TECHNICAL REPORT RDMR-WD-16-47

HIGH-VELOCITY IMPACT FRAGMENTATION OF PROJECTILES EXPERIMENTAL RESULTS

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October 2016

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REPORT DOCUMENTATION PAGE				**Form Approved** **OMB No. 074-0188**

1. AGENCY USE ONLY	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	October 2016	Final

4. TITLE AND SUBTITLE
High-Velocity Impact Fragmentation of Projectiles Experimental Results

5. FUNDING NUMBERS

6. AUTHOR(S)
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ATTN: RDMR-WDP-S
Redstone Arsenal, AL 35898-5000

8. PERFORMING ORGANIZATION REPORT NUMBER
TR-RDMR-WD-16-47

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSORING / MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION / AVAILABILITY STATEMENT	12b. DISTRIBUTION CODE
Approved for public release; distribution is unlimited.	A

13. ABSTRACT (Maximum 200 Words)
This report documents the results of experiments conducted by the joint efforts of the United States (U.S.) Army Aviation and Missile Research, Development, and Engineering Center (AMRDEC) and Armament Research, Development, and Engineering Center (ARDEC) in support of the Joint Insensitive Munitions Program (JIMTP) Tube-Launched, Optically Tracked, Wire-Guided (TOW) 2B Insensitive Munitions (IM) Warhead effort. The referenced experiments were conducted to determine the velocity reduction and fragmentation profile of barrier materials subjected to impact by the IM Fragment Impact (FI) test. Velocity reduction and the distribution in collected fragment sizes are presented for a total of 40 impact tests.

14. SUBJECT TERMS	15. NUMBER OF PAGES	16. PRICE CODE
Insensitive Munitions, Impact Fragmentation, Particle Impact Mitigation Sleeve (PIMS)	22	

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	SAR

NSN 7540-**01**-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102

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I. INTRODUCTION

This report documents the results of experiments conducted by the joint efforts of the United States (U.S.) Army Aviation and Missile Research, Development, and Engineering Center (AMRDEC) and Armament Research, Development, and Engineering Center (ARDEC) in support of the Joint Insensitive Munitions Program (JIMTP) Tube-Launched, Optically Tracked, Wire-Guided (TOW) 2B Insensitive Munitions (IM) Warhead effort.

The principle IM technology investigated in support of this effort was a Particle Impact Mitigation Sleeve (PIMS), which consists of a barrier material intended to reflect the impact shock of an incoming projectile, reducing the magnitude of shock transmitted to the explosive fill. The inclusion of PIMS is intended specifically to lower response to impact stimuli, such as IM Bullet Impact (BI) or Fragment Impact (FI). As a part of the PIMS design, a series of 41 IM FI tests were conducted against various inert plate configurations to gain insight into the PIMS defeat mechanism. The primary goals of this test series were to identify the capability of various plate materials to cause fragmentation of the projectile and the maximum velocity reduction achievable within a barrier plate weight class.

II. TEST SPECIFICS

A. Test Matrix

The materials selected for testing included 1045 steel plate, perforated 1045 steel plates (P900, perforations for weight reduction), 2024 aluminum, titanium, tungsten, and various fiber composites. The fiber composites included carbon fiber (CF) and Nextel^{TM} Fiber (NF) in varied matrix materials, including epoxy, silicon carbide (SiC), and silicon oxycarbide (SiOC). In addition to variations on plate material, the plates were also combined into spaced and unspaced arrays for several tests. Detailed test matrices can be found in Tables 1 and 2 and separated by single material shots, arrayed shots, and arranged in chronological order. The material legend for Tables 1 and 2 can be found in Table 3.

Table 1. Single Material Test Matrix

Test Number	Thickness (mm)	Material	Total Mass (g)	Projectile Velocity (ft/s)
1	3	P900 Diamond	295.30	8,510.0
2	2	Steel	251.00	8,441.5
3	9	CF/SiC/E	400.10	8,516.0
4	9	CF/NS/E	335.20	8,351.5
5	7	NF/SiOC	249.50	8,459.5
6	5.72	Aluminum	249.70	8,430.0
7	4.75	P900 Slot	415.10	8,462.0
8	6	Steel	754.70	8,380.5
12	9	Steel	1,131.40	8,097.0
13	4.5	Steel	562.00	8,214.0
17	9	P900 Round	732.20	8,372.5
18	9	P900 Steel Slot	593.10	8,183.0
19	3	Tungsten	1,358.20	8,271.0
20	4.75	P900 Slot	419.10	8,230.0
21	4.5	P900 Round	365.50	8,276.5
28	7	CF/NS/E	252.27	8,277.7
29	7	NF/E	349.03	8,133.5
31	7	NF/E	345.60	8,193.0
32	4.5	P900 Round	294.51	8,209.0
34	3	Steel	368.33	8,148.0
36	3.27	Titanium	334.66	8,137.0
37	9	CF/NS/E	336.40	8,124.3
39	7	CF/SiOC	307.31	8,029.0
33	8.64	Aluminum	379.30	8,023.0

