NASA CR 92016

DAC-59816

HYPERVELOCITY IMPACT DAMAGE IN ALUMINUM TARGETS FINAL REPORT

FEBRUARY 1968
REVISED MARCH 1968

by
R.N. TENG

Distribution of this report is provided in the interest of information exchange. Responsibility for the contents resides with the author or organization that prepared it.

Prepared under Contract No. NAS 9-7452
by Douglas Aircraft Company
Missile and Space Systems Division
Santa Monica, California
for
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

PRECEDING PAGE BLANK NOT FILMED.

PREFACE

This report was prepared by the Douglas Aircraft Company, Missile and Space Systems Division, under NASA Contract NAS 9-7452. The investigation was initiated by Manned Spacecraft Center of NASA, Houston, to determine the ballistic limit of aluminum targets when subjected to meteoroid impact. This work was administered under the direction of the Meteoroid Science Branch, William McAllum, Project Manager.

The report covers the complete work period from 14 August 1967 through 15 March 1968. It is submitted in partial fulfillment of Contract NAS 9-7452 and is cataloged by Douglas as DAC Report 59816.

At Douglas, J. L. Waisman, Director of Research and Development, and Dr. H. H. Dixon, Chief Engineer of the Advance Structures and Mechanical Department, provided technical direction; G. L. Roark acted as program manager; and R. N. Teng was study director.

At the Douglas Aerophysics Laboratory, S. G. Emigh directed the light-gas gun operation; R. C. Curtis supervised the instrumentation; and G. E. Sutila directed the design and fabrication of all the parts.

The author wishes to acknowledge the technical assistance of Mr. B. G. Cour-Palais, Mr. W. E. McAllum, and Mr. T. Lee of NASA.

PRECEDING PAGE BLANK NOT FILMED.

CONTENTS

Section 1	SUMMARY AND INTRODUCTION	1
	1.1 Summary	1
	1.2 Introduction	1
Section 2	EXPERIMENTAL TESTING APPARATUS	3
	2.1 Projectile-Launching Equipment	3
	2.2 Designs of Sabots and Techniques of Sabot Stripping	3
	2.3 Instrumentation	6
	2.4 Characteristics of Spherical Projectiles	7
	2.5 Target Configurations	7
Section 3	HYPERVELOCITY IMPACT TEST	9
	3.1 Definitions for Data Points	9
	3.2 Hypervelocity Impact Test Results	9
	3.3 Modes of Ballistic Limit in Aluminum Targets	11
Section 4	CONCLUSIONS	13
	REFERENCE	15

Table 1

RESULTS OF TEST B-30--HYPERVELOCITY IMPACT DAMAGE IN ALUMINUM TARGETS

(2024-T351)

Task Definition	Projectile Material Mass Diameter	A ** Syntactic Foam 0.11 gm 0.255 in.		B *** Aluminum 1.0 gm 0.348 in.		C ** Syntactic Foam 1.10 gm 0.551 in.		D *** Aluminum 10.38 gm 0.751 in.		E ** Syntactic Foam 10.8 gm 1.220 in.	
Semi-infinite Targets Damage	Task 1	0.80	2.0	1.90	3.0	0.190	3.00	Substituted See Below		3.35	4
		(1)		(9)		(17)				(33)	
		0.285	7.12	0.780	7.27	0.547	7.03			1.34	7.03
Single-Sheet Targets Ballistic Limit	Task 2a	0.80	0.643 S	1.90	1.625 S	1.80	1.51 S	4.250	3.72 S	3.60	3.60 S
		(2)		(10)		(18)		(26)		(34)	
		0.282	7.34	0.740	7.08	0.553	7.03	1.488	7.27	1.40	7.03
Dual-Sheet Targets Vary Back Sheet Thickness Ballistic Limit	Task 2b-1	0.025	0.078 SD	0.032	0.637 S	0.012	0.757 S	0.161	1.113 S	0.032	1.498 S
		(3)		(11)		(19)		(27)		(35)	
		3.81	7.40	5.22	7.09	8.27	7.05	11.3	7.15	17.8	7.03
(Same as Task 2b - 1)	Task 2b-2	0.025	0.080 SD	0.032	0.258 SD	0.012	0.125 SD	0.161	0.381 SD	0.032	0.243 SD
		(4)		(12)		(20)		(28)		(36)	
		7.62	7.27	10.44	7.16	16.54	7.27	22.6	7.08	35.6	7.03
(Same as Task 2b - 1)	Task 2b-3	0.025	0.080 SD	0.032	0.312 S	0.012	0.125 SD	0.161	0.245 SD	0.032	0.255 SD
		(5)		(13)		(21)		(29)		(37)	
		10.15	7.01	13.92	7.15	22.04	7.03	30.0	7.08	47.4	7.03
(Same as Task 2b - 1)	Task 2c-1	0.012	0.051 SD	0.016	0.496 S	0.008	0.759 S	0.080	0.640 S	0.020	1.25 S
		(6)		(14)		(22)		(30)		(38)	
		7.62	7.03	10.44	7.27	16.54	7.03	22.6	7.27	35.6	7.08
(Same as Task 2b - 1)	Task 2c-2	0.063	0.100 SD	0.090	0.079 SD	0.025	0.162 SD	0.322	0.315 SD	0.063	0.323 SD
		(7)		(15)		(23)		(31)		(39)	
		7.62	7.64	10.44	7.40	16.54	7.12	22.6	7.15	35.6	7.08
Dual-Sheet Targets Foam* Filled Space Vary Back Sheet Thick. Ballistic Limit	Task 2d	0.025	-0-	0.032	0.090 S	0.050	-0-	0.498	0.388 SD	0.050	0.323 SD
		(8)		(16)		(24)		(32)		(40)	
		7.62	7.27	10.44	7.15	8.27	7.03	22.6	7.27	35.6	7.03
								No Filler		No Filler	
								0.770	0.504 SD		
								(25)			
								22.6	7.27		
								No Filler			

* Polyurethane, 1.3 lb/ft^3., Open-Cell

*** "Scotchply" XP-241, 3M Co., 0.70 gm/cc

*** 2024-TB 2.18 gm/cc

LEGEND

Crater Diam (in.) | Target Thick (in.)

Data No.

Crater Depth (in.) | Impact Velocity (kmps)

Bumper Thick (in.) | Target Thick (in.)

Data No.

Bumper Spacing (in.) | Impact Velocity (kmps)

S = Spallation at Center

SD = Discrete Spallations

CROSS REFERENCE

Test Data No.	Log Run No.
(1)	A-13
(2)	A-14
(3)	A-16
(4)	A-21
(5)	A-22
(6)	A-30
(7)	A-36
(8)	A-37
(9)	B-1
(10)	B-10
(11)	B-3
(12)	B-2
(13)	B-30
(14)	B-6
(15)	B-9
(16)	B-27
(17)	C-4
(18)	C-5
(19)	C-7
(20)	C-15
(21)	C-27
(22)	C-31
(23)	C-18
(24)	C-33
(25)	D-23
(26)	D-21
(27)	D-10
(28)	D-8
(29)	D-9
(30)	D-12
(31)	D-19
(32)	D-20
(33)	E-22
(34)	E-30
(35)	E-21
(36)	E-19
(37)	E-17
(38)	E-31
(39)	E-24
(40)	E-32

FOLDOUT FRAME 1

FOLDOUT FRAME 2

Section 1
SUMMARY AND INTRODUCTION

1.1 SUMMARY

An experimental test program was conducted to determine the ballistic limits of aluminum targets under simulated meteoroid environments and to investigate the effectiveness of meteoroid shields as a function of the meteoroid's geometry, density, energy, and momentum. Forty data points of ballistic limits and hypervelocity impact on semi-infinite aluminum targets were obtained from a total of over 150 attempts. The problems encountered in launching syntactic-foam projectiles during the experiment and the techniques developed to overcome these difficulties are discussed.

1.2 INTRODUCTION

Knowledge of the meteoroid protection requirements for Earth-orbiting space stations and Mars missions is needed for planning and design exercises. The dual-wall protection system and empirical penetration criteria previously developed are based on impact energies much lower than those expected to be encountered on these extended missions. Thus, experiments are needed to guide extrapolation within these concepts. The measure of penetration resistance most useful to a spacecraft designer is the threshold of structure failure, which is commonly called the ballistic limit. The subject test program conducted at the Douglas Aerophysics Laboratory included the determination of ballistic limits for 31 dual-wall configurations, ballistic limits for 5 single-wall configurations, and 4 impacts on semi-infinite targets. All projectiles were spheres launched at 7.00 kmps minimum. The detailed information pertaining to each configuration is shown in Table 1. Although some empirical relations for predicting the ballistic limits have been formulated during the course of the test to minimize the number of shots required per datum point, the attempts to correlate these empirical relations with existing analytical theories have not been included in this report.

Section 2
EXPERIMENTAL TESTING APPARATUS

2.1 PROJECTILE-LAUNCHING EQUIPMENT

Two light-gas guns and associated ballistic ranges have been used in this test program. Range A (Figure 1) employed launch tubes of 0.500- and 0.565-in. bore and a length of 12 ft. Most launches for projectiles of 0.1- and 1-gm syntactic foam (called Series A and C) as well as of 1-gm aluminum (Series B) were made with the equipment of Range A. Range B (Figure 2) employed a launch tube with a diameter of 1.245 in. and a length of 20 ft. Projectiles of 10-gm aluminum (Series D) and 10.8-gm syntactic foam (Series E) were launched from Range B.

Both guns are of the two-stage, heavy-piston type. The operating cycle is as follows. Pressure from gunpowder ignited in the powder chamber propels a polyethylene piston down the pump tube. The piston moves subsonically, so that the launching gas (hydrogen) is compressed nearly isentropically. Initial gun conditions are set so that the piston is near the convergent (the high-pressure coupling) section when adequate pressure is generated to launch the spherical projectile and its sabot. At this time the diaphragm breaks and the projectile/sabot is accelerated down the launch tube. The piston enters the convergent section and continues to compress the reservoir gas at a rate such that the pressure on the projectile/sabot base remains effectively constant.

2.2 DESIGNS OF SABOTS AND TECHNIQUES OF SABOT STRIPPING

Three different sabot designs have been employed during the test program. Each sabot has its unique advantages and is particularly suited to a given material and size of projectile.

2.2.1 Solid Sabot and Vented Muzzle

This technique of sabot stripping was developed by the Douglas Aircraft Company and is described in Reference 1. During the projectile-acceleration phase of a typical launch cycle in a light-gas gun, the driving pressure is so great that opposing forces, such as wall friction and aerodynamic drag, have

no significant effect. However, in portions of Series A and all of Series B of the present test, vents are provided through the wall of the launch tube near its muzzle. These vents relieve the driving pressure as the projectile/sabot approaches the muzzle and the friction and aerodynamic drag forces begin to impede the sabot significantly. Then, as soon as a minute separation occurs between projectile and sabot, principally due to wall friction, the aerodynamic drag on the separated projectile within the muzzle effectively vanishes so that both friction and aerodynamic drag on the sabot work to increase the separation distance. The muzzle of the vented launch tube is purposely slightly bent. An adequate separation usually occurs prior to arriving at the bend. Because the projectile is smaller than the launch-tube bore, it continues to travel along a straight line, whereas the sabot, having the same diameter as the bore, follows the bend. While the projectile continues on course, the sabot is directed toward impact on an adjacent baffle plate.

2.2.2 The Wax Seal

During Series A of the test program, it was established that launching integral projectiles of syntactic foam would be a problem due to the relative tensile weakness of this material. (Technical data on syntactic foam are given in Table 2.) This problem was handled by a careful and conventional sabot design in Series A and by a new sabot technique in Series C and E. The objective in the latter cases was to minimize the sabot mass, thereby permitting the required projectile velocity to be achieved by application of some minimum base pressure, minimum acceleration, and minimum internal stress in the projectile.

For Series C and E, the launch-tube bore was made only slightly larger than the projectile diameter, and for a sabot, a thin wax ring was deposited around the equator of the projectile where it touches the wall. During the onset of the acceleration phase of the launch, the wax ring prevents the driving gas from blowing past the model. The wax ring is melted away to some extent in the launch tube and may be further stripped off during flight by aerodynamic and inertial forces. From photographs of the projectile in flight and from assessment of damage to the witness plate (the bumper), no evidence of wax attached to the projectile has been found. The wax seal

Table 2

TYPICAL PROPERTIES OF 3M SCOTCHPLY XP-241 SYNTACTIC FOAM

Nominal Density	42 lb/ft^3		40 lb/ft^3		38 lb/ft^3		36 lb/ft^3	
	Before	After Exposure*	Before	After Exposure*	Before	After Exposure*	Before	After Exposure*
Net buoyance (nominal) lb/ft^3 in sea water	22		24		26		28	
Water absorption, %w	-	0.92[a] 2.2[b]	-	1.10[c]	-	1.9[c]	-	2.1[c]
Compressive strength, uniaxial, ultimate, psi	13,400	12,600	12,000	10,900	10,200	10,300	9,600	9,600
Compressive yield uniaxial, psi	10,400	9,500	100,300	8,300	8,500	8,200	8,100	7,100
Compressive modulus uniaxial, psi	480,000	480,000	458,000	438,000	392,000	385,000	373,000	372,000
Hydrostatic crush point, psi	16,000		14,600		13,400		12,600	
Tensile strength, psi	4,600		3,600				3,300	
Flexural strength, psi	6,100		6,000				3,800	
Shear strength, psi	4,400		4,100				3,800	
Bulk modulus, psi	582,000		538,000		353,000		340,000	

* Refers to test values after exposure in water under conditions cited for each foam density.

a. A thousand cycles (20-min ASTM) to 10,000 psig.

b. Six weeks at static load of 10,000 psig on 1-in. diameter x 2-in. long cylindrical specimens.

c. Six weeks at static load of 5,000 psig on 1-in. diameter x 2-in. long cylindrical specimens.

NOTE: Values stated above are average for the density range cited. Minimum average specification values will be subject to negotiation. The 36-lb/ft^3 foam complies with proposed Specification MIL-S-24154A for Type I material. Specification requirements for Type II foam per MIL-S-24154A are being developed by the Navy.

technique has functioned without loss in performance when the frontal area of the projectile is greater than 95% and less than 98% of the launch-tube bore area.

2.2.3 Mechanical Stripper

A solid polycarbonate (Lexan) sabot is used in conjunction with the mechanical stripper. The stripper consists of a restrictor ring, which has an inside diameter larger than the projectile and smaller than the sabot, and is placed in a specially designed muzzle adapter. As the sabot and the projectile arrive at the muzzle, the projectile passes through the center of the restrictor ring without interference, whereas the sabot impacts against the ring. The debris of the shattered sabot is filtered by a set of baffles located downstream.

2.3 INSTRUMENTATION

The minimum requirements for determination of velocity and projectile integrity is one in-flight photograph and two time-vs-position data points. However, a certain amount of redundancy is useful for the following reasons:

1. The increase in reliability reduces the chances of a total instrumentation failure.
2. Confidence in the velocity determination is increased through comparison of several independent measurements.
3. Three or more time-vs-position data points allow a direct measurement of drag losses whenever those losses are significant.
4. Several in-flight projectile photographs decrease the possibility of any damage to the projectile being undetected.

Range A instrumentation includes the following:

1. Two flash X-ray units located 11.30 ft apart along the flight axis (Figure 1).
2. Three electro-optical projectile-detection devices located 3.00 ft apart along the flight axis.

The flash X-ray units provide shadow-image radiographs of the projectile in flight. The exposure duration for these units ranges from 25 to 70 nsec. In addition to projectile integrity, these units, in conjunction with Beckman 10-mHz counters, generate velocity data to an accuracy of 0.5%.

The outputs of the three projectile-detection devices are displayed on Tektronix oscilloscopes and provide backup velocity measurement to an accuracy of 3%.

Range B instrumentation includes the following:

1. Three parallel-light spark-shadowgraph stations spaced at 5-ft intervals along the flight-axis. Each station provides two mutually orthogonal shadowgraphs of the projectile in flight.
2. Two flash X-ray units.
3. Two electro-optical model detectors.
4. One impact-flash phototube and one photodiode at the target.

The shadowgraph systems, together with the Beckman counters, provide velocity measurement to an accuracy of 0.1%. The flash X-ray units, in conjunction with Beckman counters, generate velocity data to an accuracy of 0.5%. The outputs of the model detectors and the impact-flash phototube can provide velocity data, when displayed on Tektronix oscilloscopes, with a 3% accuracy.

2.4 CHARACTERISTICS OF SPHERICAL PROJECTILES

The characteristics of spherical projectiles used in this test program are listed below. The projectiles are pictured in Figure 3.

2.5 TARGET CONFIGURATIONS

All targets and bumpers are aluminum alloy 2024-T351 "as purchased" plate stock. When odd thicknesses were needed, plates of proper thickness were machine-milled from thicker plates.

A witness plate of 0.25-in. thick titanium, 6Aℓ-4V, is placed 5 in. downstream of the rear face of primary target.

Test Series	Diameter (in.)	Projectile Material	Density (gm/cc)	Nominal Weight (gm)
A	0.255	Syntactic foam*	0.70	0.11
B	0.348	Aluminum (2024-T3)	2.78	1.00
C	0.551	Syntactic foam	0.70	1.16
D	0.749	Aluminum (2024-T3)	2.78	10.38
E	1.220	Syntactic foam	0.70	10.80

*Scotchply XP-241 is the 3M Company trade name for syntactic foam and was employed in this test; Inlyte, the corresponding General Motors Corporation trade name, was originally specified in the Work Statement.

The list below tabulates the test conditions specified by NASA for this test program. Odd thicknesses of bumpers are substituted by the nearest standard stock thicknesses.

The filler materials used are open-cell, polyurethane foams with densities of 1.3 and 2 lb/ft^3. In Series D, impact on the semi-infinite target (Data No. 25) was substituted by one datum added to Task 2d with $\frac{t}{d} = 1$ and $\frac{S}{d} = 30$. These substitutions, made by mutual agreement between NASA and Douglas, were prompted by the unavailability of the target materials in the thickness required. To qualify as a semi-infinite target for a 10-gm aluminum projectile, a thickness of 10 in. minimum was needed. The aluminum alloy 2024-T351 cannot be manufactured to these specifications because of the heat-treat depth limitations of about 8 in.

Test Series Projectile	A 0.1 gm S. Foam	B 1 gm Al.	C 1 gm S. Foam	D 1 gm Al.	E 1 gm S. Foam
Task 2b					
t/d	0.1	0.1	0.025	0.2	0.025
$(S/d)_1$	15	15	15	15	15
$(S/d)_2$	30	30	30	30	30
$(S/d)_3$	40	40	40	40	40
Task 2c					
$(t/d)_1$	0.05	0.05	0.015	0.1	0.015
$(t/d)_2$	0.25	0.25	0.05	0.1	0.015
S/d	30	30	30	30	30
Task 2d					
t/d	0.1	0.1	0.1	0.6	0.040
S/d	30	30	15	30	30

where

t = Thickness of bumper
d = Diameter of projectile
S = Bumper-target spacing

Section 3

HYPERVELOCITY IMPACT TEST

3.1 DEFINITIONS FOR DATA POINTS

All the data points obtained for this test program conform strictly to the definitions below:

1. For semi-infinite targets (Task 1), a data point is an intact projectile on target with a measured velocity in excess of 7 kmps with no spallation or penetration of the target.
2. For finite-sheet targets (Task 2a), a data point is the ballistic limit that is defined as the minimum sheet thickness required to stop the projectile without ejecting a damaging spall from the rear target face that impacts the witness plate.
3. For dual-sheet targets (Tasks 2b, 2c, and 2d), a data point is an intact projectile of measured velocity in excess of 7 kmps, impacting a dual-sheet ballistic limit target. The ballistic limit is defined as the minimum thickness of the second sheet (target) required to stop the projectile without ejecting a damaging spall from the rear surface of the second sheet that impacts the witness sheet.

3.2 HYPERVELOCITY IMPACT TEST RESULTS

Forty data points of ballistic limits and hypervelocity impact on semi-infinite aluminum targets were obtained from a total of over 150 attempts. The results of hypervelocity impact damage in the subject aluminum-target test, designated by Douglas Aerophysics Laboratory as test B-30, are tabulated in Table 1.

Series A:

Syntactic-foam projectiles 0.255 in. in diameter and weighing 0.11 gm were used in this series. Both Ranges A and B with the launch-tube diameter of 0.500 in. were employed. Solid polycarbonate sabots, in conjunction with the vented-muzzle launch tubes, successfully launched the projectiles to as much as 7.62 kmps. Plates 1 through 8 show the damaged targets of Data Points 1 through 8.

Series B:

Aluminum-alloy 2024-T3 projectiles, 0.348 in. in diameter and weighing 1 gm, were used in this series. Range A with the launch-tube diameter of 0.500 in. was employed. Solid polycarbonate sabots, in conjunction with the vented-muzzle launch tube, successfully launched the projectiles to as much as 7.25 kmps. Plates 9 through 16 show the damaged targets of Data Points 9 through 16.

Series C:

Syntactic-foam projectiles, 0.551 in. in diameter and weighing 1.16 gm, were used in this series. Range A with the launch tube diameter of 0.565 in. was employed. A wax seal deposited around the equator of the projectile served as the sabot. Maximum velocity achieved was 7.25 kmps. Plates 17 through 24 show the damaged targets of Data Points 17 through 24.

Series D:

Aluminum-alloy 2024-T3 projectiles, 0.749 in. in diameter and weighing 10.38 gm, were used in this series. Range B with the launch tube diameter of 1.245 in. was employed. Solid polycarbonate sabots, in conjunction with a restrictor ring, successfully launched the projectiles to as much as 7.32 kmps. Plates 25 through 32 show the damaged targets of Data Points 25 through 32.

Series E:

Syntactic-foam projectiles, 1.220 in. in diameter and weighing 10.80 gm, were used in this series. Range B with the launch tube diameter of 1.245 in. was employed. A wax seal deposited around the equator of the projectile served as the sabot. Maximum velocity achieved was 7.14 kmps. Plates 33 through 40 show the damaged targets of Data Points 33 through 40.

3.3 MODES OF BALLISTIC LIMIT IN ALUMINUM TARGETS

The ballistic limit of a dual-sheet target is determined by the failure of the second sheet in any of the following various forms:

1. Large spallation or large incipient spallation at the center of the back side.
2. Discrete spalls or a grouping of small incipient spallation on the back side.
3. Punching out of a segment.

As the projectile impacts on the front sheet (the bumper) of the dual-sheet target, strong shock waves are generated in both the target and the projectile. The reflections of these shock waves at the free surfaces produce rarefraction waves which are the cause of both target and projectile fracture. As the shock wave passes through a solid, a shock of low strength will leave the material heated but in a solid state. As the shock strength is increased, rising entropy can lead successively to liquefaction and vaporization. The strength of the shock wave is a function of the impact energy and of the materials of both target and projectile.

In this test program, the debris resulting from impact is a mixture mostly of heated solids and droplets. The distribution of this debris on the second sheet (the target) dictates the failure mode. When the spacing between the dual sheets is sufficiently small, the debris concentrates fairly closely to the center of the second sheet. Large spallation will occur at the ballistic limit. When the spacing is increased to a certain value, no further large spallation will occur. The ballistic limit is primarily determined in this case by discrete spallations scattered over a large area of the second sheet. It is apparent that the ballistic limit becomes independent of spacing beyond this value.

