ratio of all 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 most direct simply uses the average value of $B = 0.62$ from above and determines A by conservation of mass.⁴ However, DNA⁵ and NASA-Kaman efforts went further and attempted to predict the variation of B from combined empirical-theoretical models and determine A by conservation, producing the Fragmentation Algorithms for Strategic and Theater Targets (FASTT) Empirical Breakup Model.⁶ By contrast, NASA EVOLVE calculations continue to use a form

$$C = 0.4478[(M_t + M_p)/m]^{-0.7496}, \quad (2)$$

which was postulated on the basis of earlier experiments. In the comparisons below, the EVOLVE value for B is rounded to 0.75, which should not reduce accuracy below, as the experiments are not reported to better precision.⁷

The accuracy of the "average B" ($=0.62$) approximation is obvious from the discussion above: it agrees precisely with the mean experimental value of B, although it does not attempt to capture all of its variations. The calculations below do, however, properly reflect the reduction in B for collisions involving very large ratios of target to projectile mass.

Training data. The FASTT model is trained on a "SOCIT subset" of the full set of the test data set indicated by Table III.A "Included." Applied to this subset, the average B process produces the average value $B = 0.693$ shown. FASTT model predictions, indicated by A_f and B_f , are also shown. The A_f former shows much less variation than the experimental A; its mean value is about 20% below that of the data. B_f 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 results from averaging over variations from +6% in SOCIT 3 (MOCK 2 Oscar) to -13% in SOCIT 4 (Oscar), which is as large as the difference between different models at issue.

The EVOLVE calculation $B \approx 0.75$ 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. These values systematically overestimate 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 of about 8.3% for the SOCIT subset.

Additional data. The tests excluded from the full set to form the SOCIT subset are shown in Table III.B "Excluded." 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 for the additional data are shown in the right column of Table III. B and displayed in Fig. 12. They systematically overestimate B below for all but the one point above 0.75 by ratios ranging up to 60-80% for $B = 0.4$ to 0.5 , which are the most likely values in this subset. The overall average error is about 42%, as shown.

The mean of the SOCIT subset overestimates the average B for the full test sample by about $0.69/0.62 \approx 11\%$. 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%. Thus, there are two issues in using the EXCEL constant $B = 0.75$ to represent the full test data set. The first is that it overestimates B for the SOCIT subset for which the FASTT mean is reasonably accurate. The second is that 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 used in selecting the SOCIT subset has effectively included 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 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. DoD 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 coefficient A and fragment production exponent 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 bimodal, has saturating variation with V and specific kinetic energy, and has little systematic variation with the ratio of target to projectile mass below about 1,000. Collection efficiency varies widely, averages $\approx 50\%$, and shows little correlation with B.

The FASTT model reproduces the SOCIT data with which it is trained. The EVOLVE prescription overestimates that data about 8%. For the remainder of the test data, the EVOLVE prediction of B is about 42% high. Overall, the EVOLVE prediction is high by about 26%.

There are two issues in using the EXCEL fragment production exponent to represent the full test data set. It overestimates B for the SOCIT subset, and the SOCIT subset is not representative of the full data set. The selection process for the SOCIT test set includes those tests with large values of the exponent and excludes those with small values. This process biases the sample so far from the whole population that the value of its fragment production is not

appropriate for averaging over debris distributions or estimating fragment production rates. The average exponent is a more appropriate parameter for those purposes.

References

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- ¹ D. McKnight, R. Maher, L. Nagl, "Fragmentation Algorithms for Strategic and Theater Targets (FASTT) Empirical Breakup Model," DNA/SPSP report January 1994 (Kaman Sciences Corporation, Washington).
 - ² G. Gleghorn, Orbital Debris (Washington, National Academy Of Science, National Research Council, 1995), p. 89, Fig. 4-9.
 - ³ G. Canavan, Los Alamos letter P/AC:97-139, 27 June 1997, to F. R. Naka.
 - ⁴ G. Canavan, O. Judd, and F. Naka, "Comparison of Space Debris Estimates," SAB report.
 - ⁵ D. McKnight, R. Maher, L. Nagl, "Fragmentation Algorithms for Strategic and Theater Targets (FASTT) Empirical Breakup Model," op. cit.
 - ⁶ D. McKnight, N. Johnson, M. Fudge, and T. Maclay, "Analysis of SOCIT Debris Data and Correlation to NASA's Breakup Models," NASA 9-19215 JSC-SNC (Kaman Sciences Corp. July 1995).
 - ⁷ N. Johnson, NASA JSC letter to W. Ballhaus, 2 May 1997.

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 III. Averages for partitioned test sets.							
A	Included						
	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	0.63	0.6927	0.494	0.682	-0.0155	0.0827
B	Excluded						.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	0.95	0.5575				0.4161

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.

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

B vs KE/Mt

ratio of kinetic energy to target mass

Fig. 6. B versus ratio of projectile kinetic energy to target mass.

B vs M_t/M_p

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

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