Table 2. Layered Materials Test Matrix

Test Number	Layer 1 Thickness	Layer 1 Material	Layer 2 Thickness (mm)	Layer 2 Material	Layer 3 Thickness (mm)	Layer 3 Material	Total Thickness (mm)	Total Mass (g)	Projectile Velocity (ft/s)
9	3	Steel	3	Air Gap	3	Steel	8.99	748.4	8376
10	3	Steel	6	Air Gap	6	CF/SiC/E	15.21	638.3	8116
11	4.75	Alumina	4	Aluminum	--	--	8.63	1099.2	8415
14	3	Steel	6	CF/SiC	--	--	5.94	636.8	8325
15	2	Steel	4.5	Air Gap	7	NF/E	13.41	489.7	8201
16	3	CF/SiC	4.5	Air Gap	3	P900 Round	10.76	452.6	8305
22	6	CF/SiC	4.5	Air Gap	3	Tungsten	13.82	1626	8198
23	3	CF/SiC	4.5	Air Gap	9	P900 Round	16.62	871	8158
24	3	P900 Round	4.5	Air Gap	3	CF/SiCE	10.54	449	8189
25	3	CF/SiC	4.5	P900 Slot	3	Tungsten	10.49	1760	8267
26	9	CF/SiC	9	CF/NS	--	--	18.20	725	8155
27	4.5	P900 Slot	1.5	Air Gap	9	P900 Slot	14.59	894	8232
30	7	NF/E	4.5	Air Gap	3	Steel	14.22	714	8231
35	3	Steel	3	Air Gap	8.62	Aluminum	14.61	749	8146
38	2	Steel	10.5	Air Gap	3	Steel	15.47	615	8264
40	3.5	CF/SiOC	3.5	SiOC	3.27	Titanium	17.12	965	8182

Table 3. Material Legend for Test Matrices

Key	Material
CF	carbon fiber
SiC	silicon carbide
SiOC	silicon oxycarbide
E	Epoxy
NF	Nextel™ Fiber
NS	nano-silica
P900	Steel Plate With Through Holes

B. Test Setup

Tests were conducted at the General Dynamics Rock Hill in Defuniak Springs, FL test facility In Accordance With (IAW) MIL-STD 2105D and the North Atlantic Treaty Organization (NATO) Standard Agreement (STANAG) 4496. The STANAG steel fragment weighing 18.6 grams (g) with a diameter of 14.3 millimeters (mm) and a length to diameter ratio of 1 was used for all tests. Fragment mass and hardness were recorded for test shots. Fragments were fired from the 40 mm powder gun. Velocity screens and high-speed cameras were used to record velocity. All shots had a target velocity of 8,300 feet per second (ft/s) and a projectile mass of approximately 18.6 g. Inert plates were placed perpendicular to the shotline with aimpoint near the center of the plates. The test setup is shown in Figures 1 and 2.

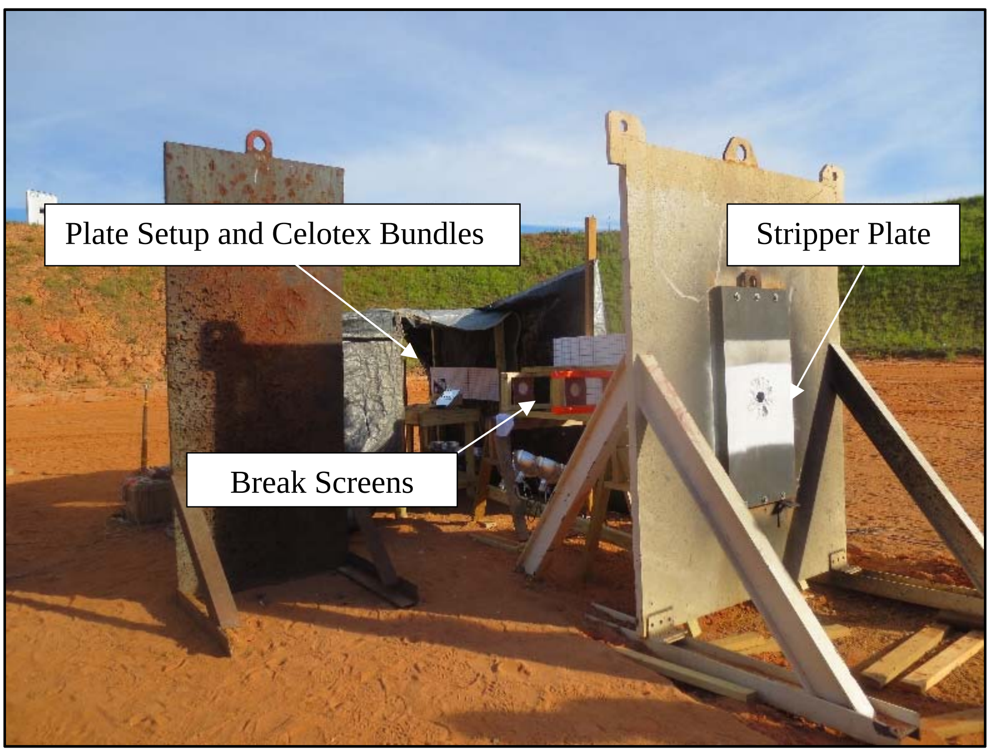


Figure 1. Test Setup

Figure 2. Target Setup

Time of Arrival (TOA) break screens were used to collect and calculate fragment velocity. Celotex bundles were used to catch debris from the engagement. A laser boresight was used to mark the aimpoint of the gun on the front plate and Celotex bundles, as shown in Figure 1. A board marked with lines forming 1-inch squares was used as a fiducial to determine impact orientation and residual velocity. The board was also used to provide a secondary estimate of impact velocity via High-Speed Video (HSV).