In some cases, where the debris weakens the second sheet sufficiently at a certain area, the momentum of the spray of particles is large enough to push the weakened portion out. In the extreme case where the projectile and first-sheet material become completely vaporized upon impact, punching out a portion of the second sheet may occur, without prior damage to the sheet by debris, due to the momentum of the vapor.

To identify the failure modes of the test data points, S or SD are assigned to each datum point: S stands for large spallation or large incipient spallation at the center and SD stands for discrete spalls or a grouping of small incipient spallations. This identification appears in the space for target thickness in Table 1.

Section 4
CONCLUSIONS

Based on the limited parametric impact tests of the aluminum targets carried out in this program, the following conclusions can be drawn:

1. The tensile strength of the syntactic foam is very low (4, 600 psi). Hence, the front part of the projectile spalls off if the conventional light-gas gun launching cycle is used.

2. Some small fragments of syntactic foam tend to chip off the projectile during launch with or without a sabot, due either to Item 1 or to stress concentrations at the sabot contact.

3. The definition of ballistic limit established at the beginning of the test program did not prove precise enough. In Series A and B test shots, the 0. 25-in. -thick titanium witness plates were never damaged by the spalls from the target plate. Flash X-ray pictures revealed that the velocities of the spallations were mostly under 1, 000 fps. To improve the definition, the range of a typical ballistic limit bounded by the upper limit (incipient spallation on the back of the target) and the lower limit (incipient perforation of the target) was determined with a series of shots in Series B. The upper limit is represented by target thickness of shot B-20, 1. 250-in. thick, and the lower limit is estimated to be near 0. 375-in. thick based on the shot B-3. Therefore, the accuracy of the reported ballistic limits in Series A and B may be questionable.

4. The reported ballistic limits of Series C, D, and E used the incipient or slightly over incipient spallation as criteria. Therefore, the data for these test series should be more consistent than Series A and B.

5. The foam filler proved to be very effective. More tests are needed to determine the exact degree of effectiveness.

6. Figure 4 shows the observed failure modes during the test of targets at the ballistic limits. The figure is a qualitative presentation of the characteristics of the debris spray formed by the interaction of the projectile with the bumper.

7. For hole size prediction in the bumper sheet, the General Motors (DRL) equation, $D/d = 0.45v\left(\frac{t_s}{d}\right)^{2/3} + 0.90$ where D is diameter of hole in bumper sheet, d is diameter of projectile, and t_s is thickness of bumper sheet, correlates with experimental measurements for holes produced by large (>10 gram) projectiles of aluminum and syntactic foam for $t_s/d < 1$.

8. For sytactic foam, the experimental data indicate that the optimum t_s/d ratio is of the order of 0.02 to minimize total two-sheet weight to resist the projectile. A greater weight penalty $(t_s + t_b)$ where t_b is thickness of backup sheet, has to be paid if the t_s/d ratio is less than 0.02 than if it is greater than 0.02.

   At the optimum t_s/d ratio of about 0.02, a significant increase in penetration resistance is obtained for S/d ratios greater than 15, where S is spacing between sheets. It is of interest to note in Series A that for a nonoptimum t_s/d ratio of about 0.1, the penetration resistance was insensitive over the S/d range from 15 to 40. This effectis probably caused by large discrete aluminum particles produced in the late stages of the projectile-bumper interaction.

   For optimum T_s/d ratio of about 0.02 and $S/d > 15$, the t_s/t_b ratio for minimum total weight is of the order of 0.1.

9. For aluminum projectiles the experimental data (Series B and D) indicate that the optimum t_s/d ratio is of the order of 0.2 to minimize total two-sheet weight to resist the projectile. A greater weight penalty (t_s+t_b) is imposed if the t_s/d ratio is less than 0.2. At the optimum t_s/d ratio of about 0.2, a significant increase in penetration resistance is obtained for increasing S/d ratios over the range 15 to 40.

   For the optimum t_s/d ratio of the order of 0.2 and S/d ratios ≤ 30, the t_s/t_b ratio for minimum total weight is not indicated in conclusive fashion by the data. The limited data suggest that the optimum t_s/t_b ratio lies in the range from 0.4 to 1.

10. Optimum t_s/d and t_s/t_b ratios differ markedly for Inlyte and aluminum projectiles. However, the dominant requirements for aluminum will satisfy the requirements for Inlyte in terms of successfully resisting the Inlyte projectile.

REFERENCE

1. R. N. Teng, Advances in Light-Gas Gun Model-Launching Techniques. Technical Note, AIAA Journal, Vol. 5, No. 11, November 1967, Pages 2082-2084.

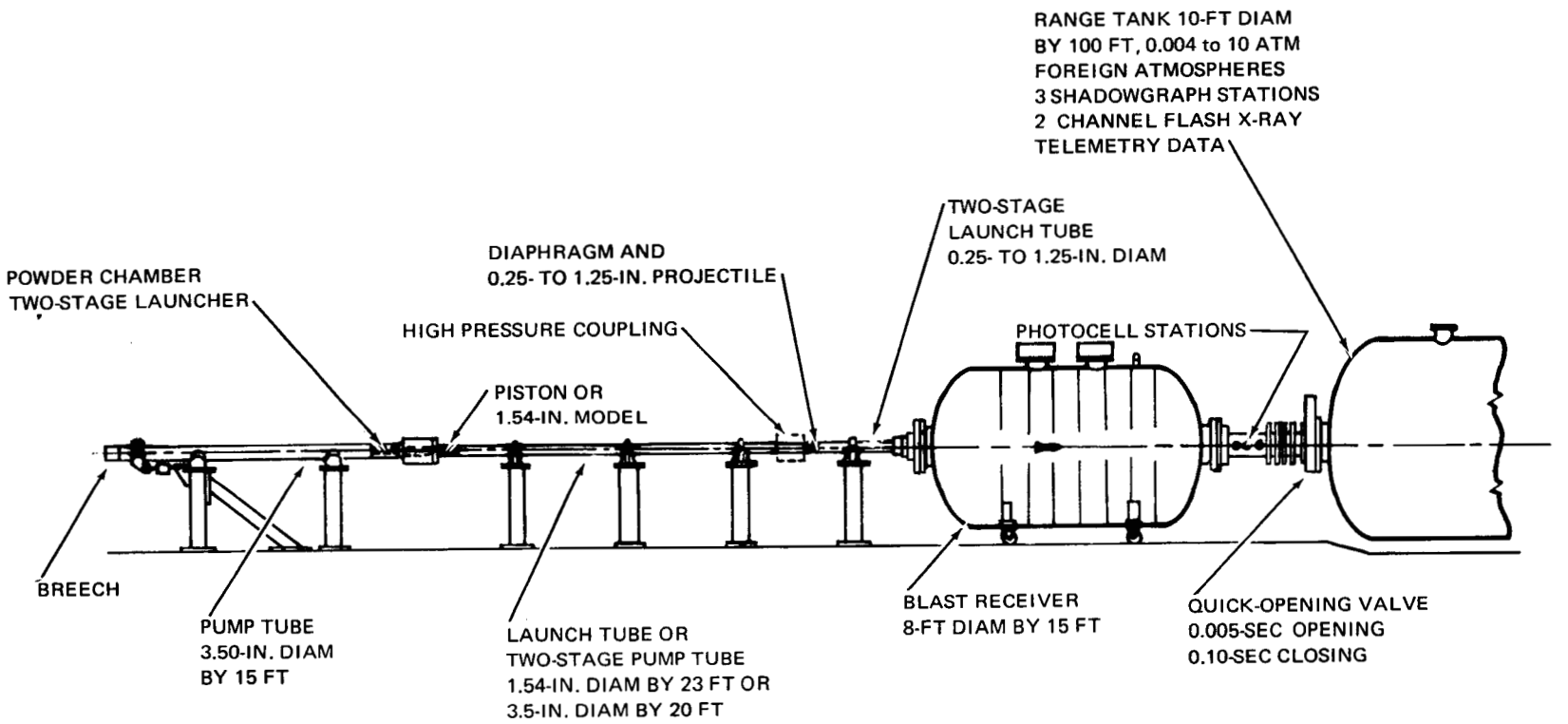


Figure 2. Light-Gas Gun – Ballistic Range B

PRECEDING PAGE BLANK NOT FILMED.

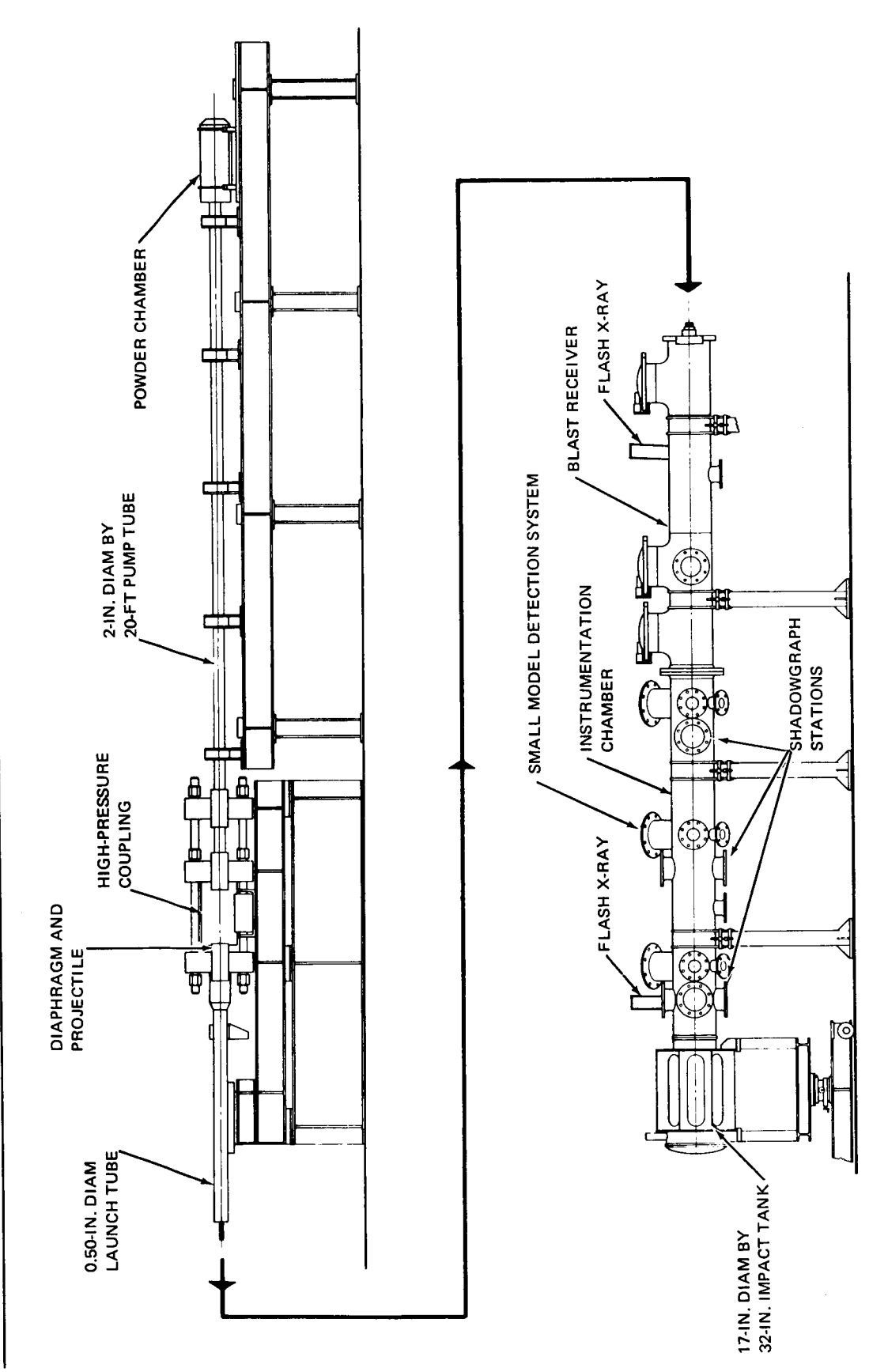


Figure 1. Light-Gas Gun – Ballistic Range A

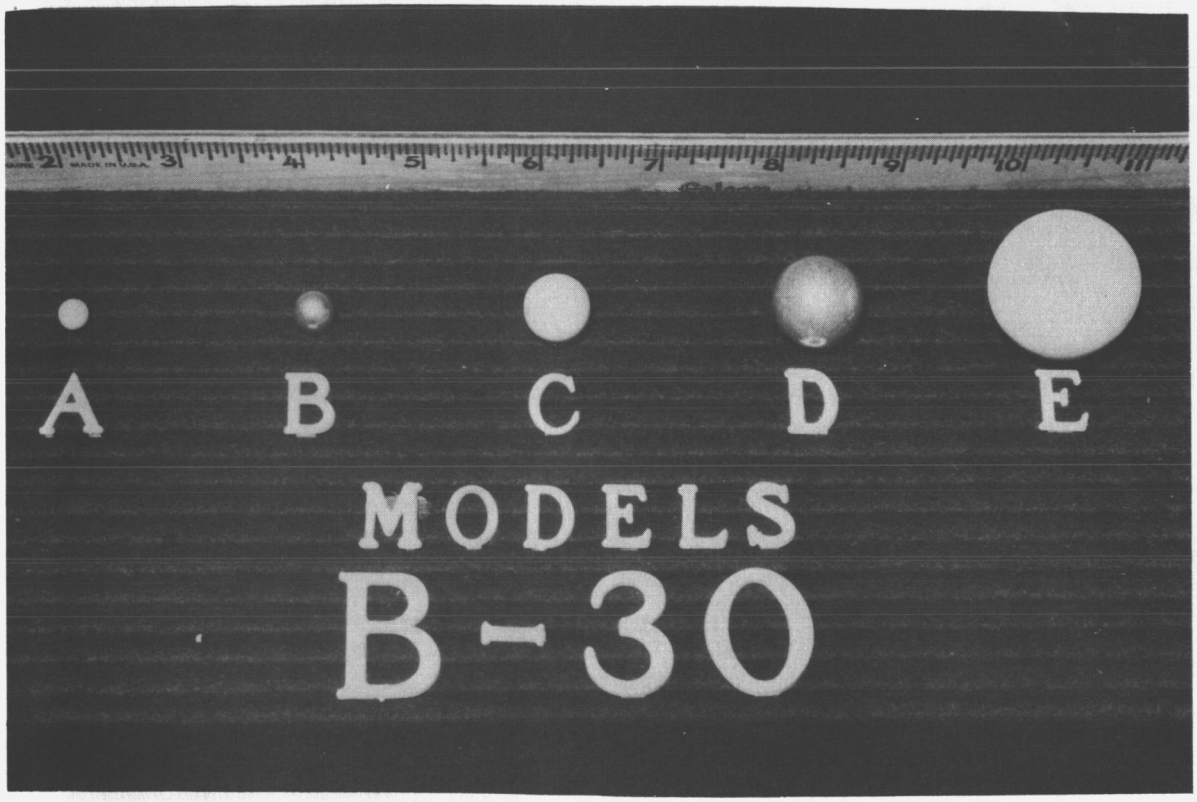


Figure 3. Projectiles

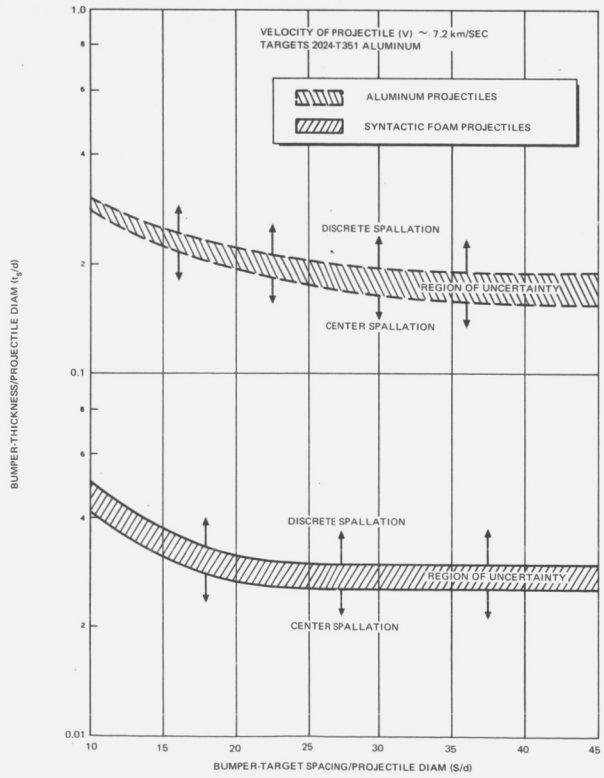
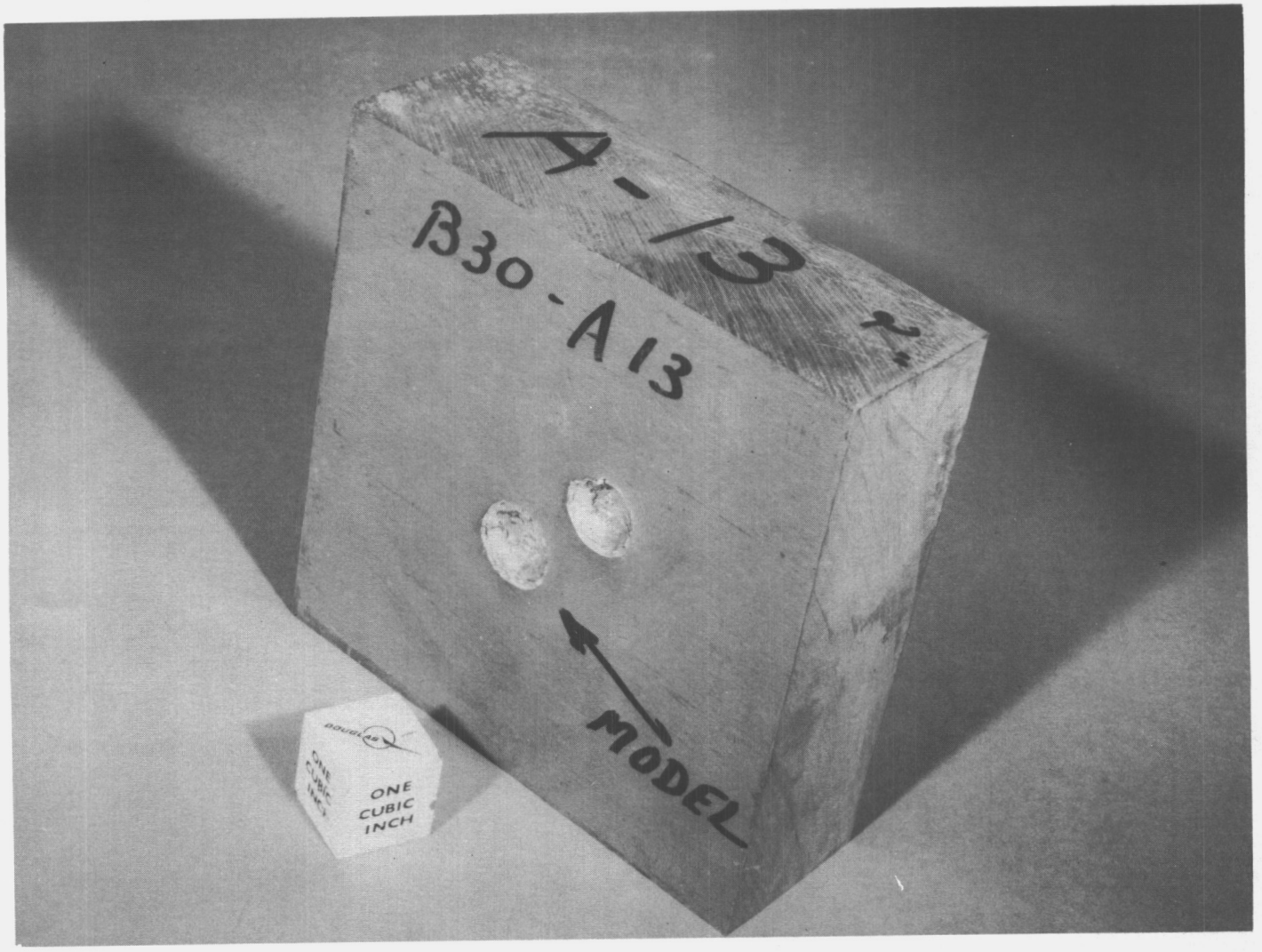
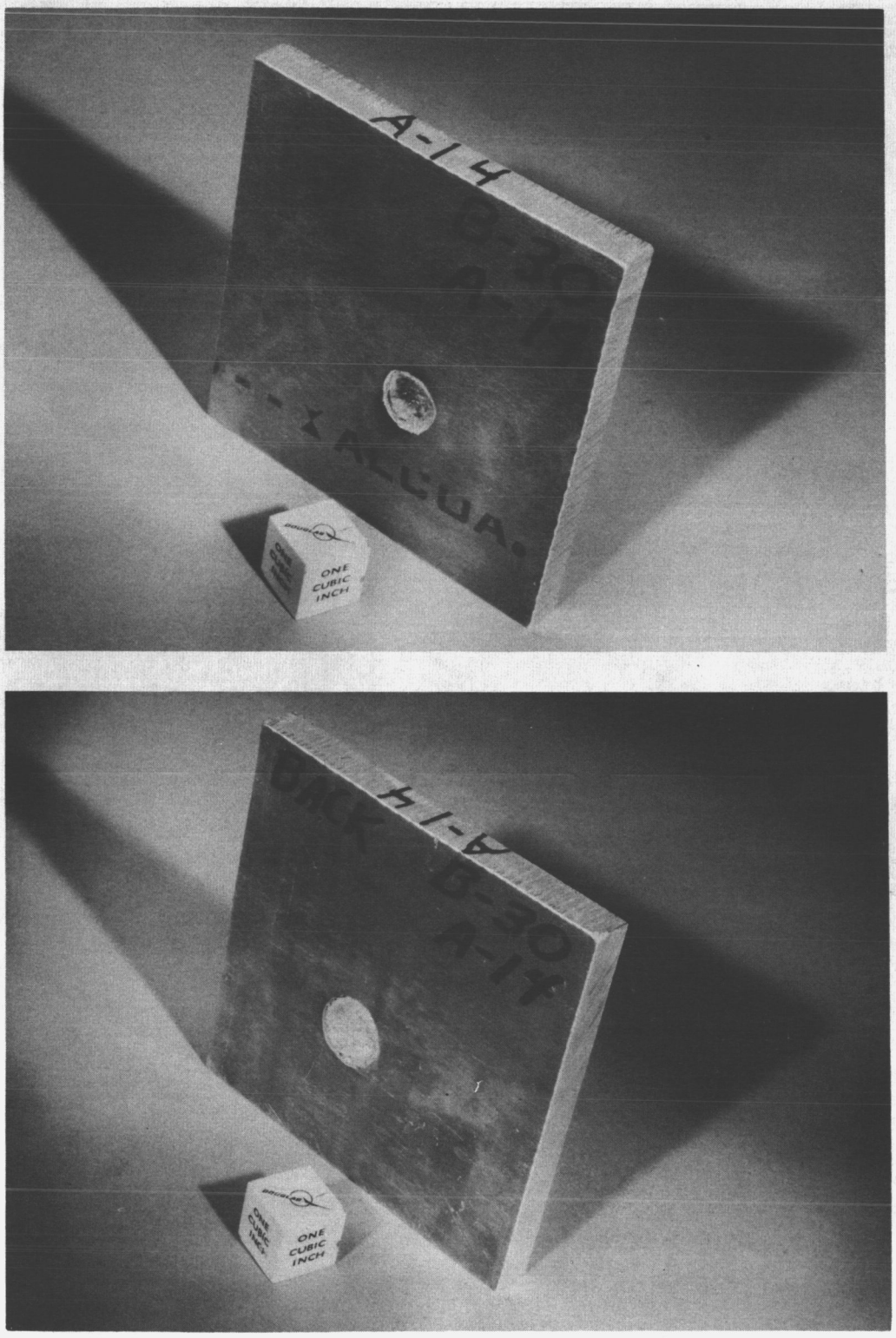