Cameras were positioned perpendicular to the break screens. The view area of each camera was adjusted to include fiducial lines on both sides of the target plate. Measurements were taken from each camera to the shotline and shotline to fiducial grid and were used to account for parallax due to the fragment being away from the grid. Scale factors were calculated by measuring the distance between grid squares to calibrate velocity measurements. Frame rates of 21,000 to 26,000 Frames per Second (FPS) were used resulting in a fragment travel of approximately 4 to 5 inches per frame. Camera resolutions of 512-by-200 and 512-by-256 were used, resulting in pixel-to-pixel resolution of approximately 0.09 inches. This resolution permits velocity measurements across two frames to have a resolution of ±100 ft/s. Figure 3 shows the resulting projectile fragments exiting an inert plate.

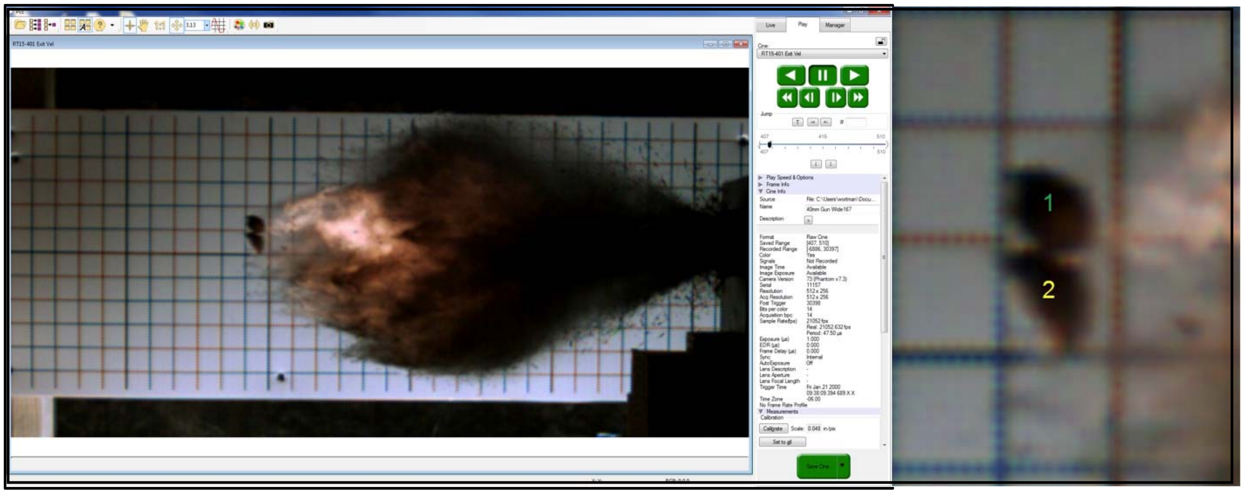


Figure 3. HSV Data

Leading-edge fragments were numbered, and velocity measurements were taken for each fragment. Residual velocity was calculated for the fastest residual fragment and for the average of the leading edge fragment group. Residual velocity was calculated by the following equation:

$$V_r = \frac{N_p * SF}{N_f * FPS}$$

where, N_p is the number of pixels the fragment travels between one or more camera frames, *SF* is the scaling factor, N_f is the number of frames, and *FPS* is the frame rate. Fragments exiting the plates were often obscured for a few frames by a fireball or fine debris exiting the plates. A few composite cases had so much debris for the entire viewable section after the plates that it was impossible to distinguish individual fragments. In these cases, the leading edge of the debris cloud was measured and used for residual velocity. The maximum residual velocity (the fastest fragment) and average residual velocity (average of leading edge fragments) were recorded for further analysis.

III. TEST RESULTS

On completion of the test series, the impact and exit velocities were computed from TOA and HSV evidence, leading to a percent velocity reduction for plates of a given mass. Areal density was calculated along the shotline thickness and used for generating mass-independent comparisons. As an additional metric, a mass efficiency was calculated by dividing the total velocity reduction by the plate mass.

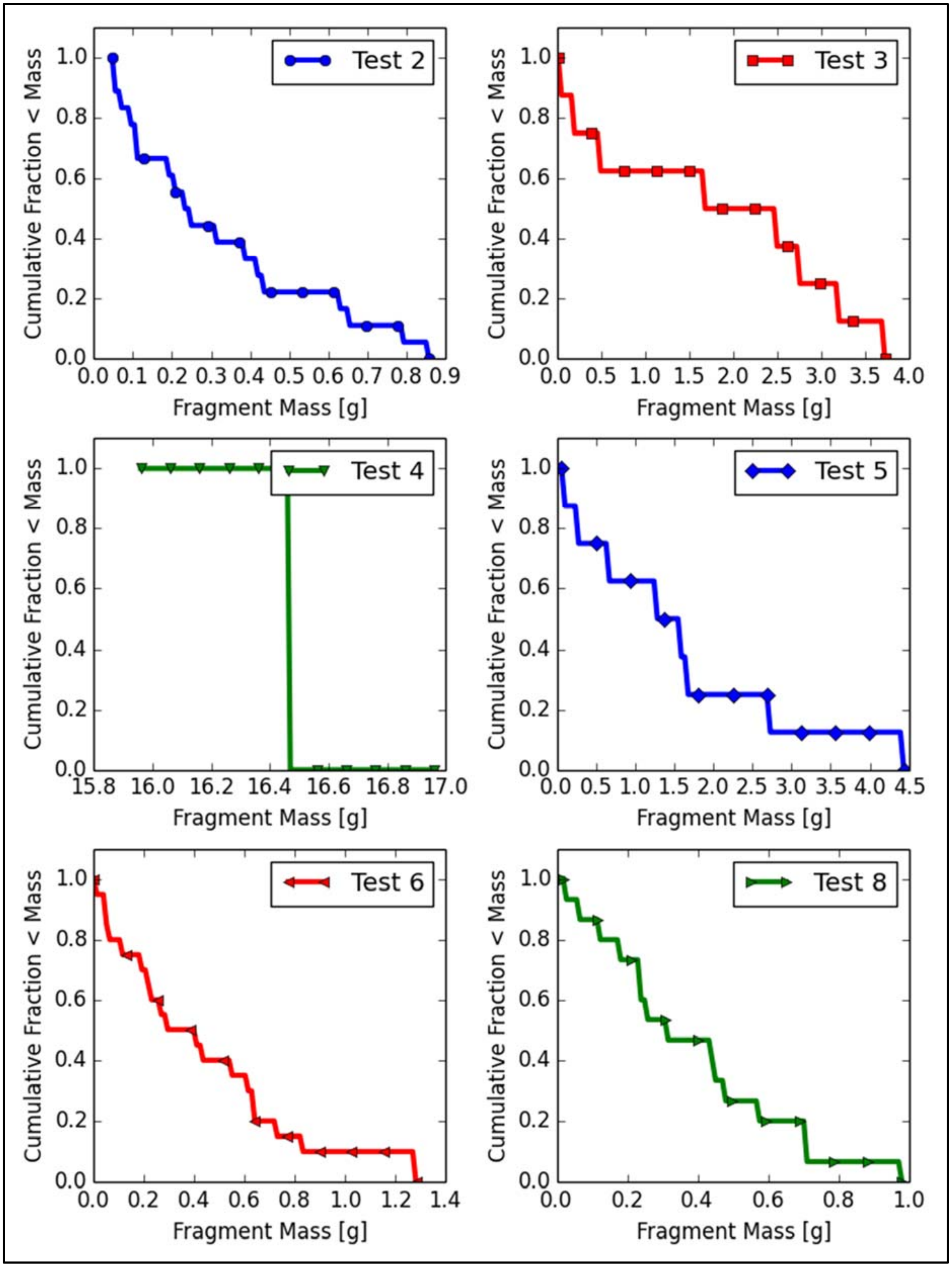
Fragments recovered from the collection media were cleaned and individually weighed to provide the distribution in fragment sizes. Velocity reduction data and summary statistics from the recovered fragments appear in Table 4. The cumulative distribution in fragment sizes from each test in which fragments were recovered can be found in Figure 4.

Table 4. Summary Test Results

Test Number	**Velocity Reduction (ms)**	**Percent Reduction (%)**	**Areal Density (g/cm^2)**	**Mass Efficiency (m/s/g)**	**Number Fragments**	**Number > 0.5g**	**MAX (g)**	**AVG (g)**	**STDEV (g)**
1	1085	12.7	1.83	8.43	-	-	-		
2	845	10.0	1.56	8.27	18	4	0.86	0.32	0.26
3	1,311	15.4	1.72	9.63	8	5	3.73	1.81	1.44
4	1,147	13.7	1.44	9.66	1	1	16.46	-	-
5	922	10.9	1.61	8.80	8	6	4.44	1.57	1.44
6	995	11.8	1.55	9.44	21	5	1.28	0.44	0.38
7	1,708	20.2	2.57	8.80	-	-	-	-	-
8	2,213	26.4	4.68	6.24	15	4	0.98	0.38	0.27
9	2,630	31.4	4.64	6.94	21	5	2.24	0.48	0.55
10	2,149	26.5	3.45	8.14	18	6	1.27	0.46	0.35
11	1,783	21.2	3.45	6.57	26	8	2.17	0.43	0.54
12	3,068	37.9	7.01	5.51	37	4	0.68	0.39	0.46
13	1,594	19.4	3.48	5.92	15	5	2.71	0.24	0.19
14	1,462	17.6	3.45	5.61	18	6	3.53	0.62	0.71
15	1,800	21.9	2.56	8.75	19	8	2.25	0.58	0.83
16	1,606	19.3	2.55	8.01	-	-	-	0.67	0.67
17	2,574	30.7	4.54	7.20	17	2	4.15	0.59	1.02
18	2133	26.1	3.68	7.86	20	4	1.53	0.40	0.42
19	1,994	24.1	5.85	4.62	23	4	1.33	0.35	0.39
20	1,196	14.5	2.60	7.73	-	-	-	-	-
21	461	5.6	2.27	4.29	18	5	2.87	0.58	0.76
22	3,490	42.6	7.00	6.12	16	4	2.37	0.45	0.56
23	2,735	33.5	5.14	6.69	12	6	3.18	0.75	0.88
24	803	9.8	2.53	5.57	13	5	2.78	0.73	0.72
25	2,800	33.9	8.14	4.56	10	5	2.90	0.73	0.83