Figure 4. Target Failure Modes at Ballistic Limits



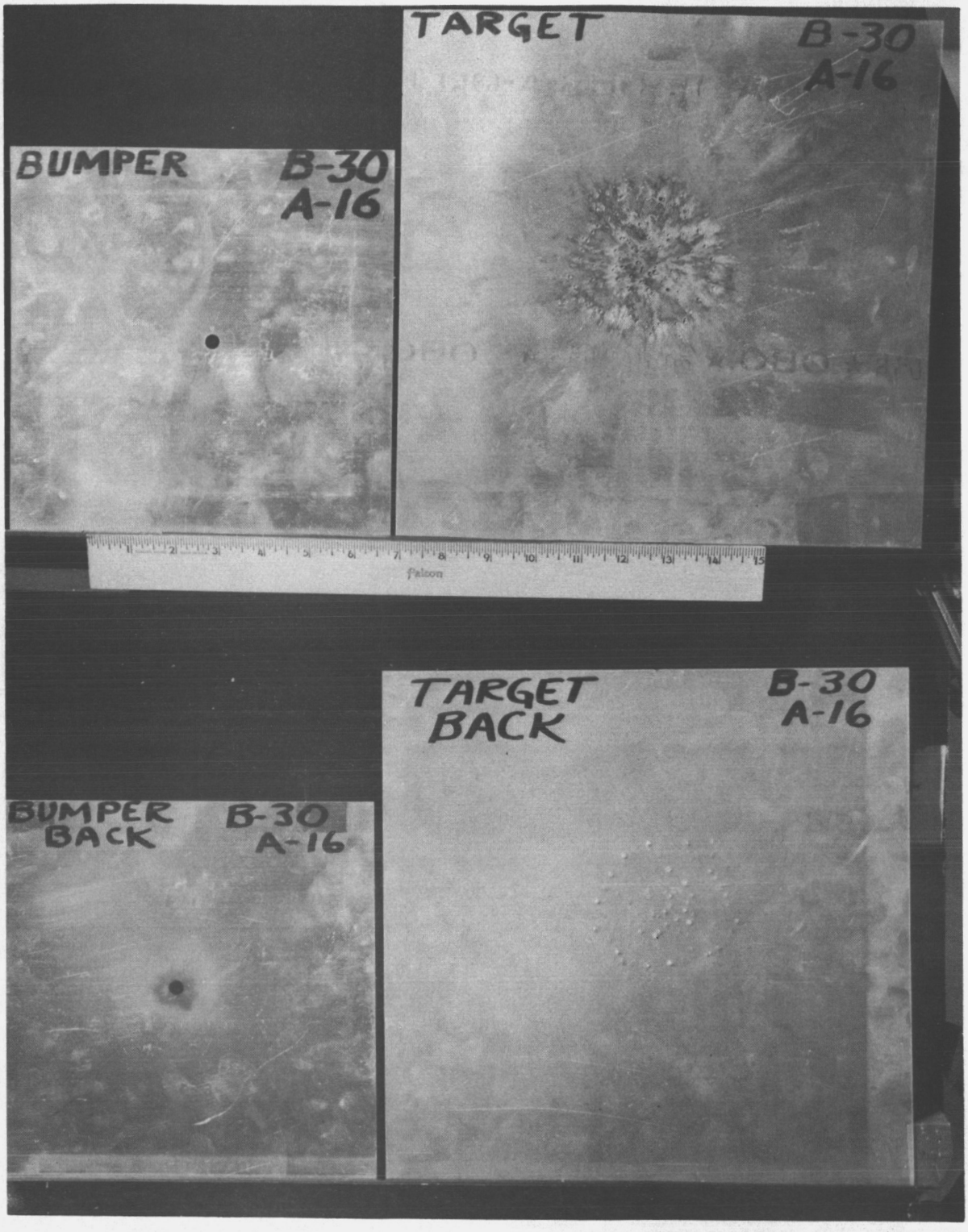
PROJECTILE MATERIAL AND MASS: SYNTACTIC FOAM SPHERE: 0.110 gm, IMPACT VELOCITY: 7.12 kmps
TARGET THICKNESS: 2 IN.

Plate 1. Semi-Infinite Target, Data No. 1



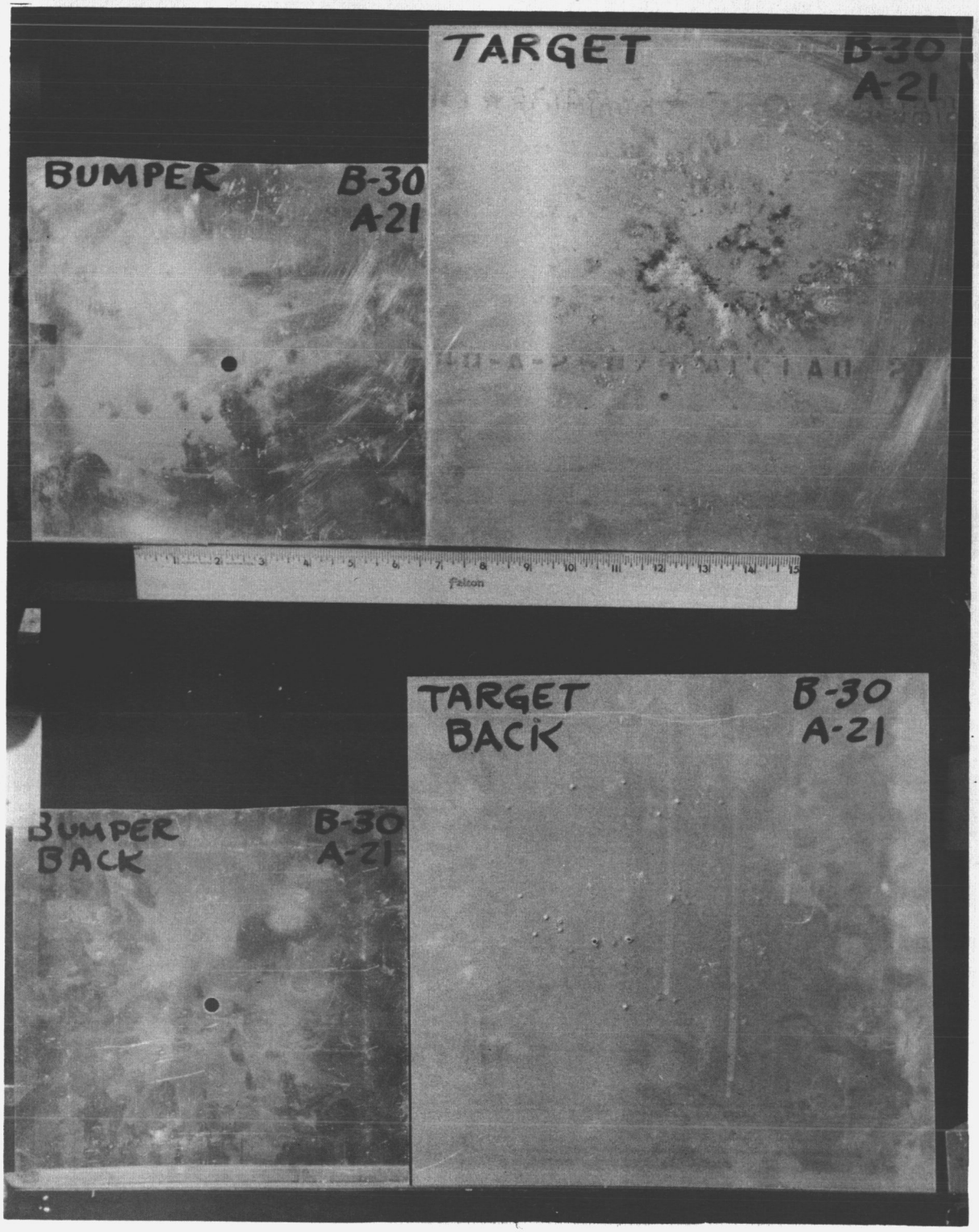
PROJECTILE MATERIAL AND MASS: SYNTACTIC FOAM SPHERE: 0.110 gm, IMPACT VELOCITY: 7.34 kmps
TARGET THICKNESS: 0.643 IN.

Plate 2. Finite-Sheet Target, Data No. 2



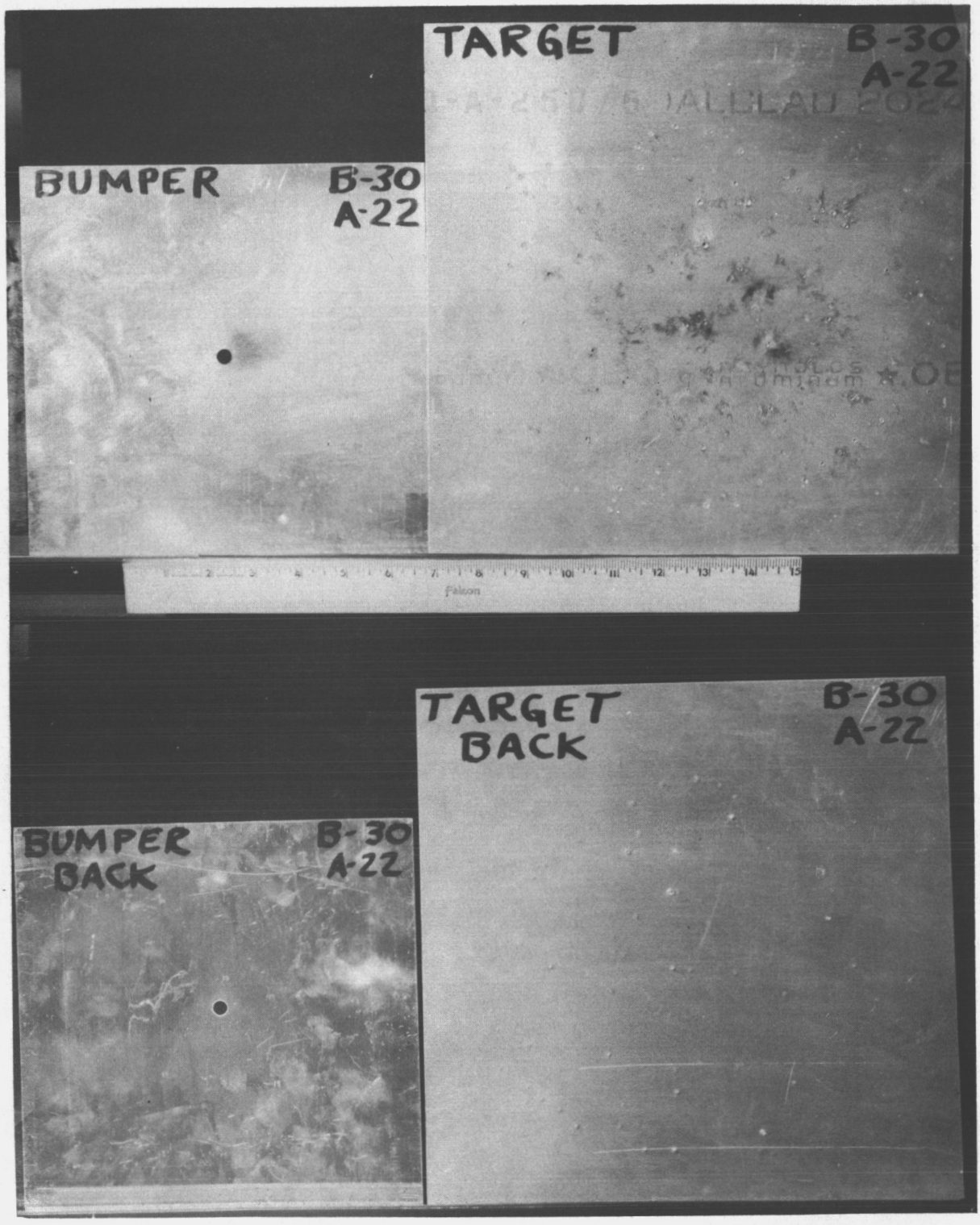
PROJECTILE MATERIAL AND MASS: SYNTACTIC FOAM SPHERE: 0.110 gm, IMPACT VELOCITY: 7.40 kmps
BUMPER THICKNESS: 0.025 IN., TARGET THICKNESS: 0.078 IN., SPACING: 3.81 IN.

Plate 3. Dual-Sheet Target, Data No. 3



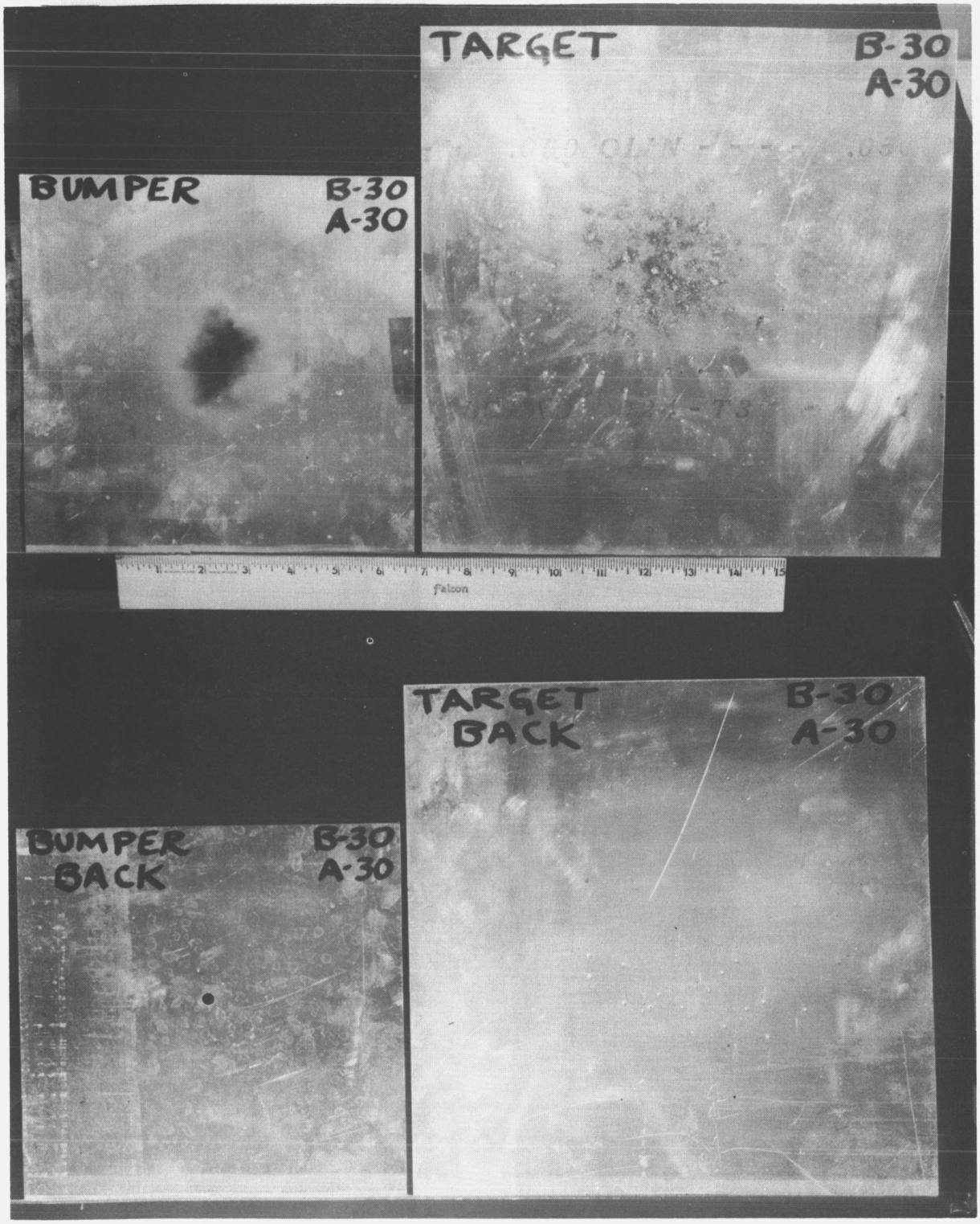
PROJECTILE MATERIAL AND MASS: SYNTACTIC FOAM SPHERE: 0.110 gm, IMPACT VELOCITY: 7.27 kmps
BUMPER THICKNESS: 0.025 IN., TARGET THICKNESS: 0.080 IN., SPACING: 7.62 IN.

Plate 4. Dual-Sheet Target, Data No. 4



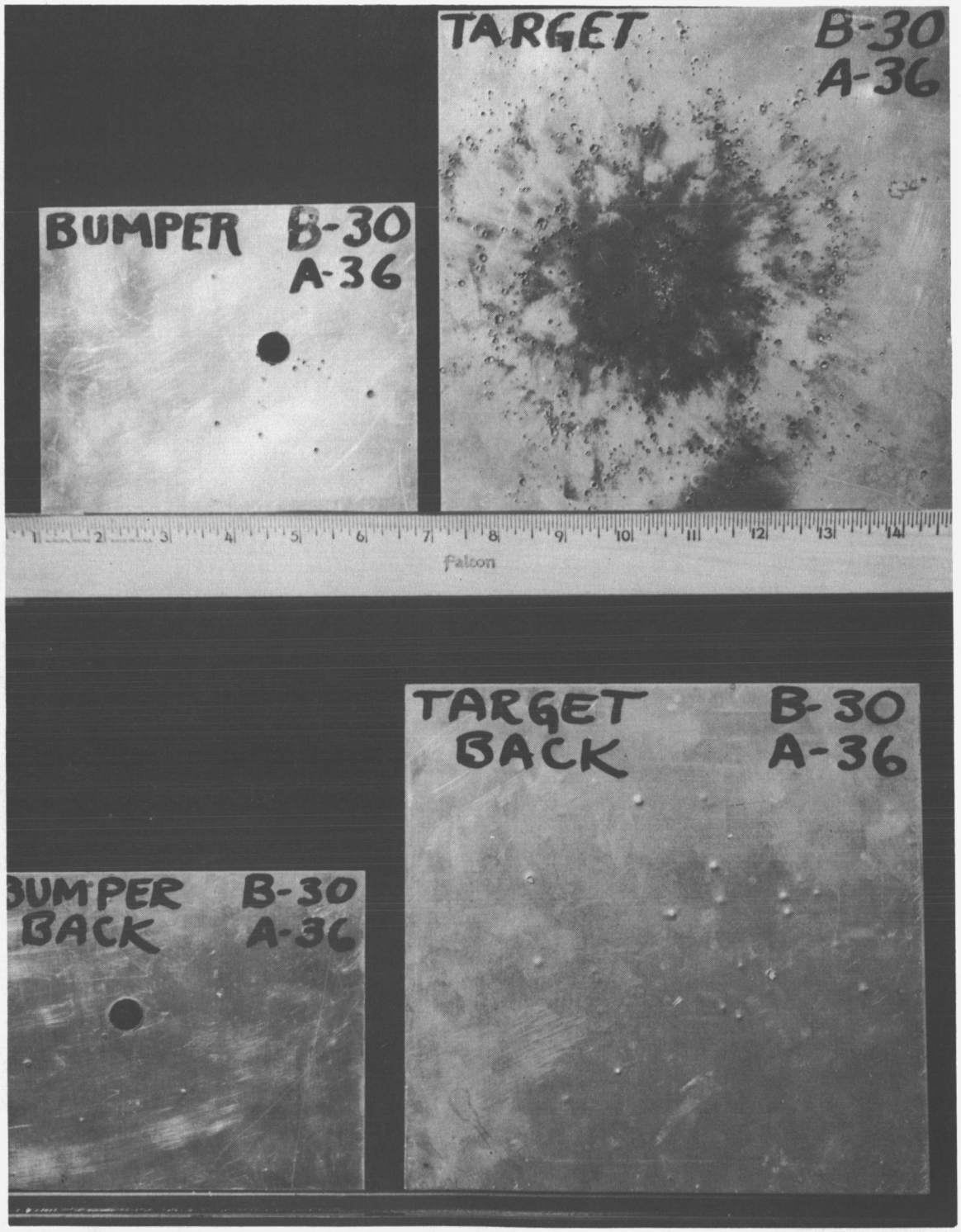
PROJECTILE MATERIAL AND MASS: SYNTACTIC FOAM SPHERE: 0.110 gm, IMPACT VELOCITY: 7.01 kmps
BUMPER THICKNESS: 0.025 IN., TARGET THICKNESS: 0.080 IN., SPACING: 10.15 IN.

Plate 5. Dual-Sheet Target, Data No. 5



PROJECTILE MATERIAL AND MASS: SYNTACTIC FOAM SPHERE: 0.110 gm, IMPACT VELOCITY: 7.03 kmps
BUMPER THICKNESS: 0.012 IN. , TARGET THICKNESS: 0.051 IN., SPACING: 7.62 IN.

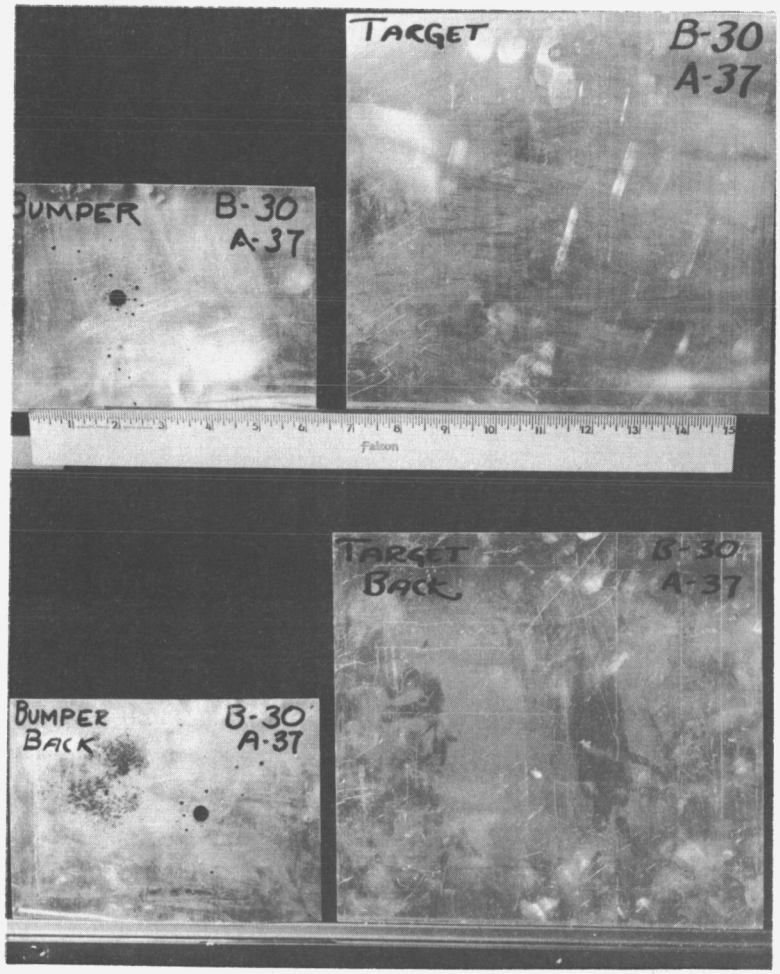
Plate 6. Dual-Sheet Target, Data No. 6



PROJECTILE MATERIAL AND MASS: SYNTACTIC FOAM SPHERE: 0.110 gm, IMPACT VELOCITY: 7.64 kmps
BUMPER THICKNESS: 0.063 IN., TARGET THICKNESS : 0.100 IN., SPACING: 7.62 IN.