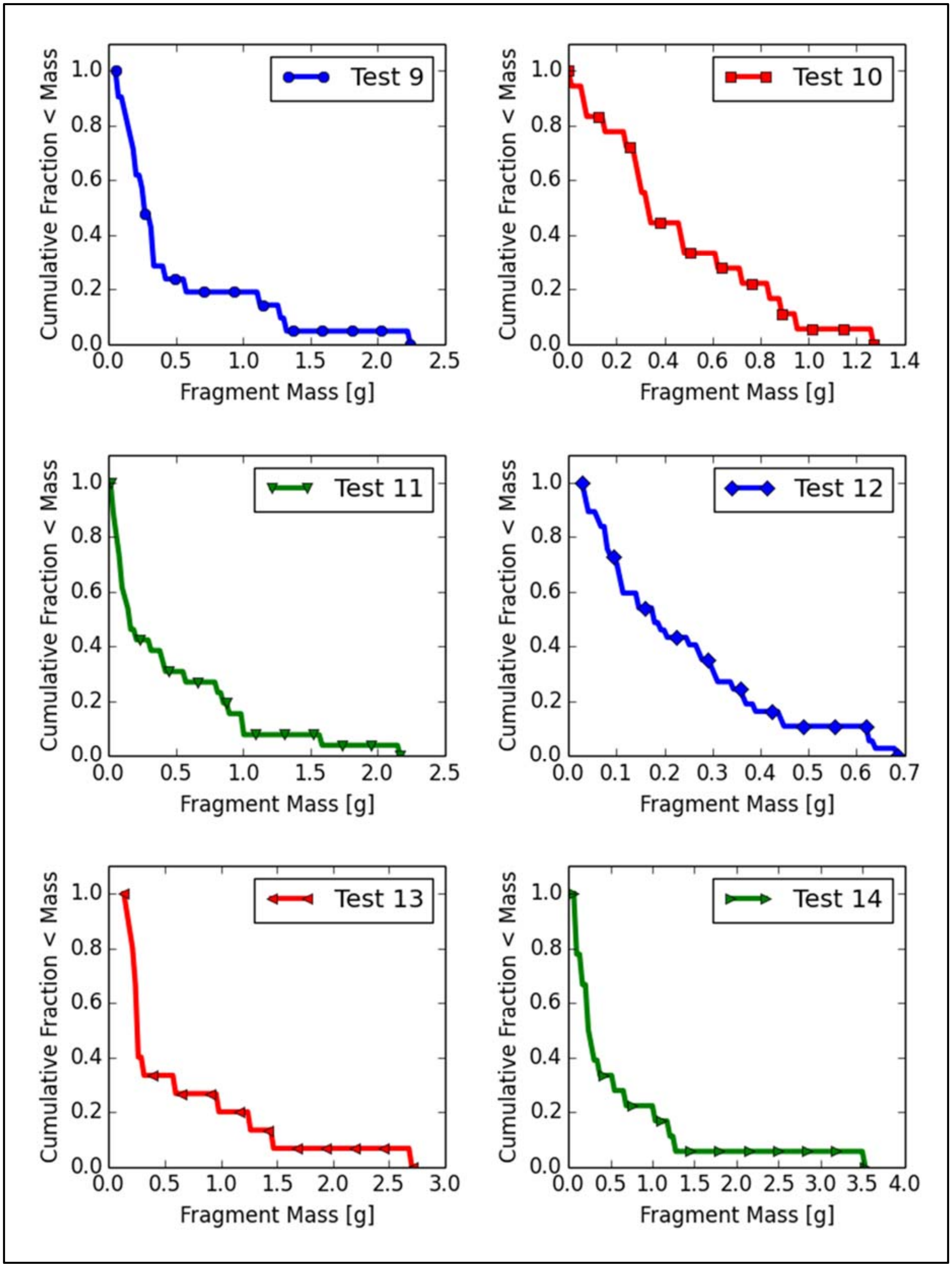
Table 4. Summary Test Results (Concluded)

Test Number	Velocity Reduction (ms)	Percent Reduction (%)	Areal Density (g/cm^2)	Mass Efficiency (m/s/g)	Number Fragments	Number > 0.5g	MAX (g)	AVG (g)	STDEV (g)
26	1,989	24.4	3.12	8.74	13	7	3.94	1.17	1.17
27	2,297	27.9	5.55	6.12	16	3	1.31	0.29	0.34
28	599	7.2	1.09	6.71	-	-	-	-	-
29	776	9.5	1.50	7.42	-	-	-	-	-
30	1,668	20.3	3.76	6.23	26	9	3.51	0.63	0.90
31	593	7.2	1.49	6.66	13	7	2.53	0.96	0.71
32	896	10.9	1.83	8.76	-	-	-	-	-
33	1,429	17.8	2.35	7.81	14	8	3.08	0.92	0.88
34	895	11.0	2.28	6.99	9	4	1.37	0.61	0.43
35	2,394	29.4	4.65	7.17	15	6	2.89	0.66	0.70
36	871	10.7	1.44	9.43	14	6	3.05	0.75	0.86
37	1,139	14.0	1.45	9.56	1	1	16.43	-	-
38	2,106	25.5	3.81	7.49	13	3	2.59	0.55	0.65
39	578	7.2	1.32	6.33	1	1	17.88	-	-
40	2,296	28.1	4.15	7.26	3	3	5.23	3.60	2.57



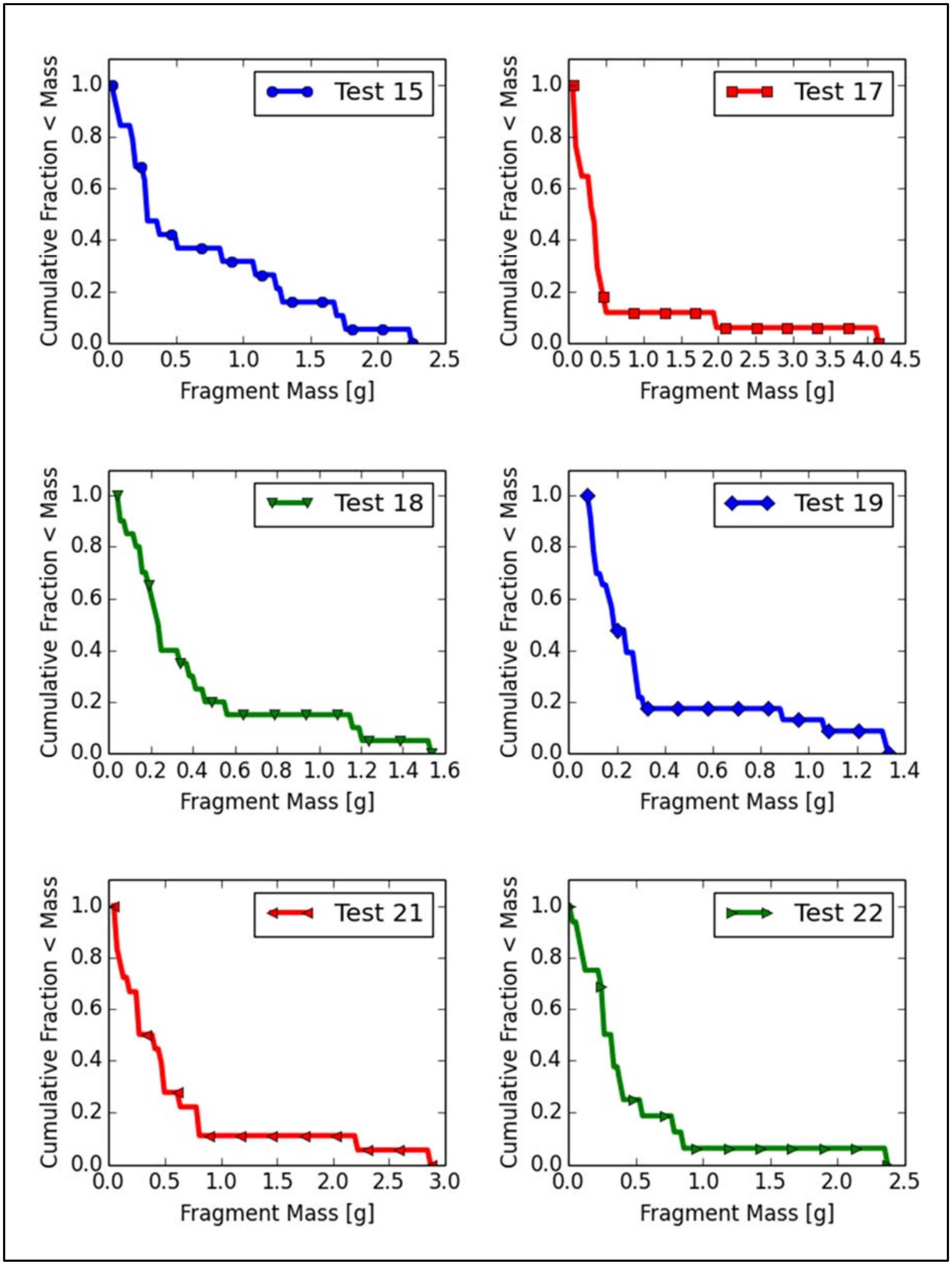
(a) Tests 2-8

Figure 4. Cumulative Distribution of Fragment Sizes



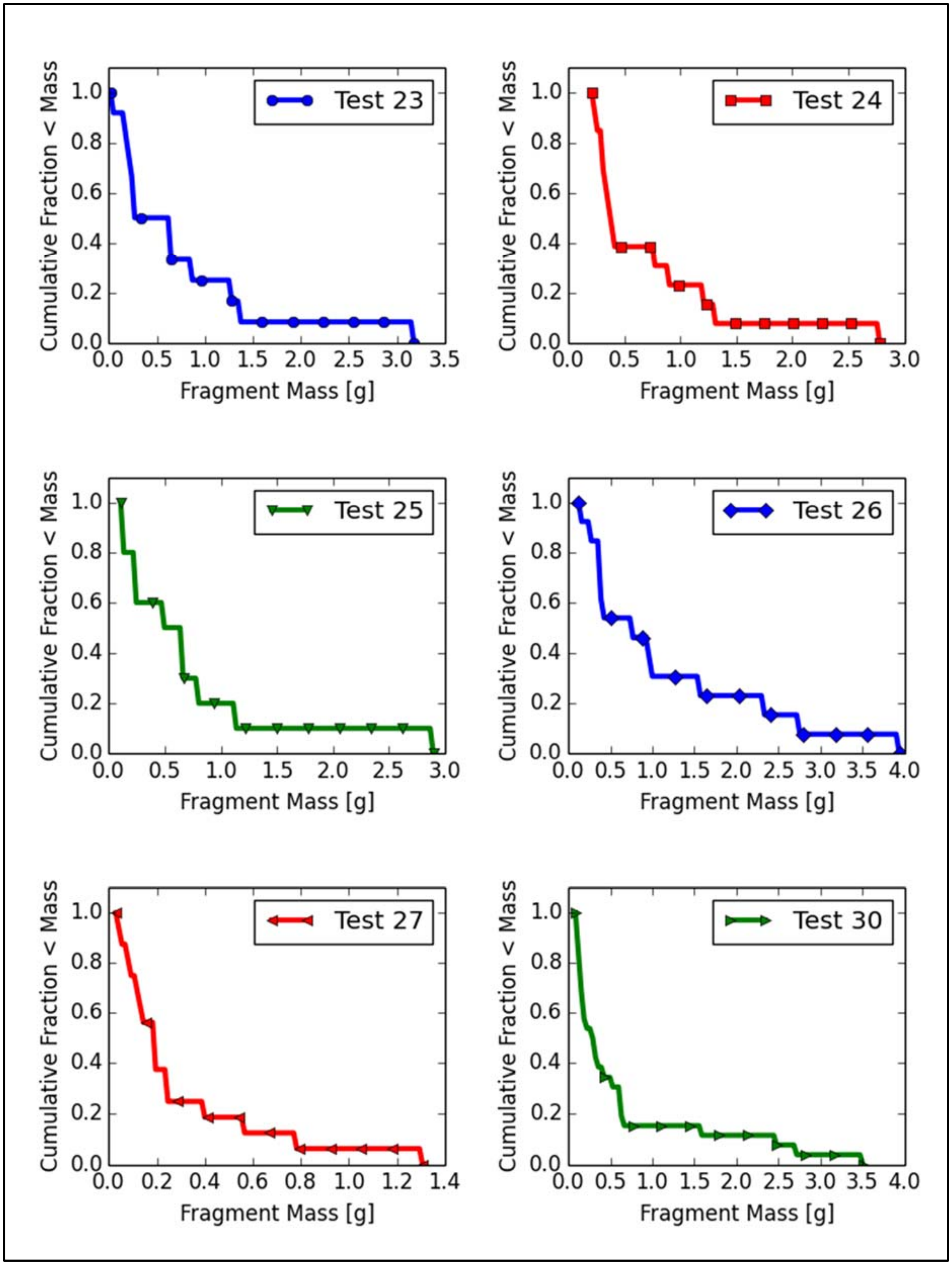
(b) Tests 9-14