Plate 7. Dual-Sheet Target, Data No. 7

PROJECTILE MATERIAL AND MASS: SYNTACTIC FOAM SPHERE: 0.110 gm, IMPACT VELOCITY: 7.27 kmps BUMPER THICKNESS: 0.025 IN., TARGET THICKNESS: 0, SPACING: 7.62 IN.



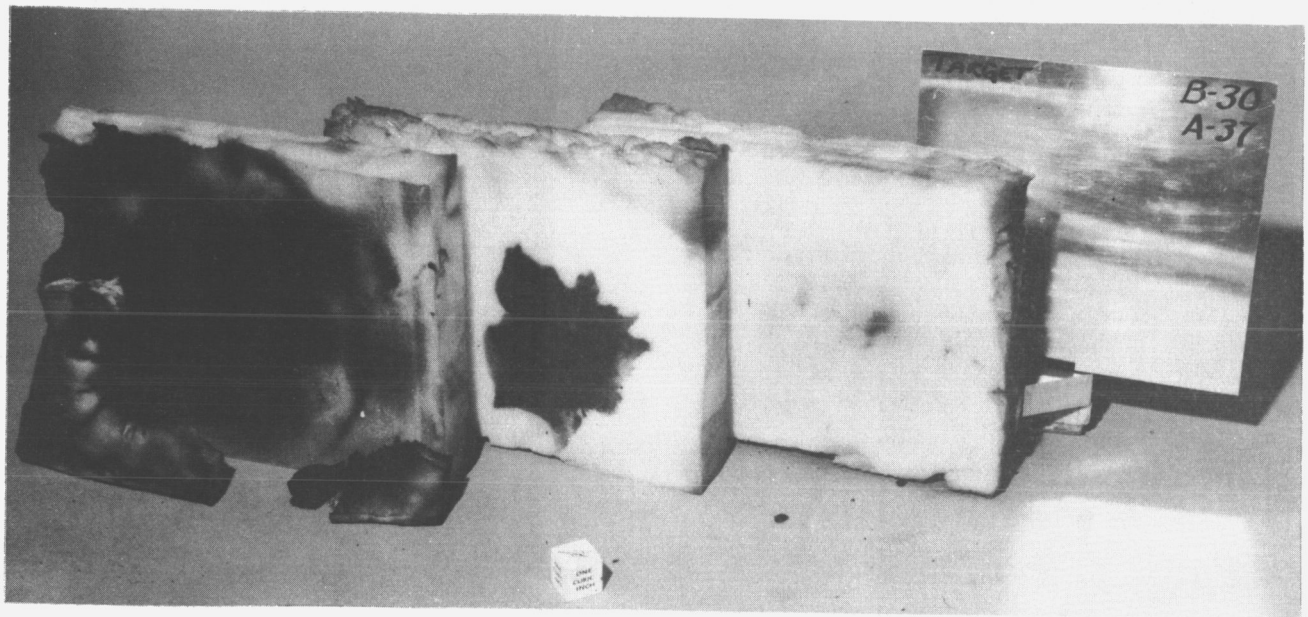
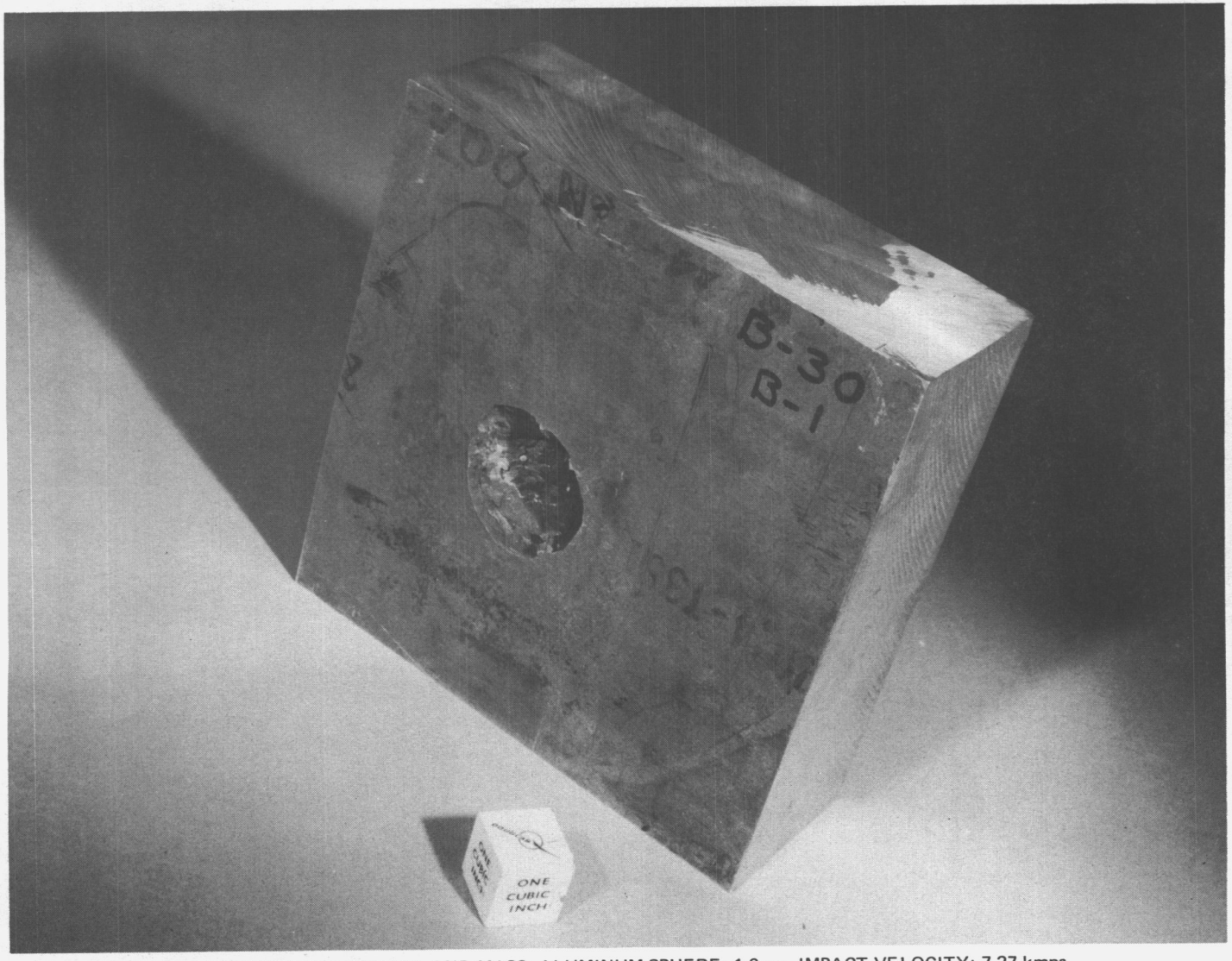
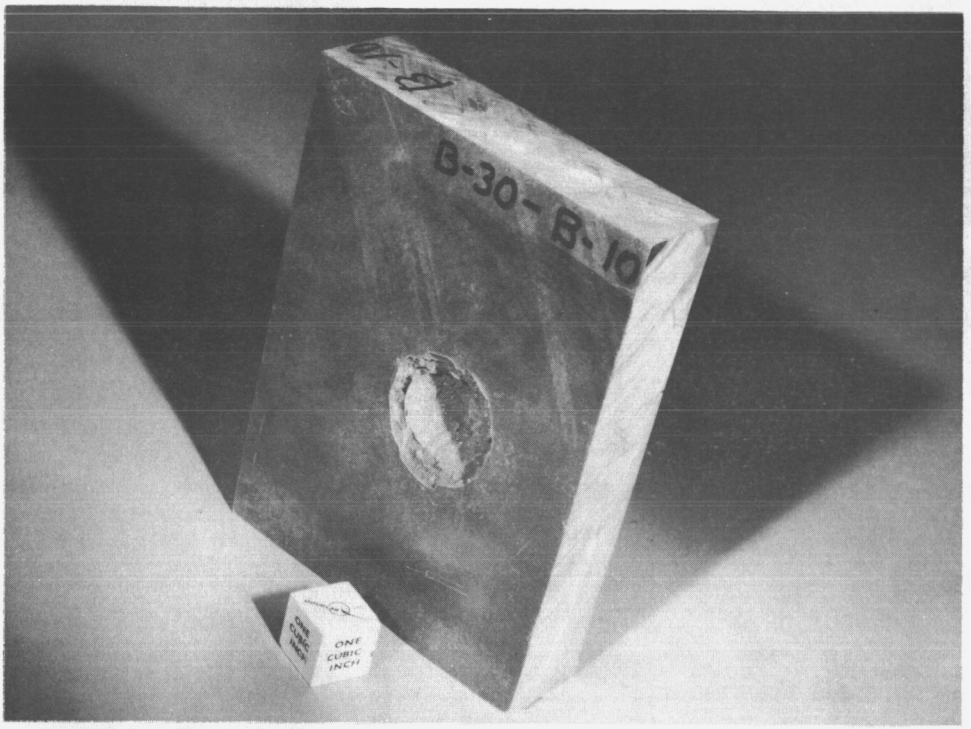


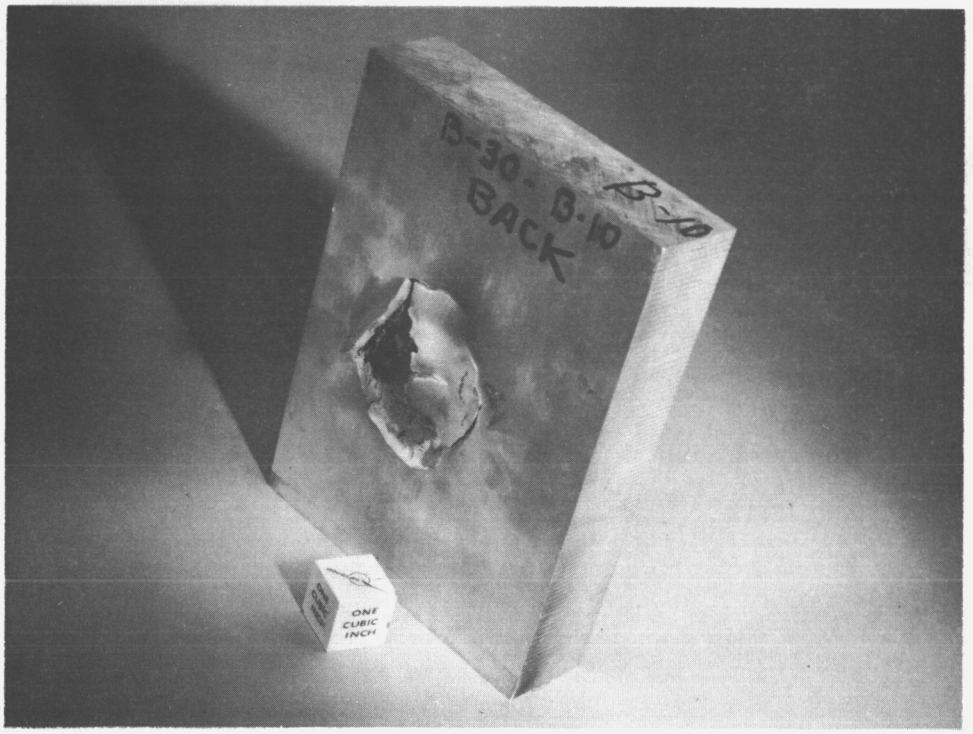
Plate 8. Dual-Sheet Target, Data No. 8



PROJECTILE MATERIAL AND MASS: ALUMINUM SPHERE: 1.0 gm, IMPACT VELOCITY: 7.27 kmps
TARGET THICKNESS: 3.0 IN.

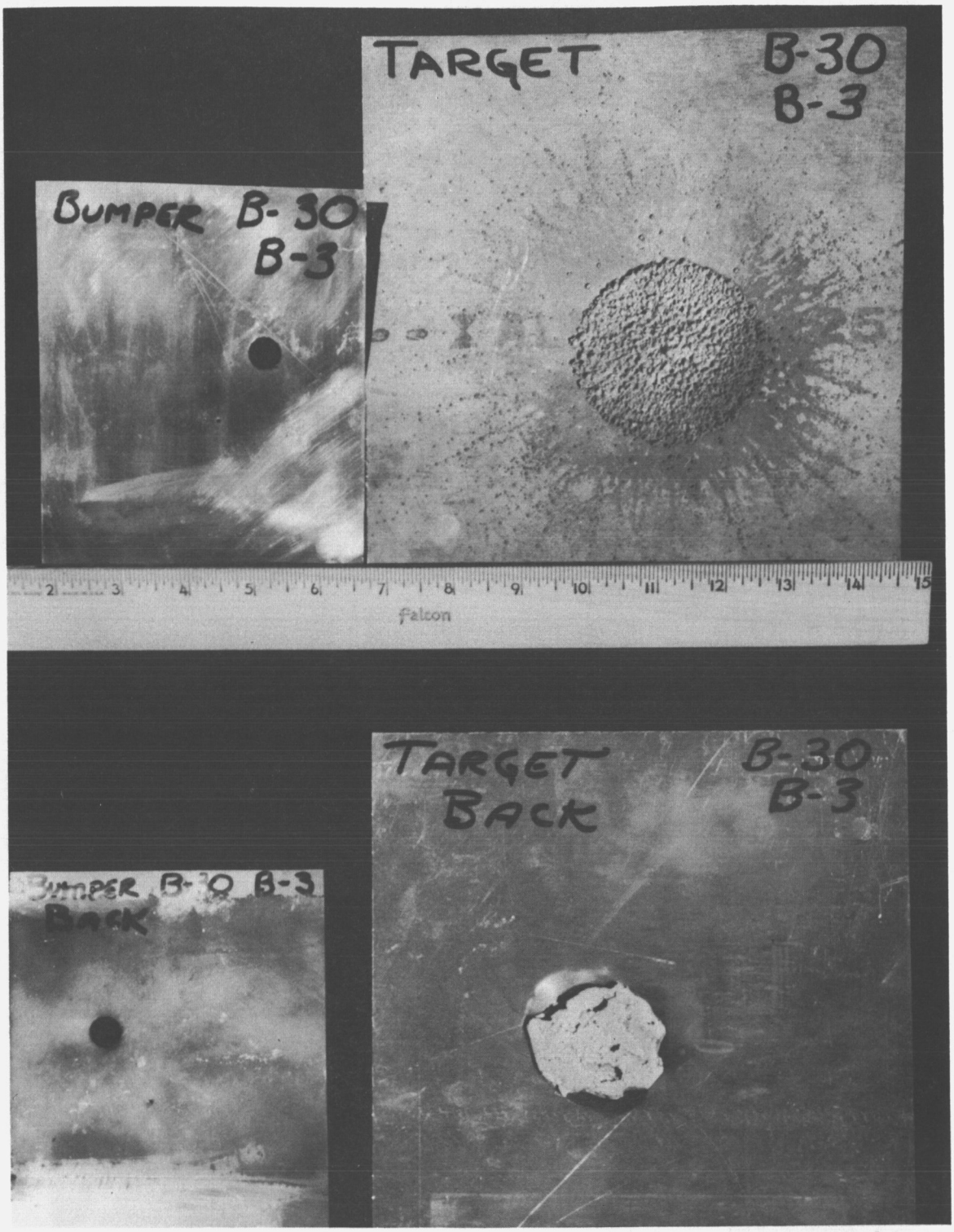
Plate 9. Semi-Infinite Target, Data No. 9





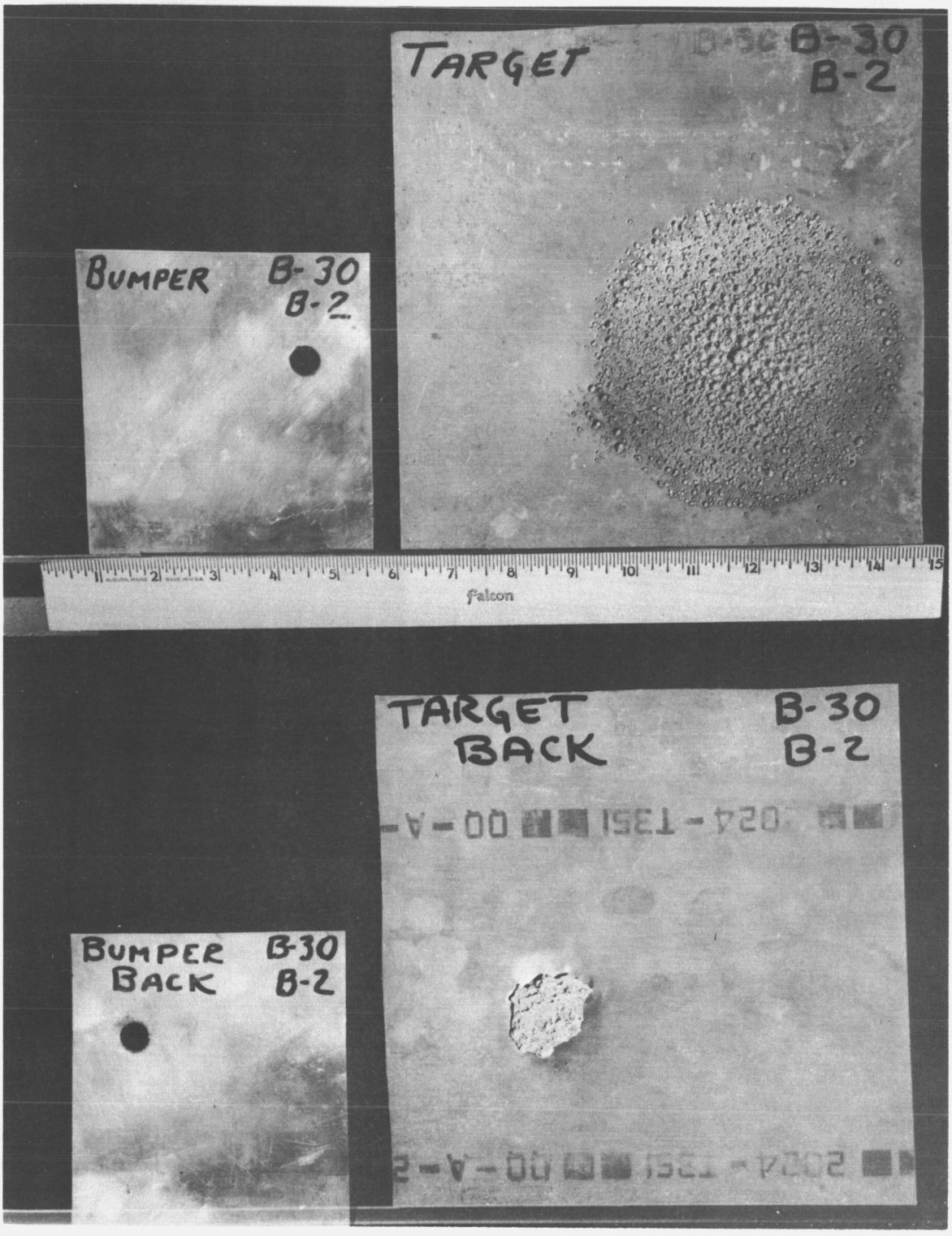
PROJECTILE MATERIAL AND MASS: ALUMINUM SPHERE: 1.01 gm, IMPACT VELOCITY: 7.08 kmps
TARGET THICKNESS: 1.625 IN.

Plate 10. Finite-Sheet Target, Data No. 10



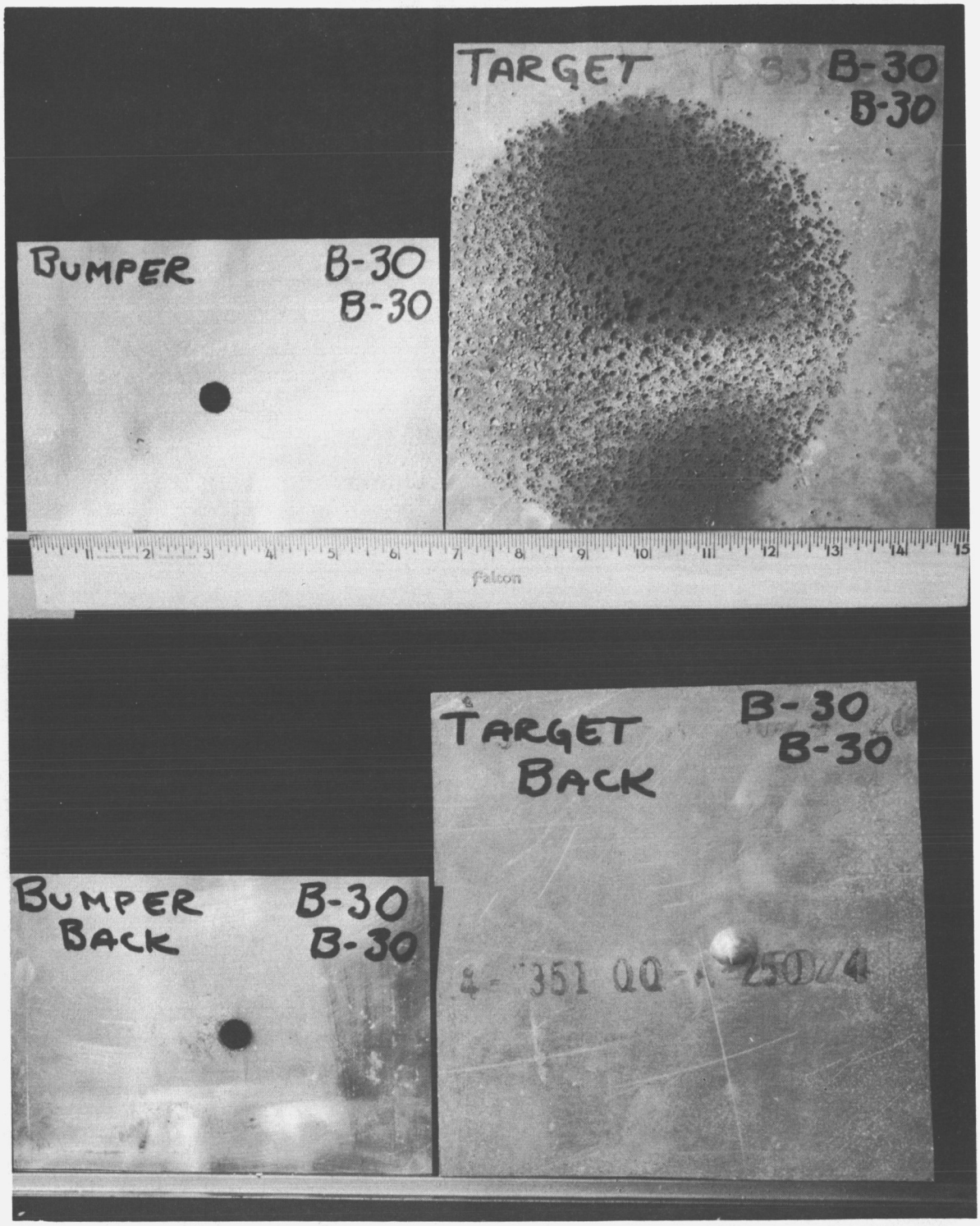
PROJECTILE MATERIAL AND MASS: ALUMINUM SPHERE: 1.01 gm, IMPACT VELOCITY: 7.09 kmps
BUMPER THICKNESS: 0.032 IN., TARGET THICKNESS: 0.637 IN., SPACING 5.22 IN.