Figure 4. Cumulative Distribution of Fragment Sizes (Continued)



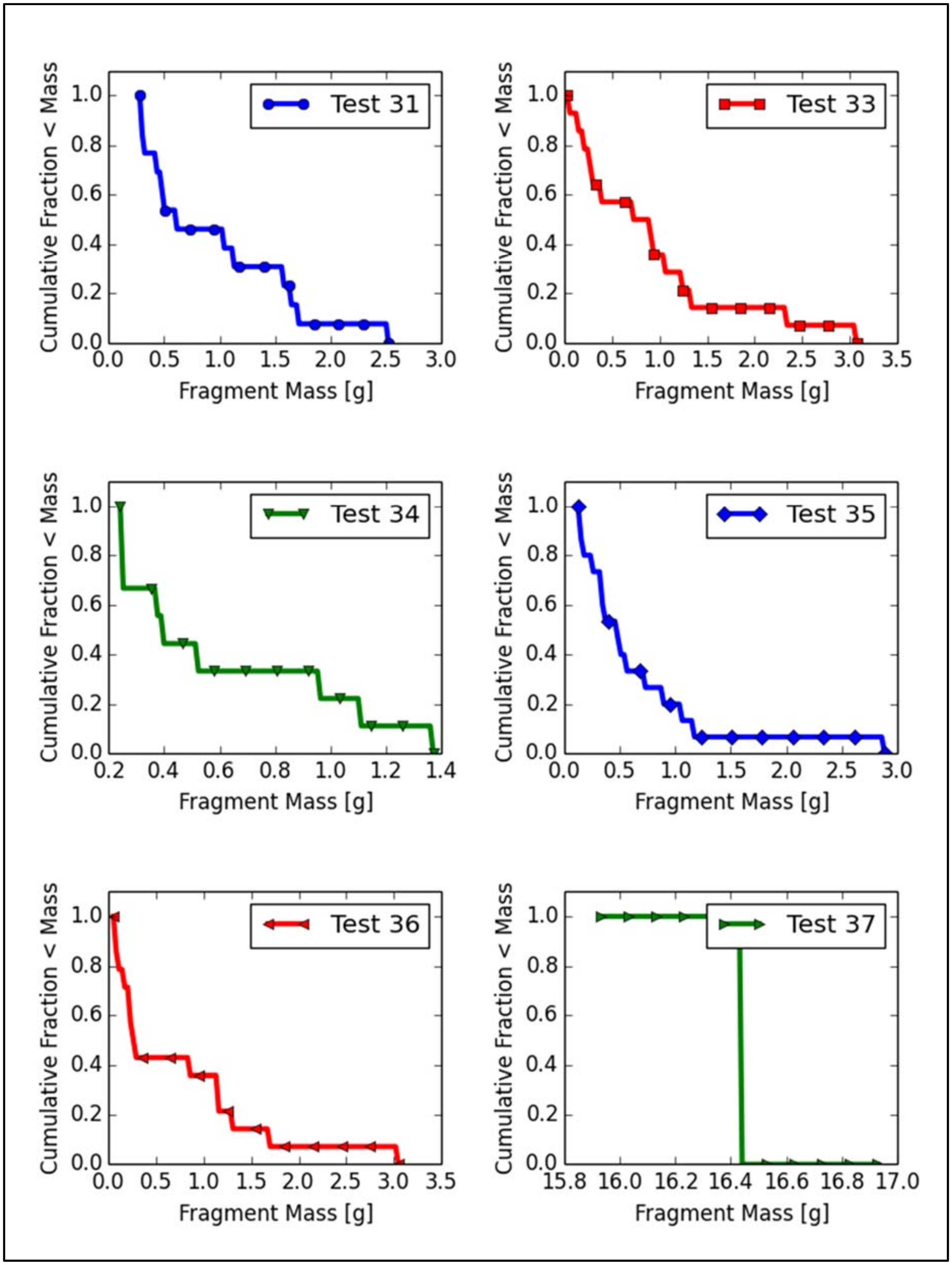
(c) Tests 15-22

Figure 4. Cumulative Distribution of Fragment Sizes (Continued)



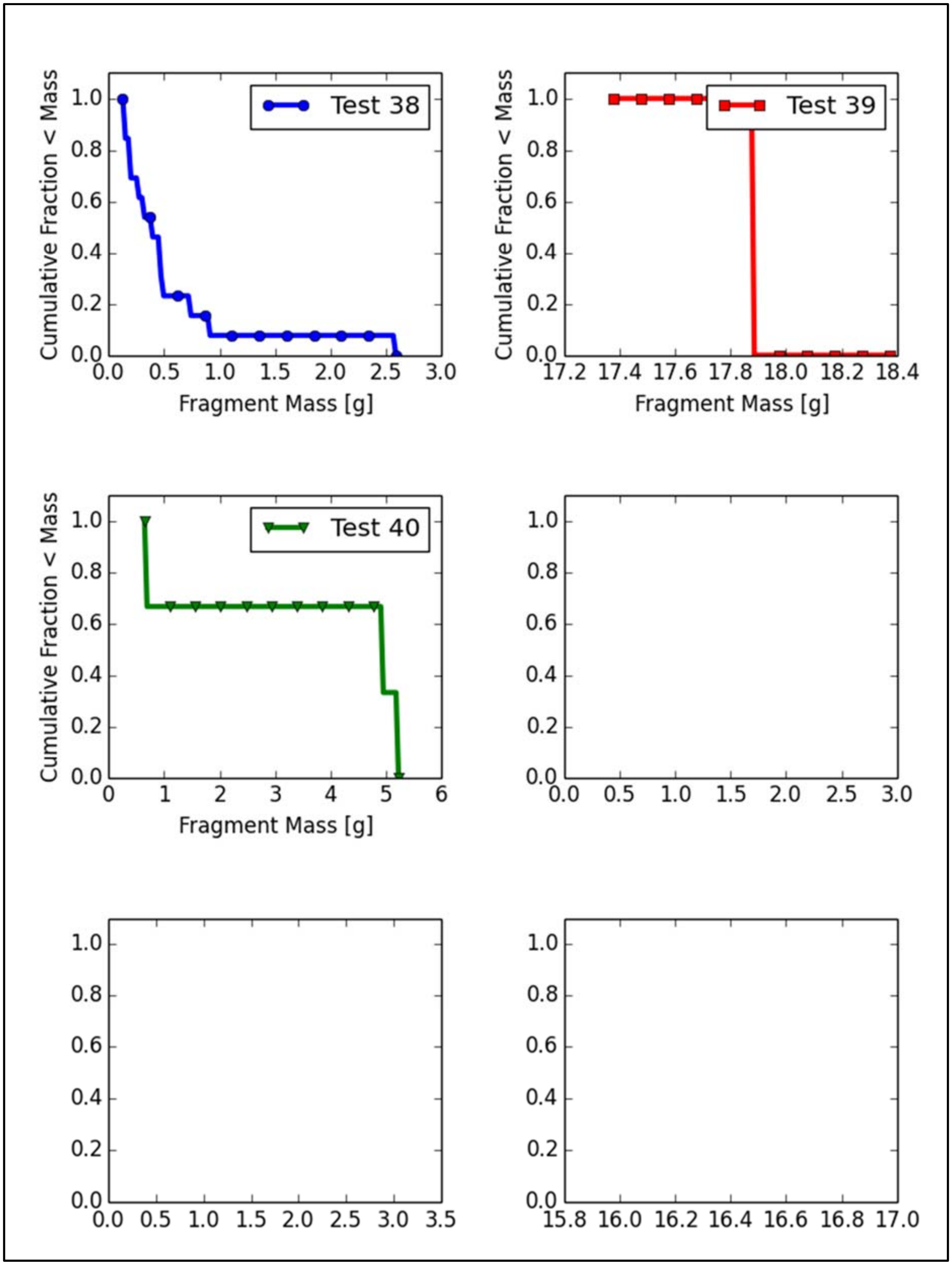
(d) Tests 23-30

Figure 4. Cumulative Distribution of Fragment Sizes (Continued)



(e) Tests 31-37

Figure 4. Cumulative Distribution of Fragment Sizes (Continued)



(f) Tests 38-40

Figure 4. Cumulative Distribution of Fragment Sizes (Concluded)

IV. FINAL SUMMARY AND CONCLUSIONS

This test series has provided insight into the use of different material classes and geometric configurations in the construction of PIMS and other barrier methods as they relate to dispersing the energy of a high-velocity projectile. Further analysis will be performed using these data to optimize protective features for a given energy dispersal mechanism, whether that mechanism is reduction of velocity or fragmentation of the projectile.

LIST OF ABBREVIATIONS, ACRONYMS, AND SYMBOLS

%	percent
~	Approximately
>	greater than
<	less than
±	plus or minus
AMRDEC	Aviation and Missile Research, Development, and Engineering Center
ARDEC	Armament Research, Development, and Engineering Center
AVG	Average
BI	Bullet Impact
CF	carbon fiber
E	Epoxy
FI	Fragment Impact
FPS	Frames per Second
ft/s	feet per second
g	gram
g/cm^2	grams per square centimeter
HSV	High-Speed Video
IAW	In Accordance With
IM	Insensitive Munitions
JIMTP	Joint Insensitive Munitions Program
m/s	meters per second
m/s/g	meters per second per grams
MAX	Maximum
MIL-STD	Military Standard
mm	millimeter
NATO	North Atlantic Treaty Organization
NF	Nextel™ Fiber

LIST OF ABBREVIATIONS, ACRONYMS, AND SYMBOLS (CONCLUDED)

NS	Nano-Silica
PIMS	Particle Impact Mitigation Sleeve
SC	silicon carbide
SiOC	silicon oxycarbide
STANAG	Standardization Agreement
STDEV	Standard Deviation
TOA	Time of Arrival
TOW	Tube-Launched, Optically Tracked, Wire-Guided
U.S	United States