Plate 11. Dual-Sheet Target, Data No. 11



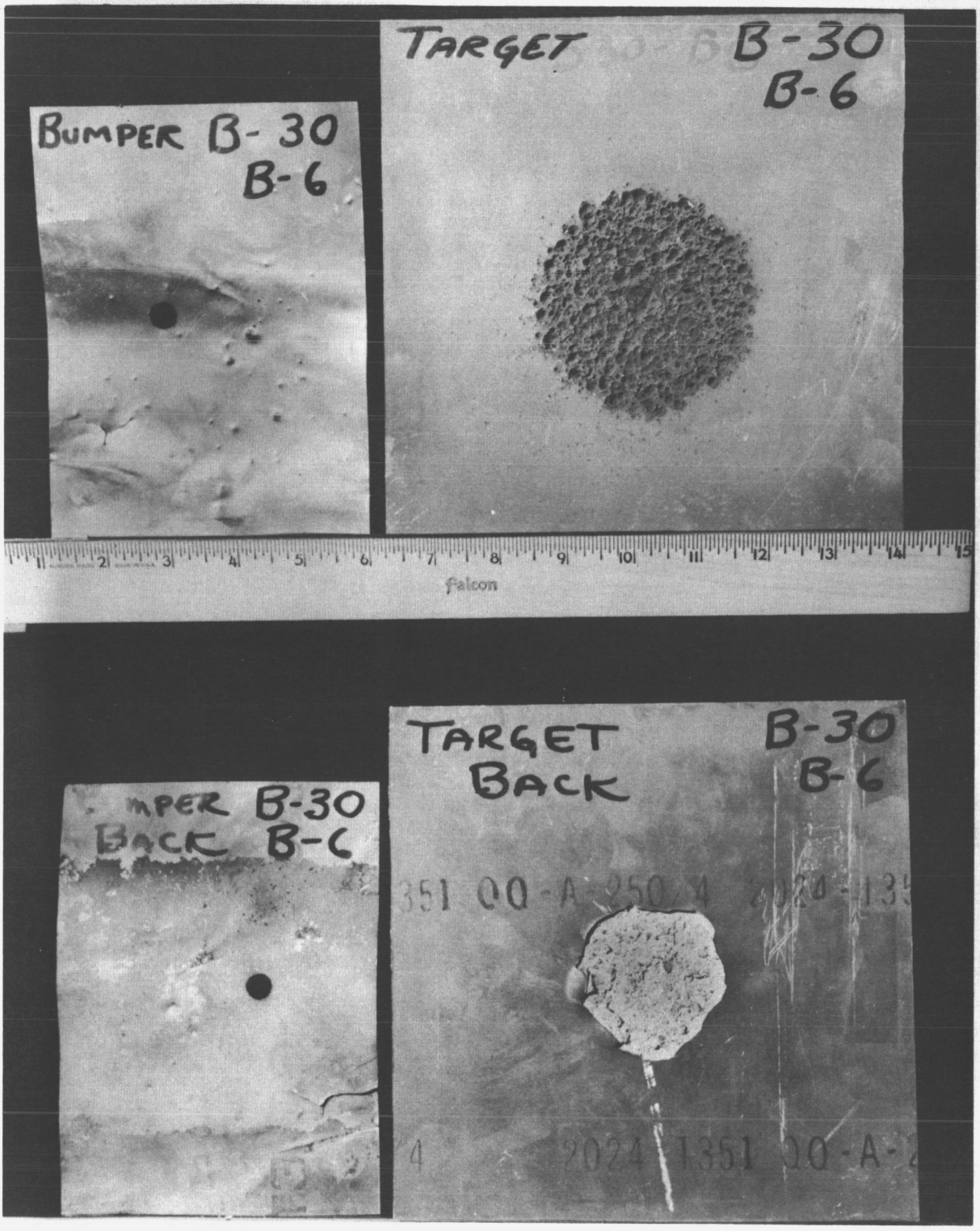
PROJECTILE MATERIAL AND MASS: ALUMINUM SPHERE: 1.01 gm, IMPACT VELOCITY: 7.16 kmps
BUMPER THICKNESS: 0.032 IN., TARGET THICKNESS: 0.258 IN., SPACING: 10.44 IN.

Plate 12. Dual-Sheet Target, Data No. 12



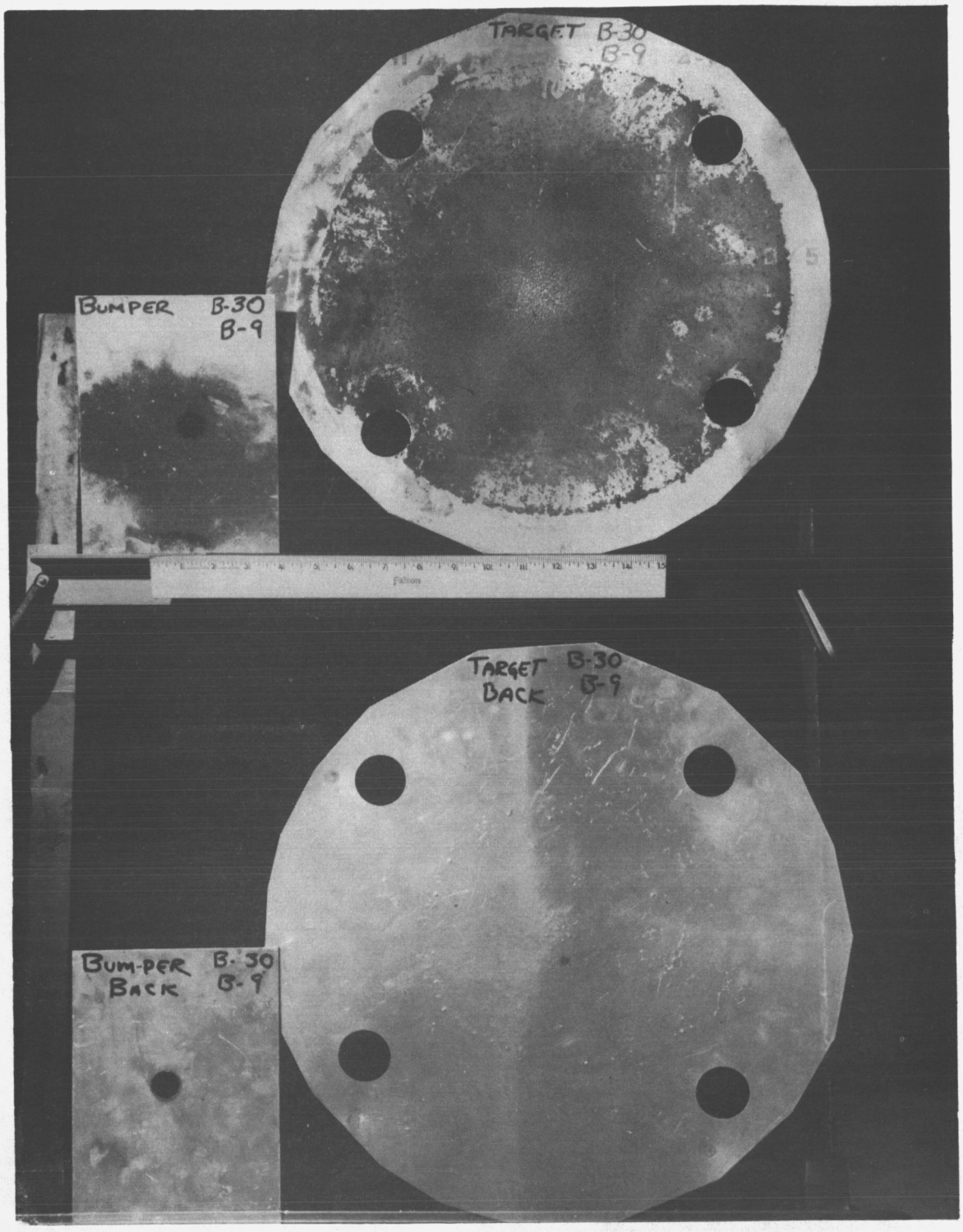
PROJECTILE MATERIAL AND MASS: ALUMINUM SPHERE: 1.01 gm, IMPACT VELOCITY: 7.15 kmps
BUMPER THICKNESS: 0.032 IN., TARGET THICKNESS: 0.312 IN., SPACING: 13.92 IN.

Plate 13. Dual-Sheet Target, Data No. 13



PROJECTILE MATERIAL AND MASS: ALUMINUM SPHERE: 1.01 gm, IMPACT VELOCITY: 7.27 kmps
BUMPER THICKNESS: 0.016 IN., TARGET THICKNESS: 0.496 IN., SPACING: 10.44 IN.

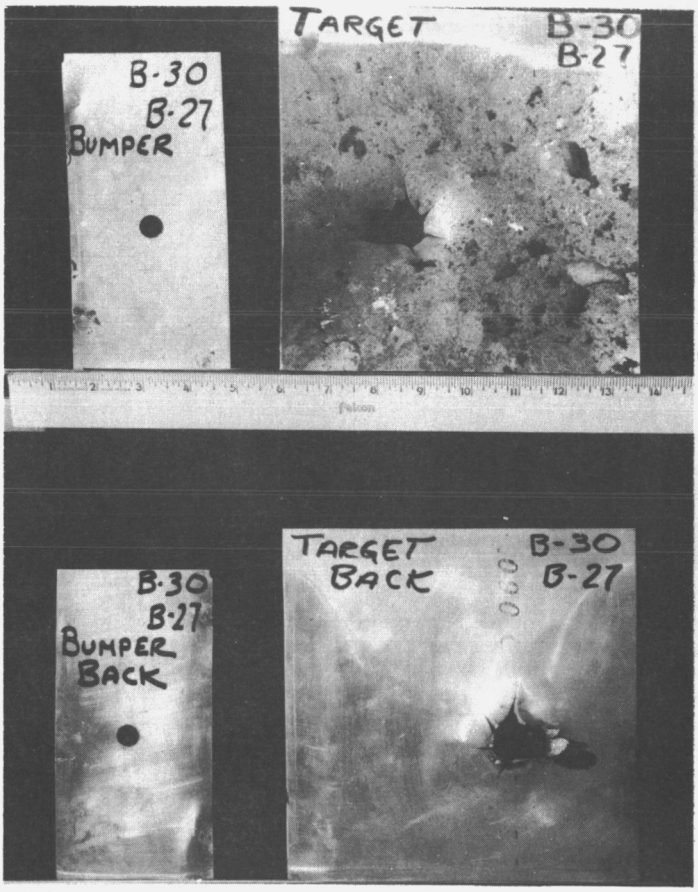
Plate 14. Dual-Sheet Target, Data No. 14



PROJECTILE MATERIAL AND MASS: ALUMINUM SPHERE: 1.01 gm, IMPACT VELOCITY: 7.08 kmps,
BUMPER THICKNESS: 0.090 IN., TARGET THICKNESS: 0.079 IN., SPACING: 10.44 IN.

Plate 15. Dual-Sheet Target, Data No. 15

PROJECTILE MATERIAL AND MASS:
ALUMINUM SPHERE: 1.01 gm
IMPACT VELOCITY: 7.15 kmps
BUMPER THICKNESS: 0.032 IN.
TARGET THICKNESS: 0.090 IN.
SPACING: 10.44 IN.



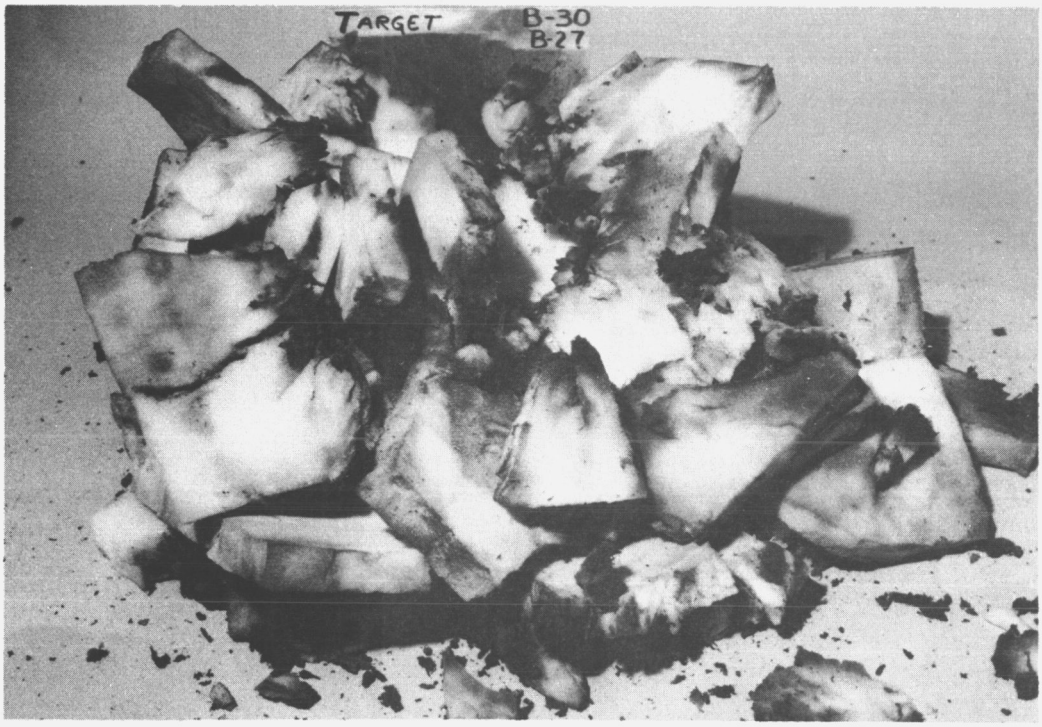
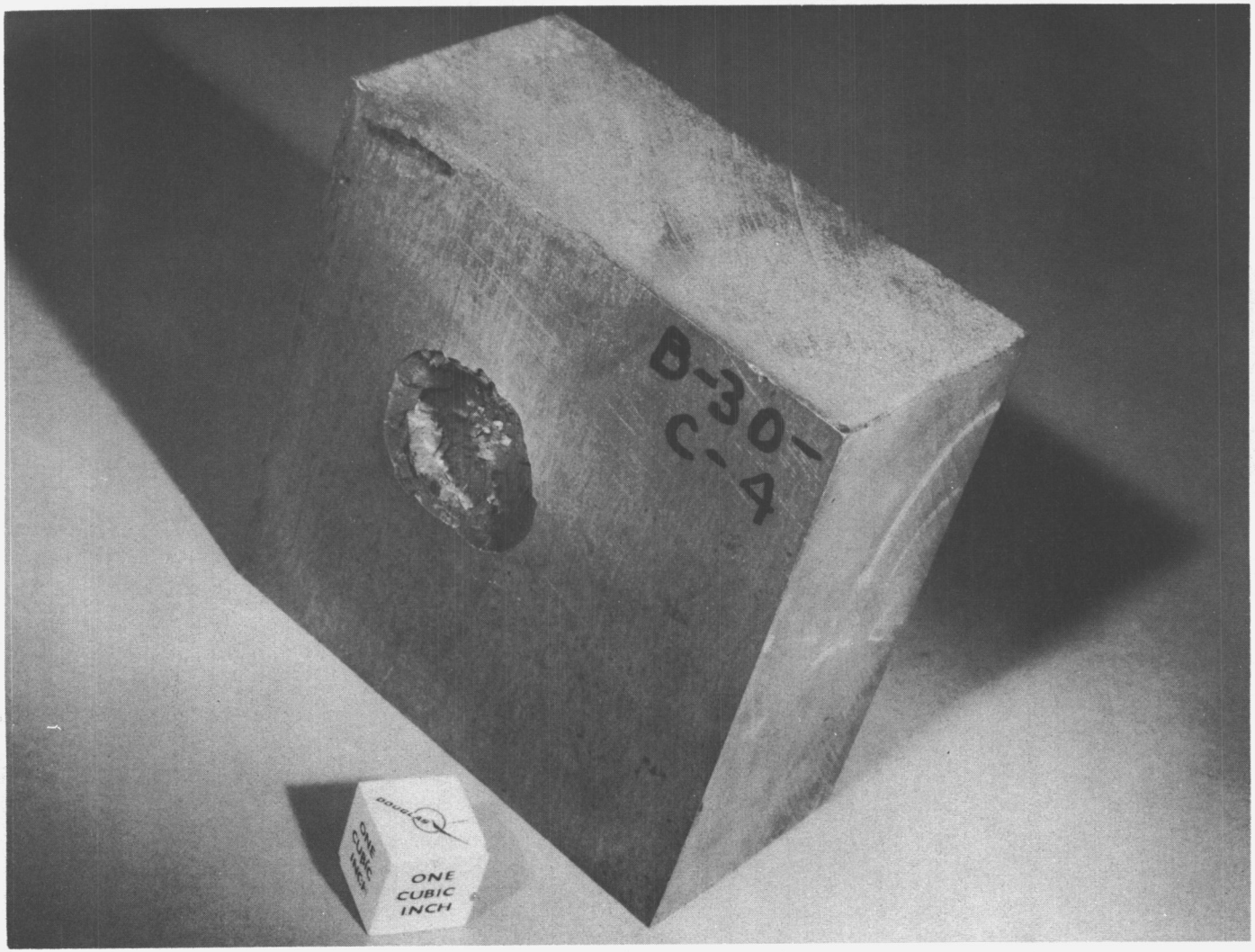
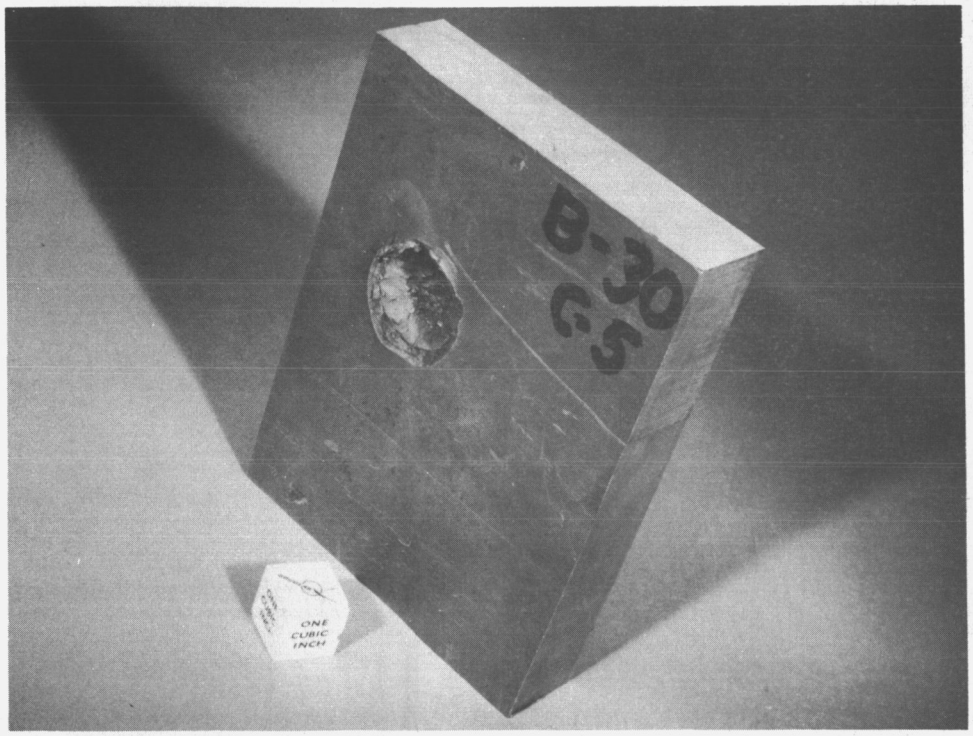


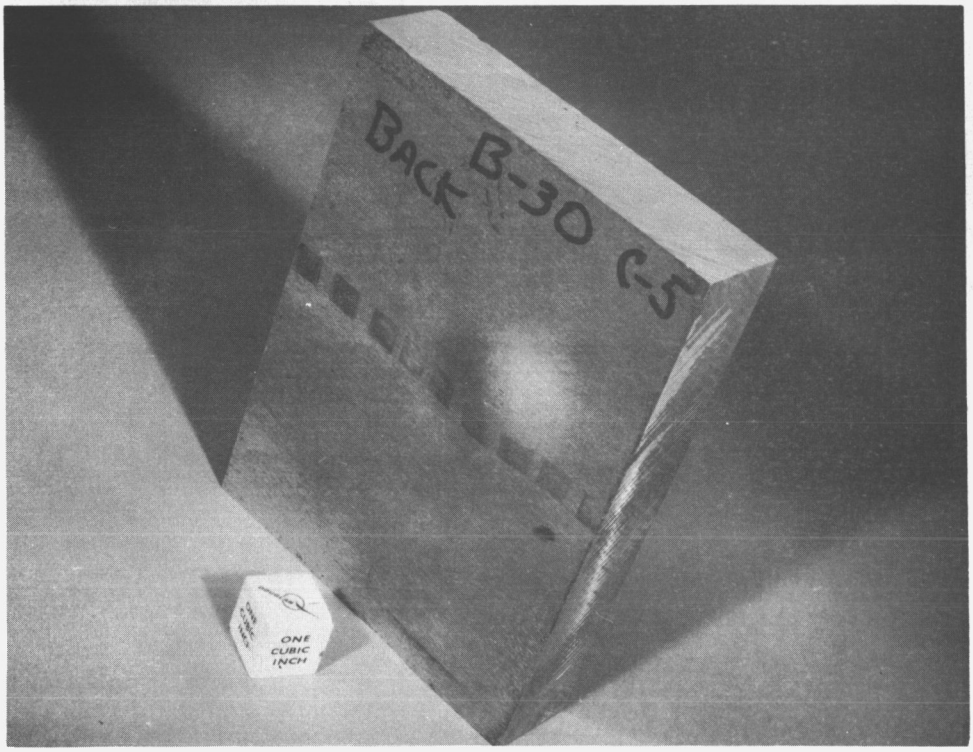
Plate 16. Dual-Sheet Target, Data No. 16



PROJECTILE MATERIAL AND MASS: SYNTACTIC FOAM SPHERE: 1.17 gm , IMPACT VELOCITY: 7.03 kmps
TARGET THICKNESS: 3.0 IN.

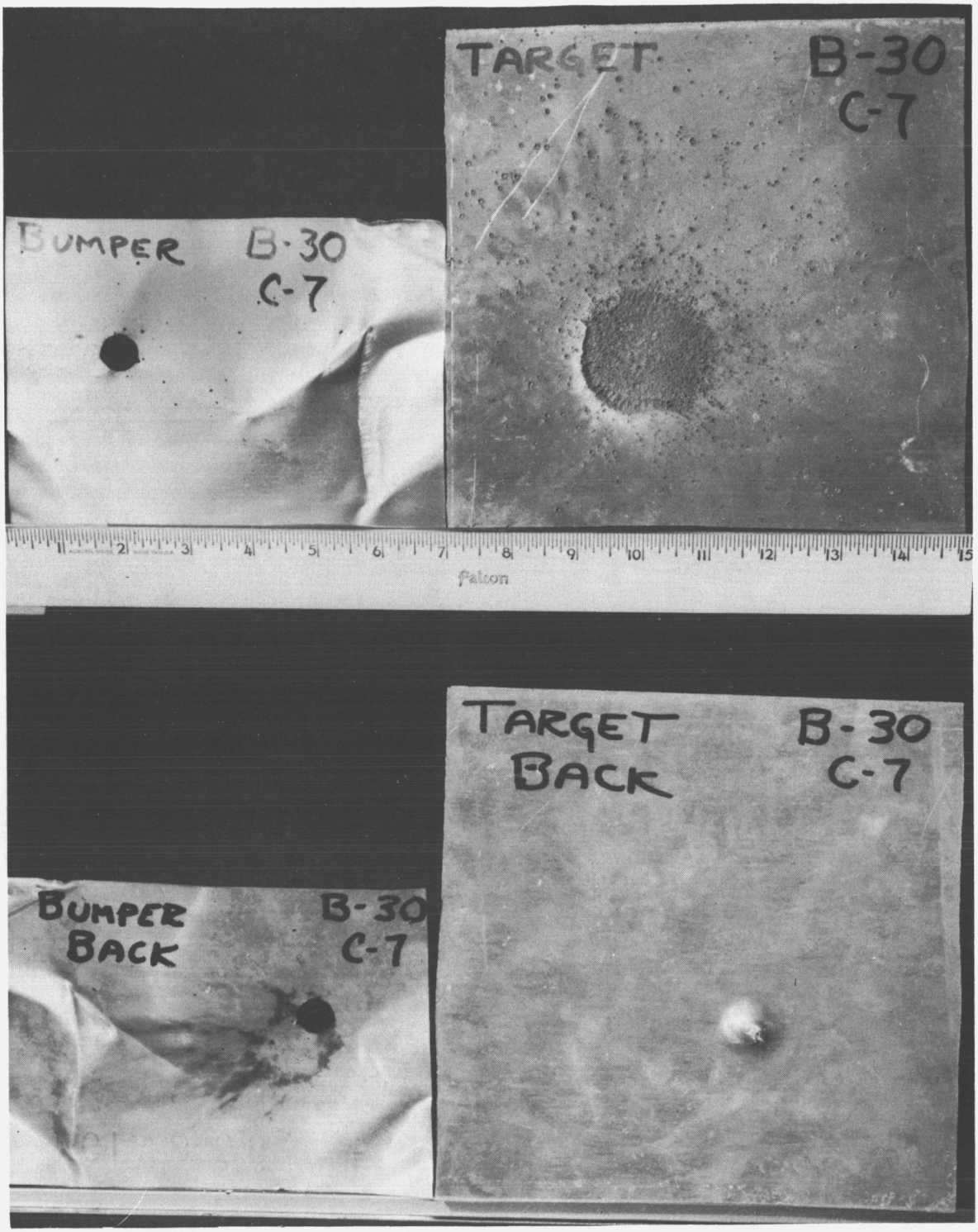
Plate 17. Semi-Infinite Target, Data No. 17





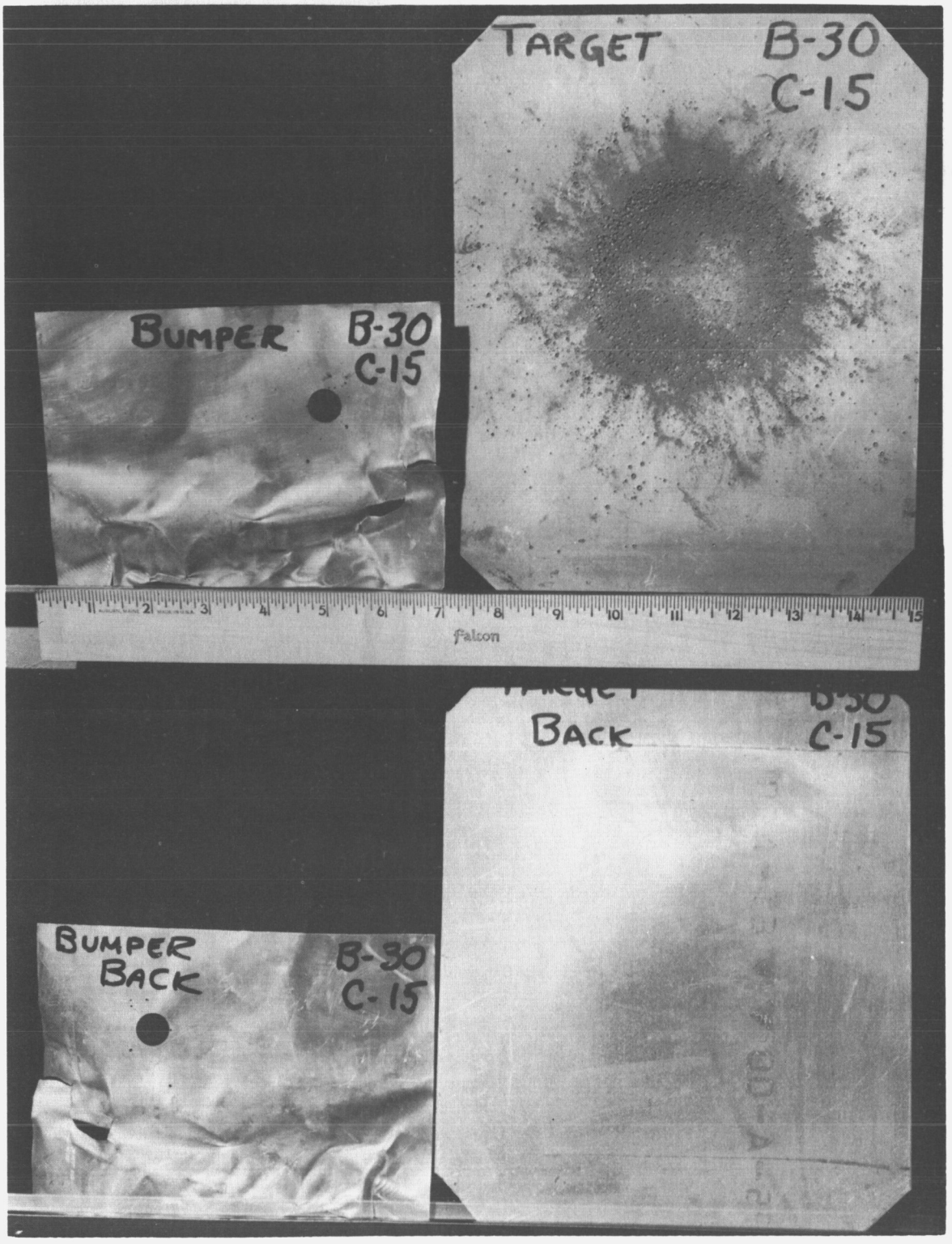
PROJECTILE MATERIAL AND MASS: SYNTACTIC FOAM SPHERE: 1.17 gm, IMPACT VELOCITY: 7.03 kmps
TARGET THICKNESS: 1.51 IN.

Plate 18, Finite-Sheet Target, Data No. 18



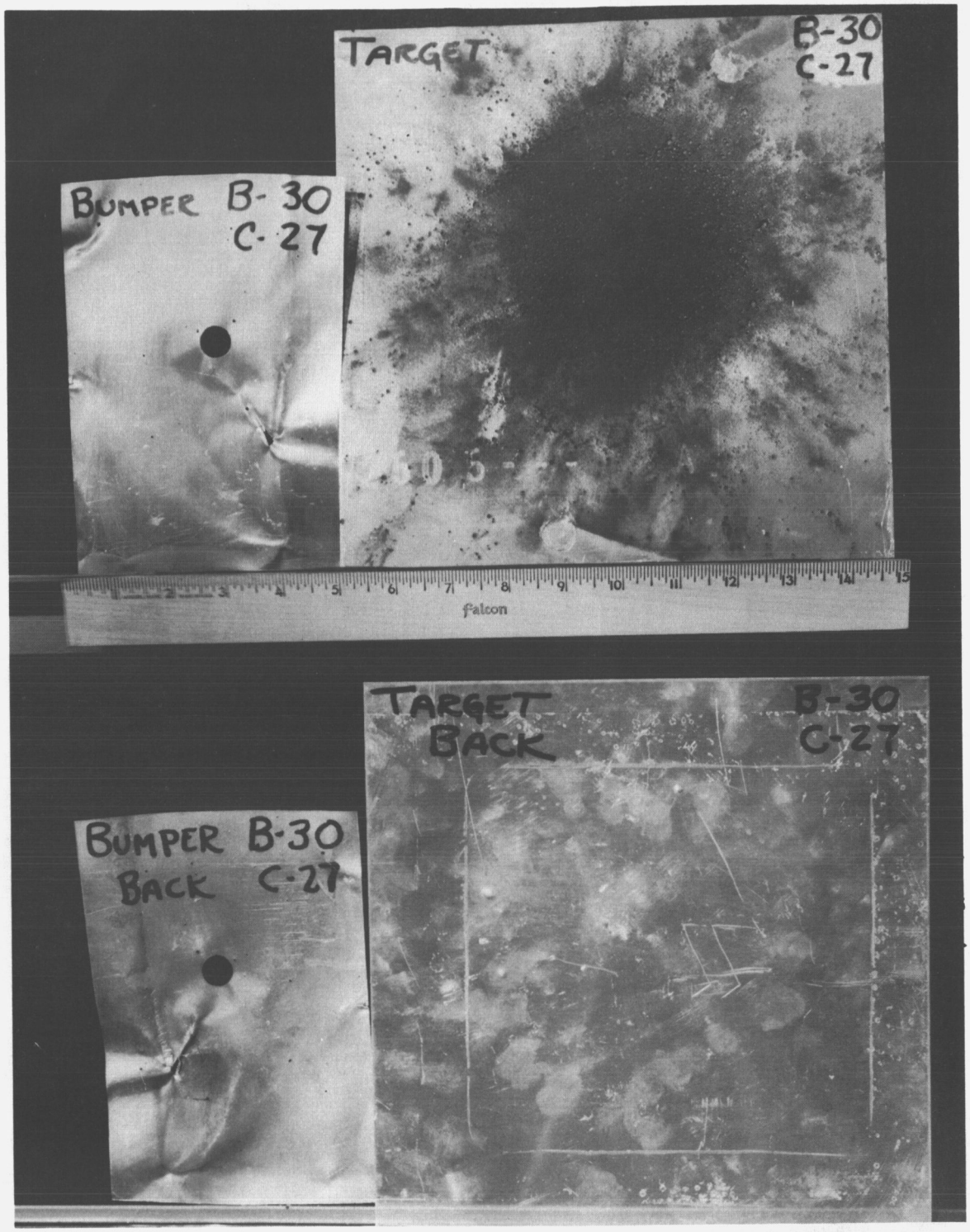
PROJECTILE MATERIAL AND MASS: SYNTACTIC FOAM SPHERE: 1.165 gm, IMPACT VELOCITY: 7.05 kmps
BUMPER THICKNESS: 0.012 IN., TARGET THICKNESS: 0.757 IN., SPACING: 8.27 IN.

Plate 19. Dual-Sheet Target, Data No. 19



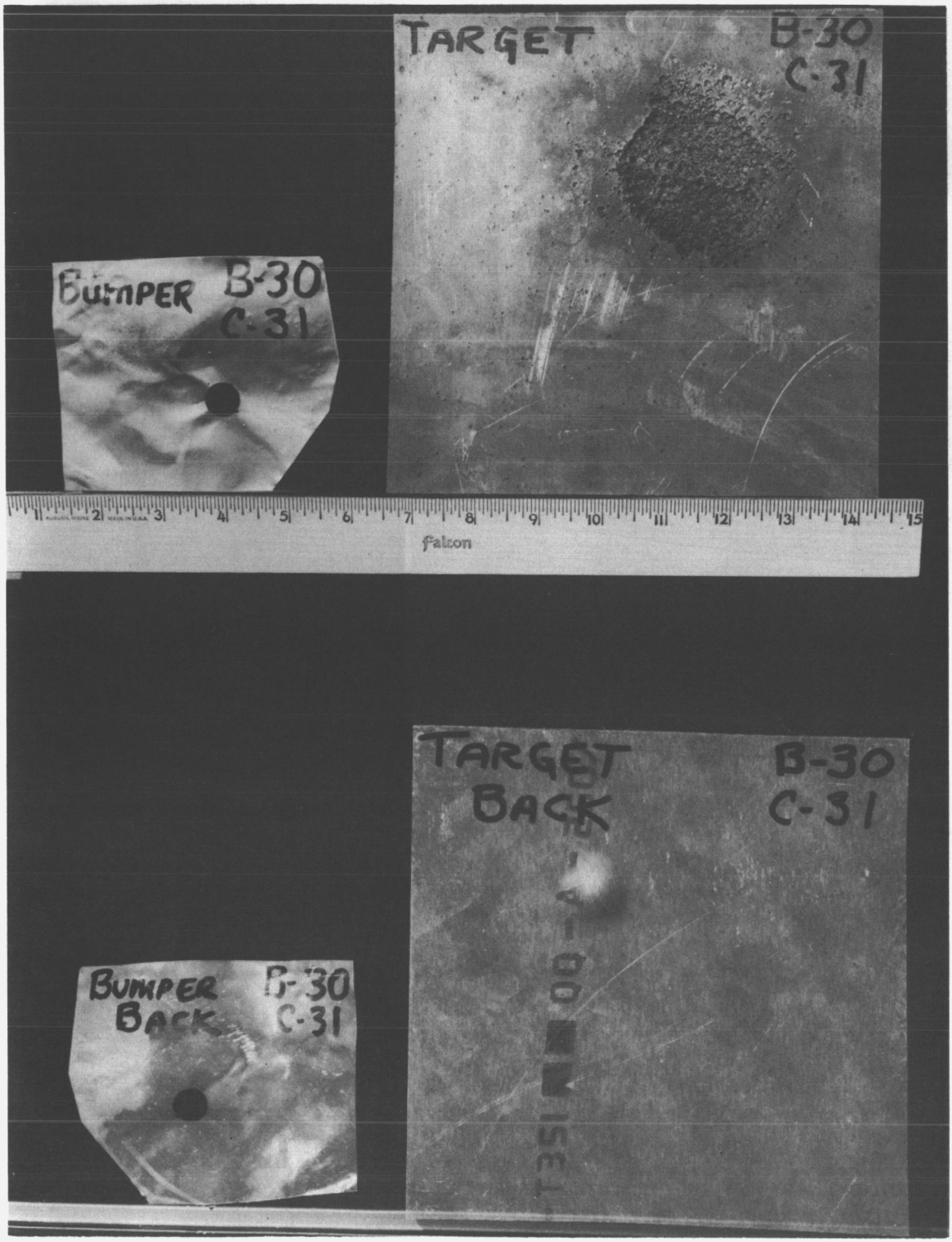
PROJECTILE MATERIAL AND MASS: SYNTACTIC FOAM SPHERE: 1.165 gm, IMPACT VELOCITY: 7.27 kmps
BUMPER THICKNESS: 0.012 IN. TARGET THICKNESS: 0.125 IN., SPACING: 16.54.

Plate 20. Dual-Sheet Target, Data No. 20



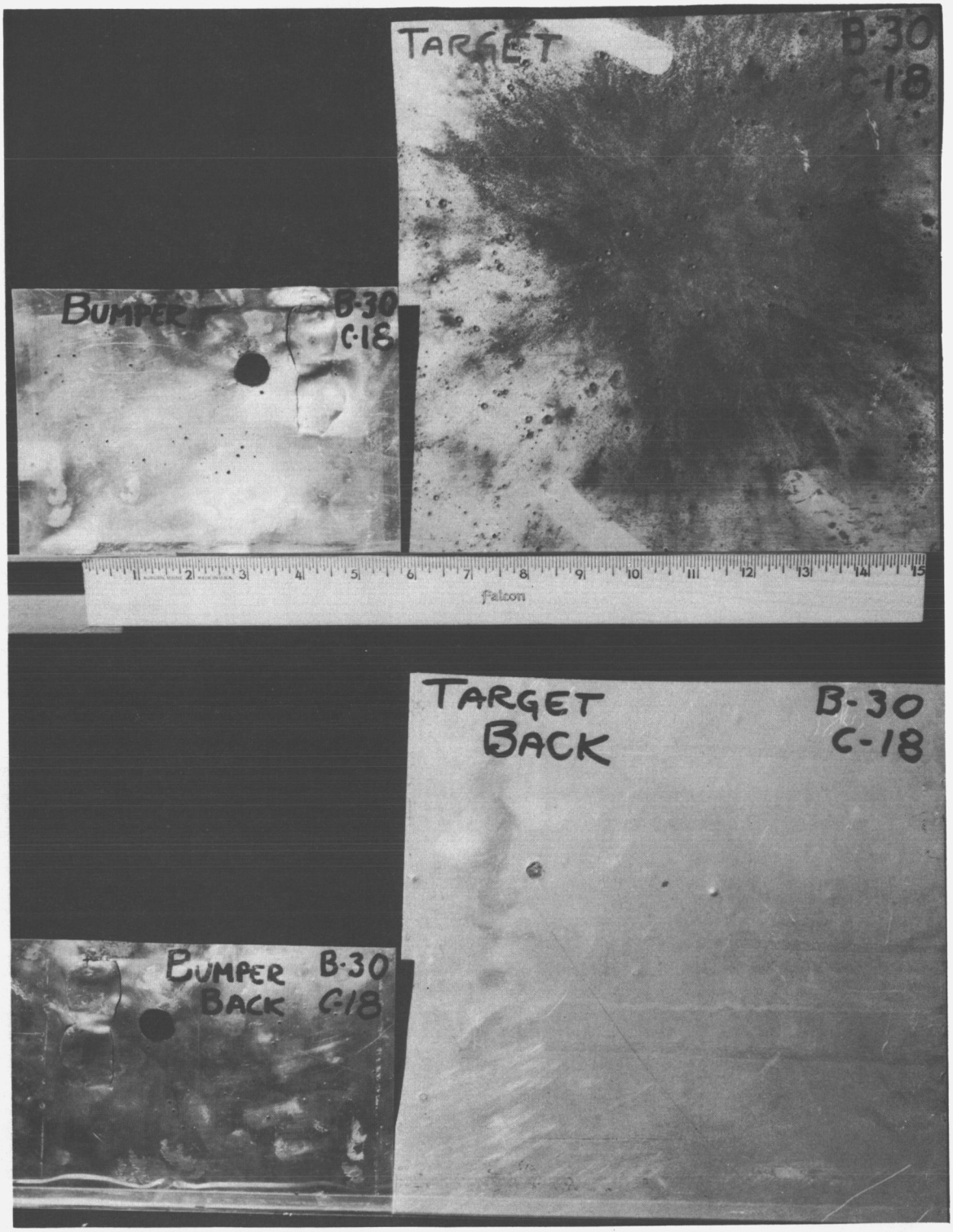
PROJECTILE MATERIAL AND MASS: SYNTACTIC FOAM SPHERE: 1.165 gm, IMPACT VELOCITY: 7.03 kmps
BUMPER THICKNESS: 0.012 IN., TARGET THICKNESS: 0.125 IN., SPACING: 22.04 IN.

Plate 21. Dual-Sheet Target, Data No. 21



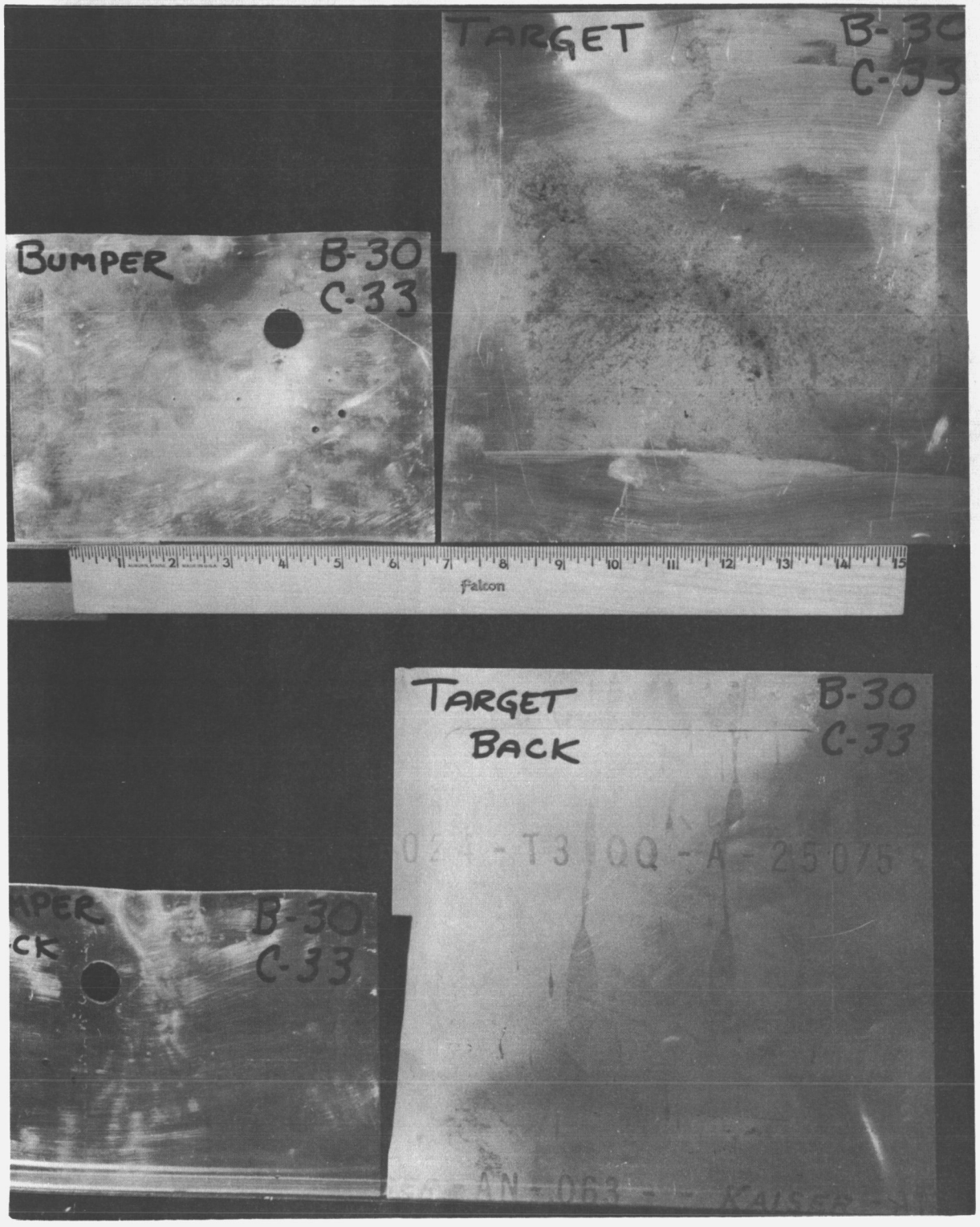
PROJECTILE MATERIAL AND MASS: SYNTACTIC FOAM SPHERE: 1.160 gm. IMPACT VELOCITY: 7.03 kmps
BUMPER THICKNESS: 0.008 IN., TARGET THICKNESS: 0.759 IN., SPACING: 16.54 IN.

Plate 22. Dual-Sheet Target, Data No. 22



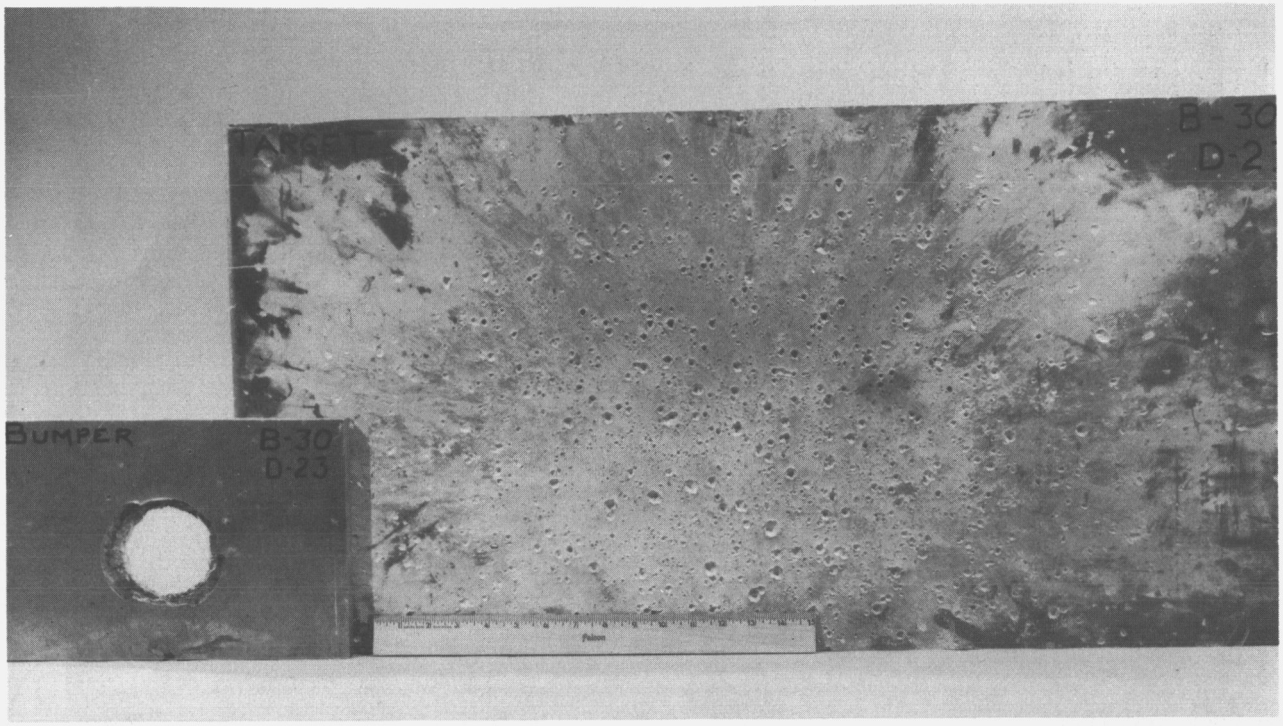
PROJECTILE MATERIAL AND MASS: SYNTACTIC FOAM SPHERE: 1.085 gm, IMPACT VELOCITY: 7.12 kmps
BUMPER THICKNESS: 0.025 IN., TARGET THICKNESS: 0.162 IN., SPACING 16.54 IN.

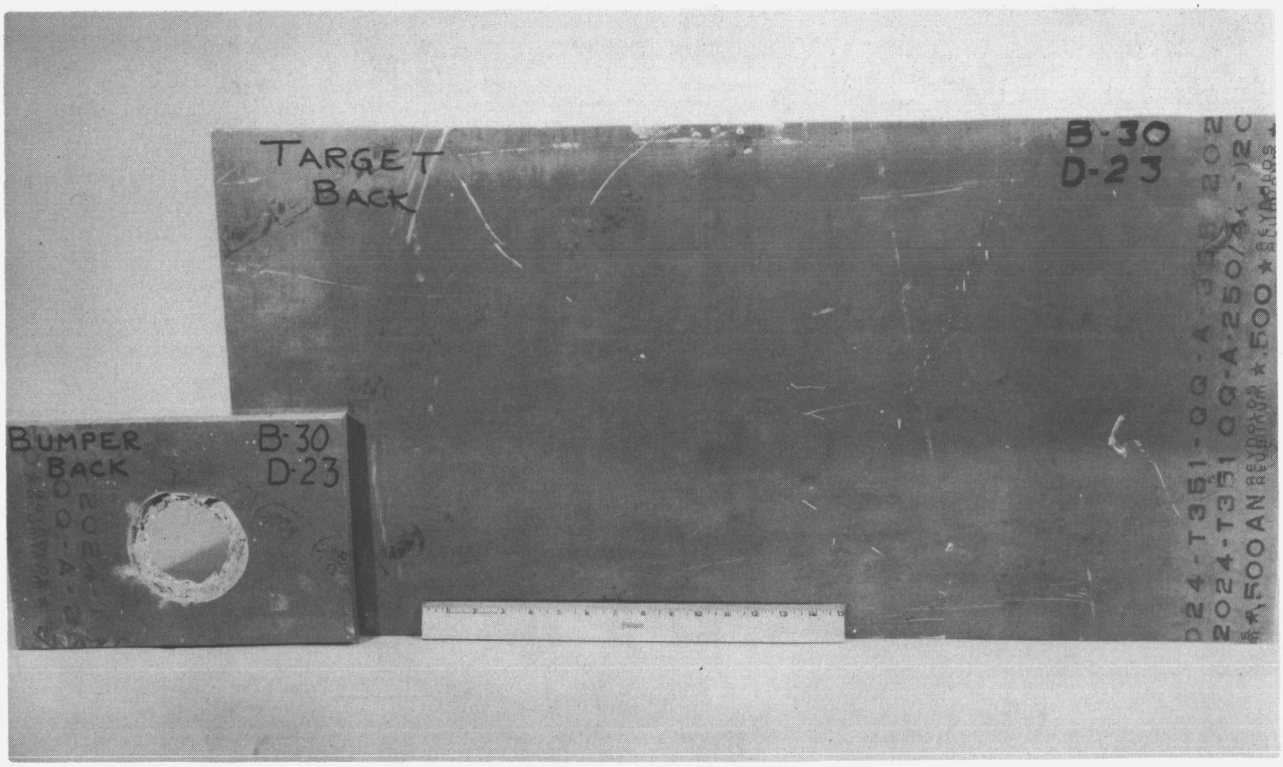
Plate 23. Dual-Sheet Target, Data No. 23



PROJECTILE MATERIAL AND MASS: SYNTACTIC FOAM SPHERE: 1.160 gm, IMPACT VELOCITY: 7.03 kmps
BUMPER THICKNESS: 0.050 IN., TARGET THICKNESS: 0.125 IN., SPACING: 8.27 IN.

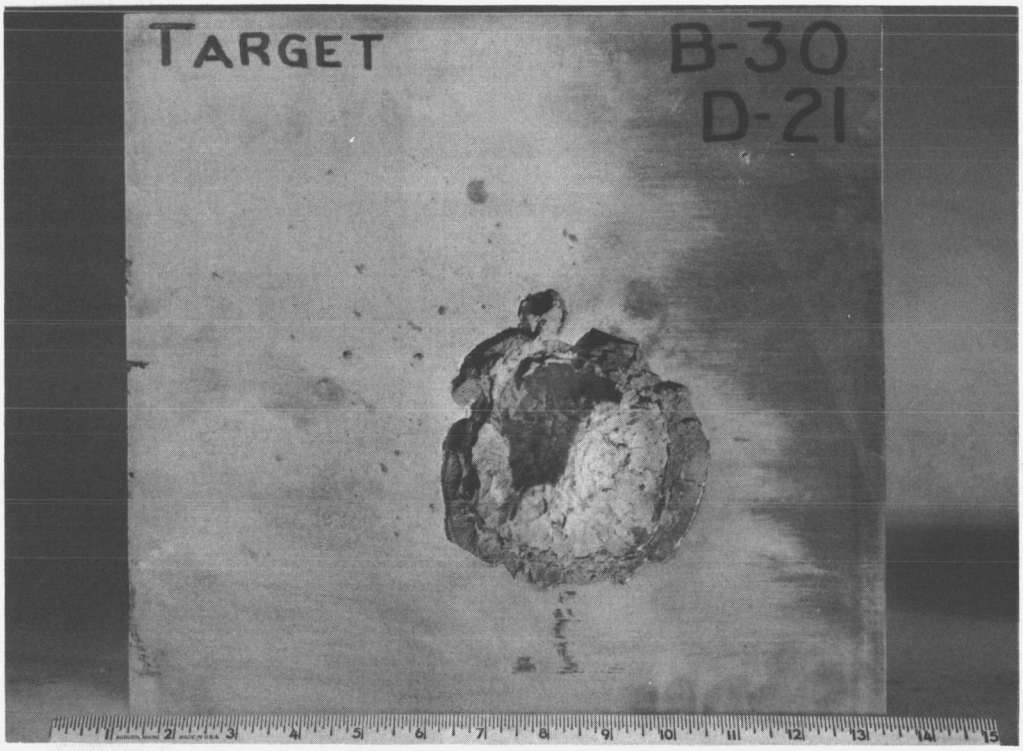
Plate 24. Dual-Sheet Target, Data No. 24

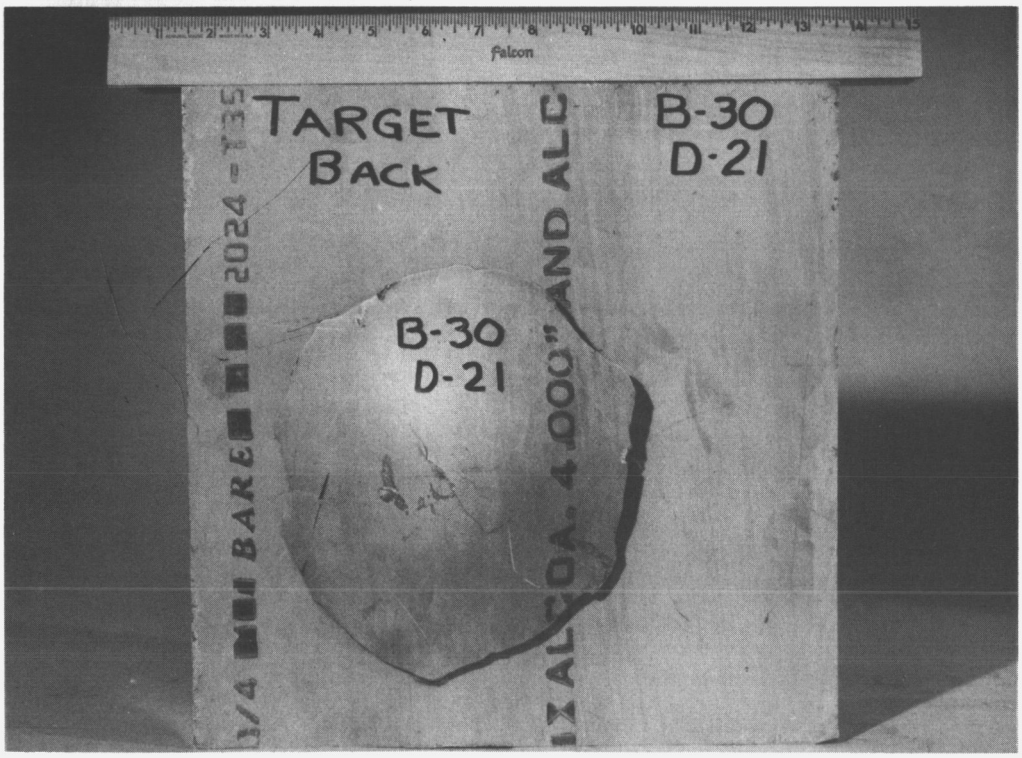




PROJECTILE MATERIAL AND MASS: ALUMINUM SPHERE: 10.38 gm, IMPACT VELOCITY: 7.27 kmps
BUMPER THICKNESS: 0.770 IN. , TARGET THICKNESS: 0.504 IN., SPACING: 22.60 IN.

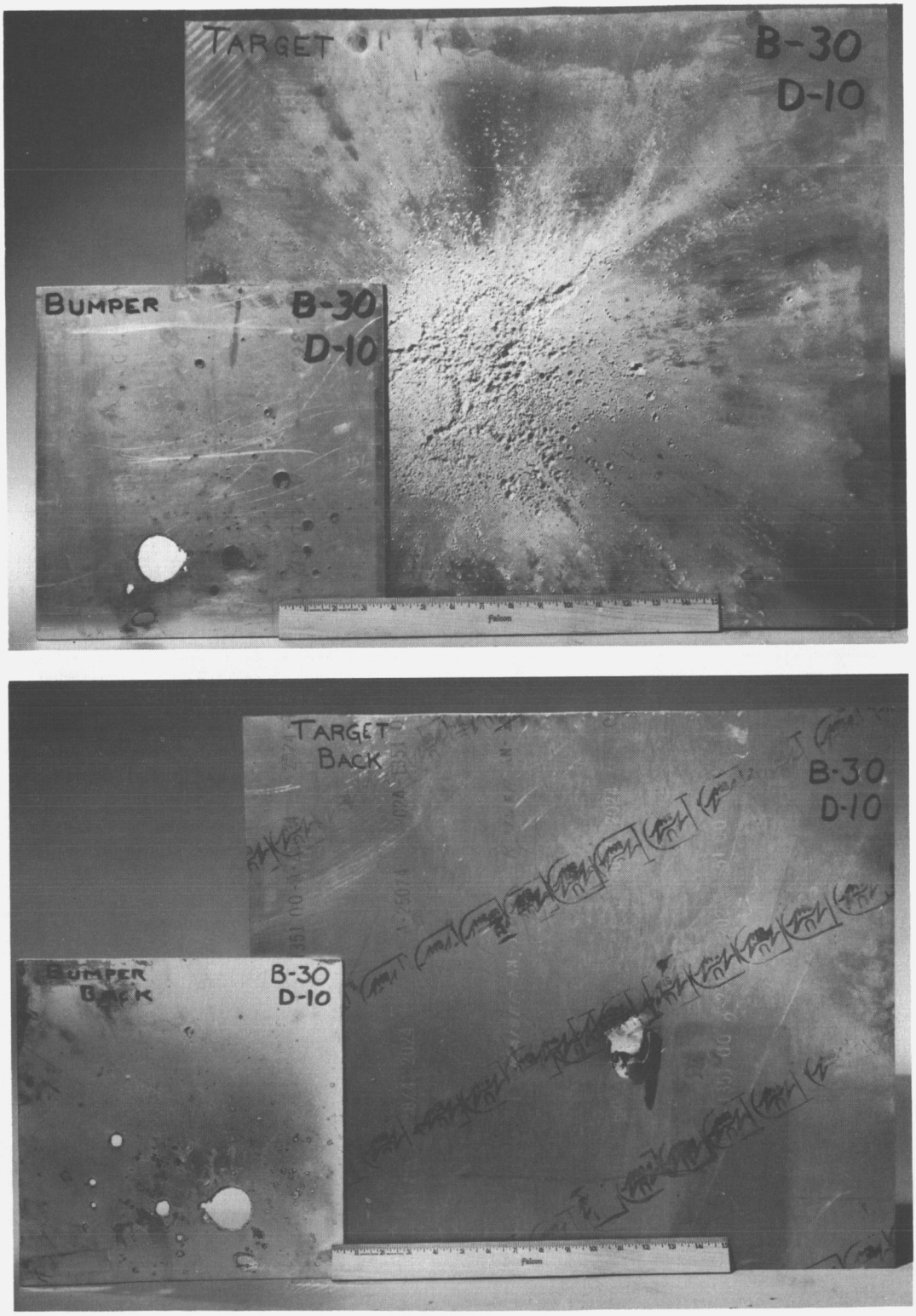
Plate 25. Dual-Sheet Target, Data No. 25.





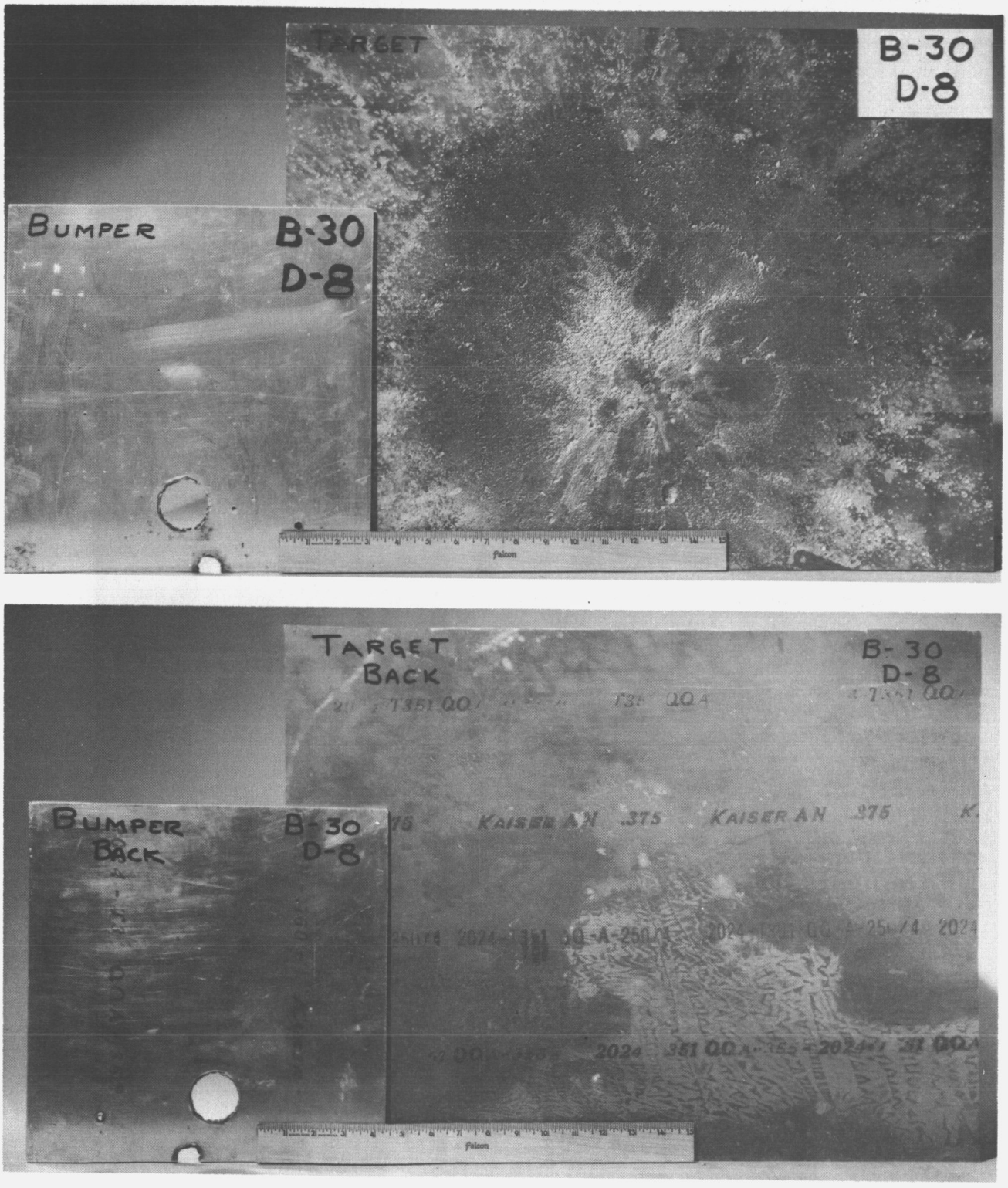
PROJECTILE MATERIAL AND MASS: ALUMINUM SPHERE: 10.38 gm, IMPACT VELOCITY: 7.27 kmps
TARGET THICKNESS: 3.72 IN.

Plate 26. Finite-Sheet Target, Data No. 26



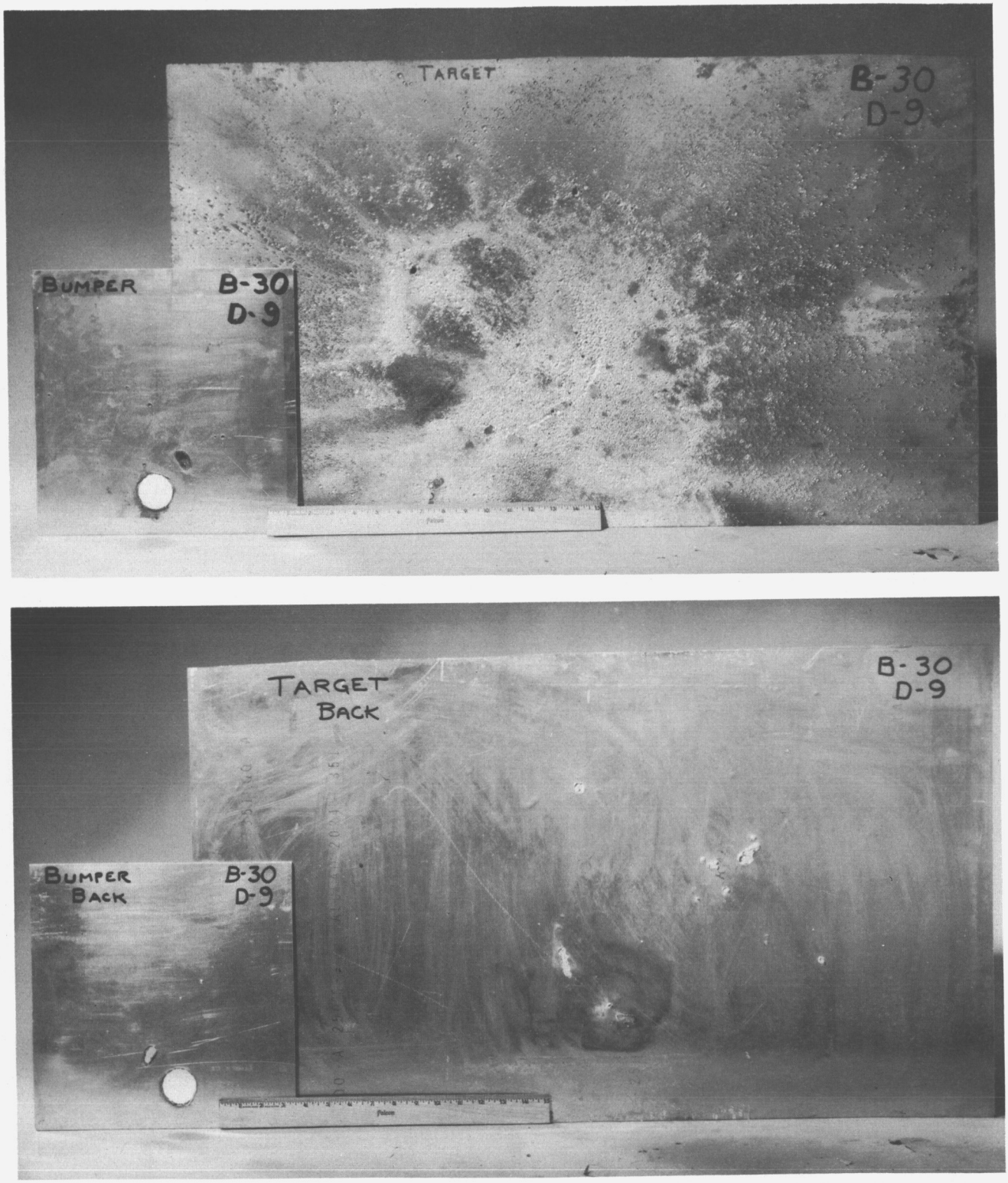
PROJECTILE MATERIAL AND MASS: ALUMINUM SPHERE: 10.38 gm, IMPACT VELOCITY: 7.15 kmps
BUMPER THICKNESS: 0.161 IN., TARGET THICKNESS: 1.113 IN., SPACING: 11.30 IN.

Plate 27. Dual-Sheet Target, Data No. 27



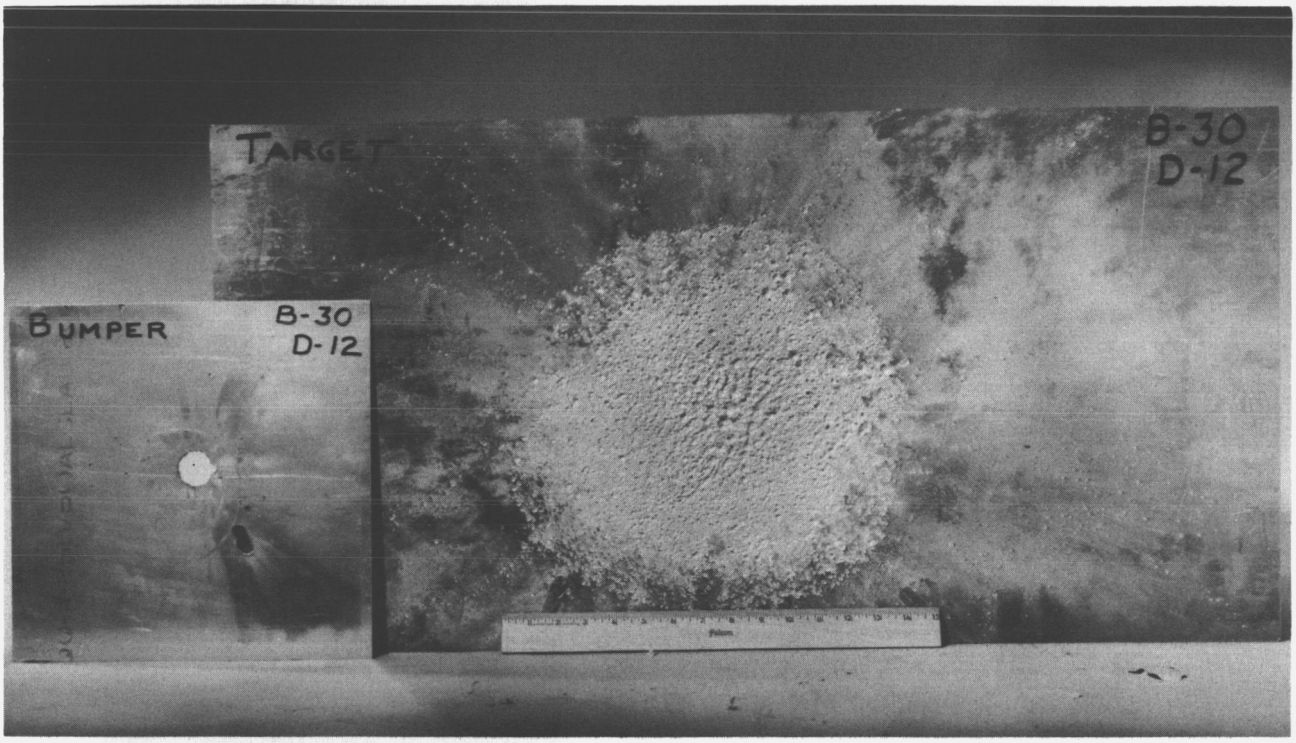
PROJECTILE MATERIAL AND MASS: ALUMINUM SPHERE: 10.38 gm, IMPACT VELOCITY: 7.08 kmps
BUMPER THICKNESS: 0.161 IN., TARGET THICKNESS: 0.381 IN., SPACING: 22.60 IN.

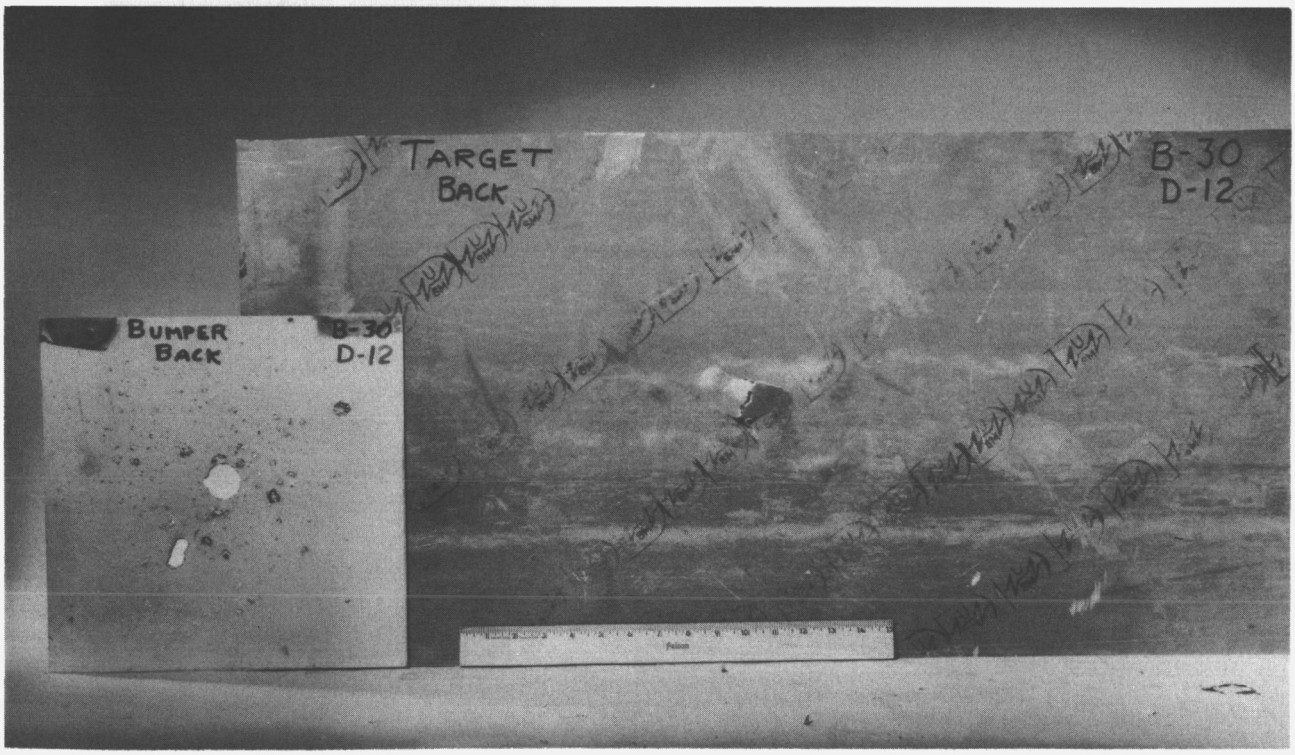
Plate 28. Dual-Sheet Target, Data No. 28



PROJECTILE MATERIAL AND MASS: ALUMINUM SPHERE 10.38 gm, IMPACT VELOCITY: 7.08 kmps
BUMPER THICKNESS: 0.161 IN., TARGET THICKNESS: 0.245 IN., SPACING: 30.00 IN.

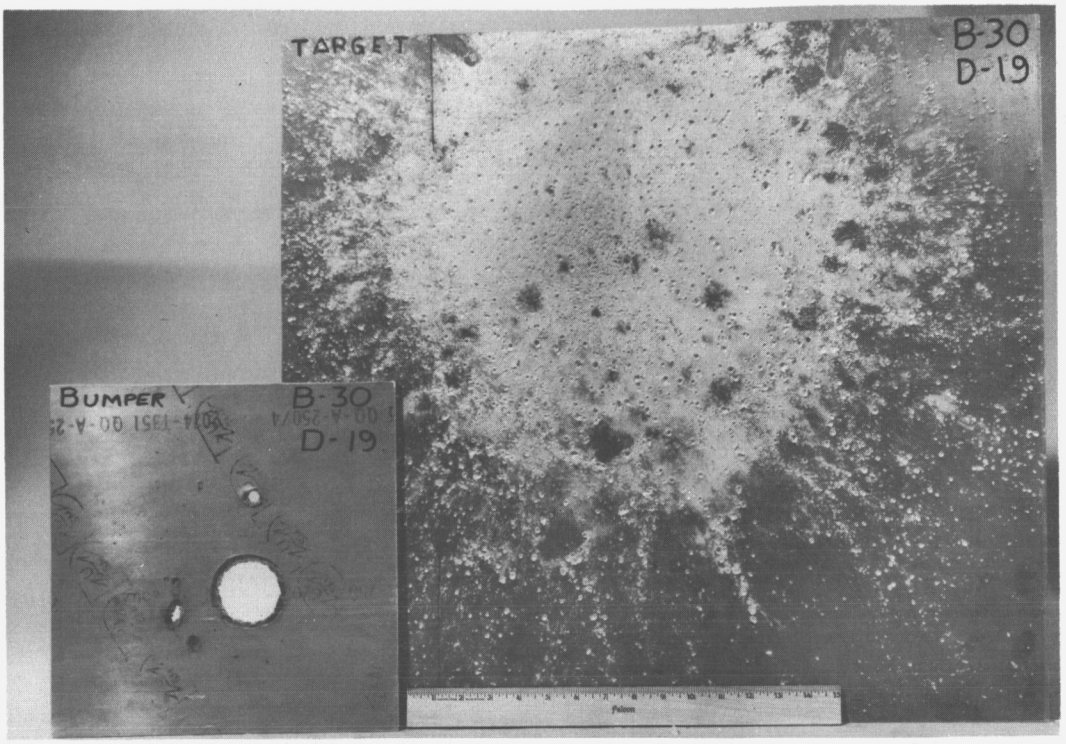
Plate 29. Dual-Sheet Target, Data No. 29

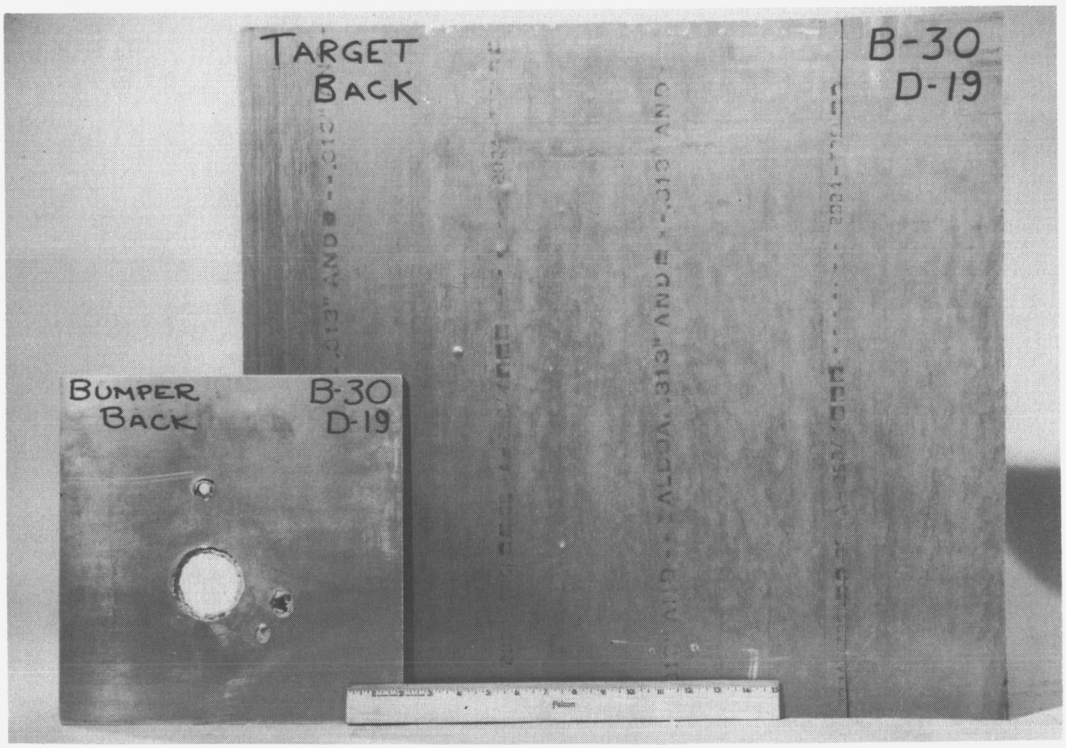




PROJECTILE MATERIAL AND MASS: ALUMINUM SPHERE 10.38 gm, IMPACT VELOCITY: 7.27 kmps
BUMPER THICKNESS: 0.080 IN., TARGET THICKNESS: 0.640 IN., SPACING 22.60 IN.

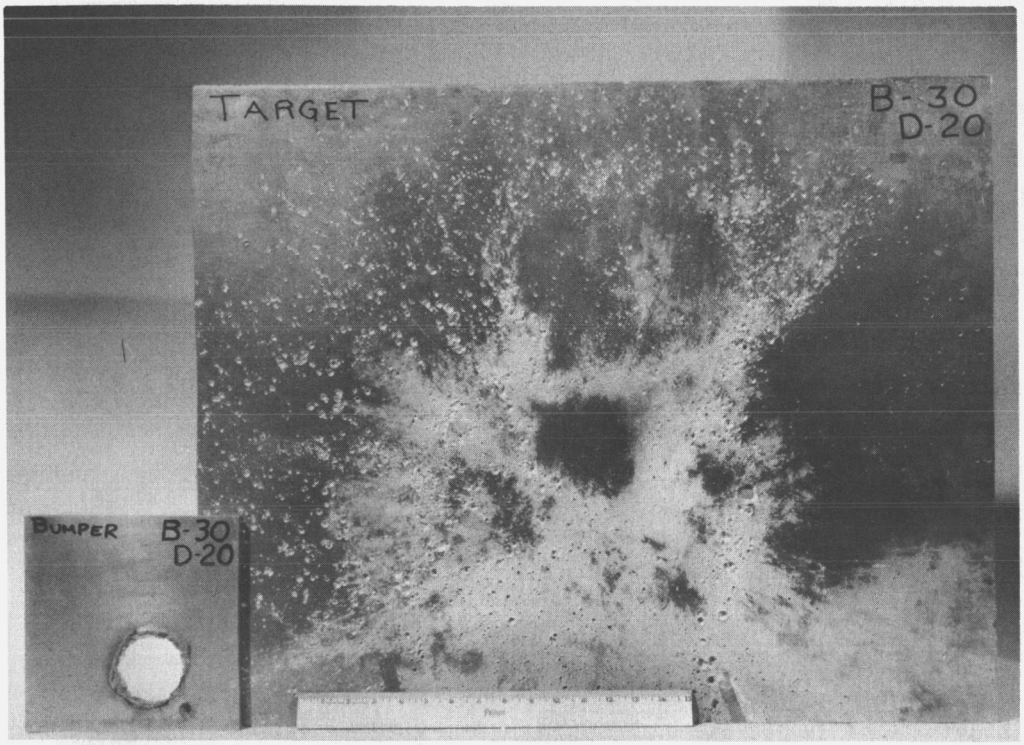
Plate 30. Dual-Sheet Target, Data No. 30

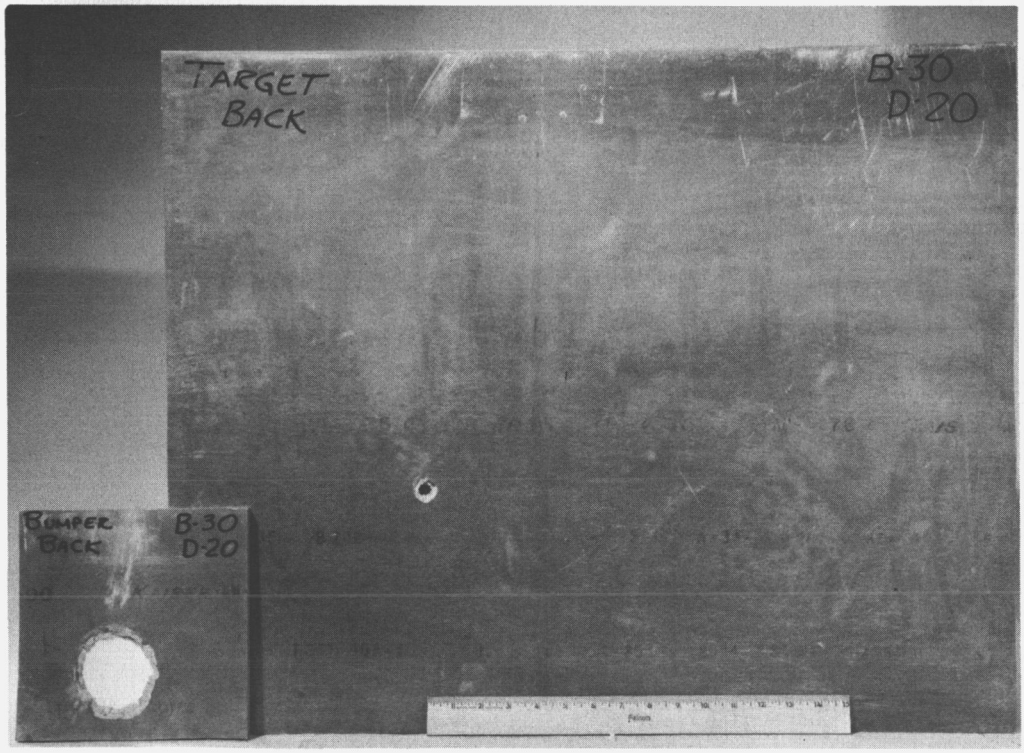




PROJECTILE MATERIAL AND MASS: ALUMINUM SPHERE: 10.38 gm, IMPACT VELOCITY: 7.15 kmps
BUMPER THICKNESS: 0.322 IN., TARGET THICKNESS: 0.315 IN., SPACING: 22.60 IN.

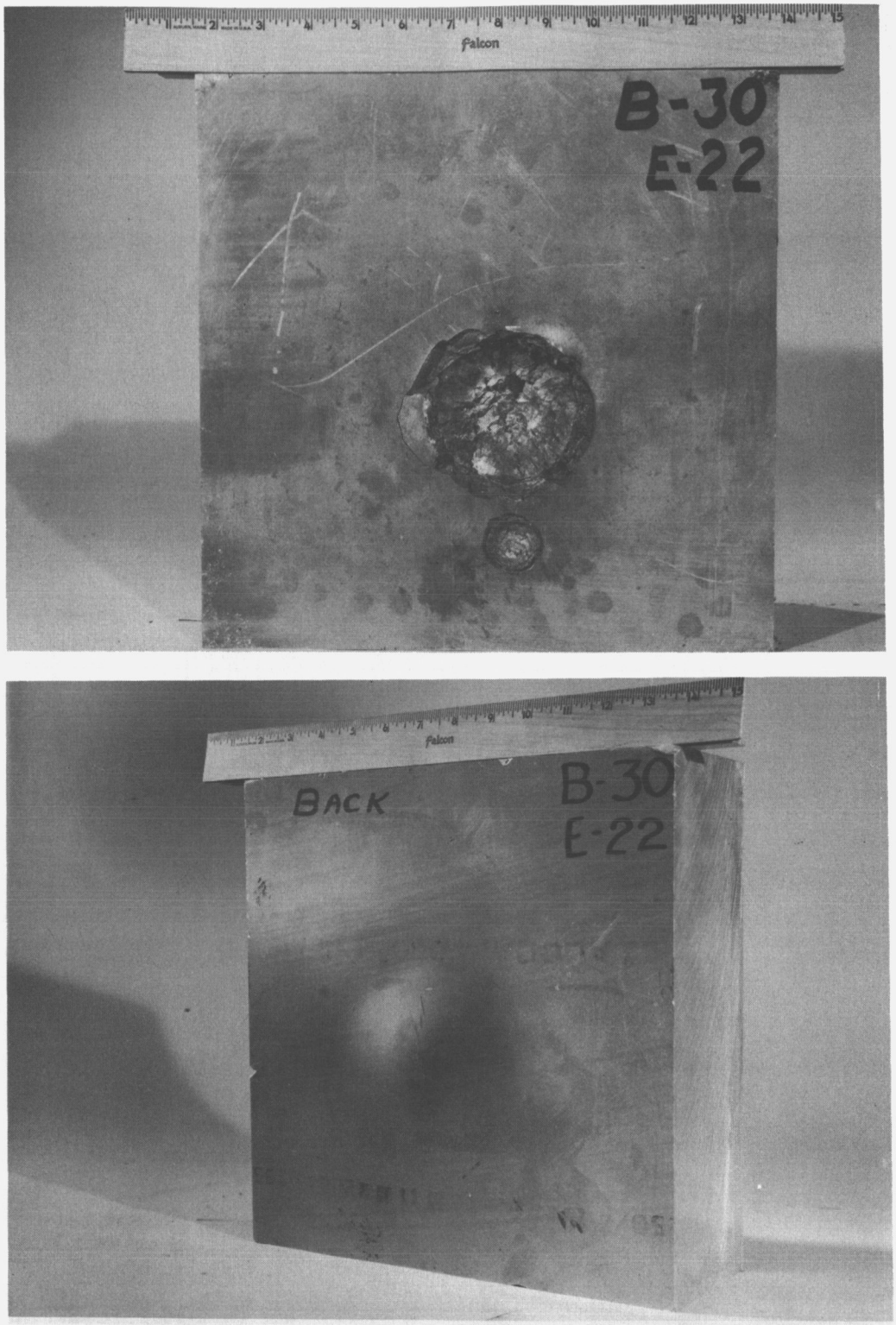
Plate 31. Dual-Sheet Target, Data No. 31





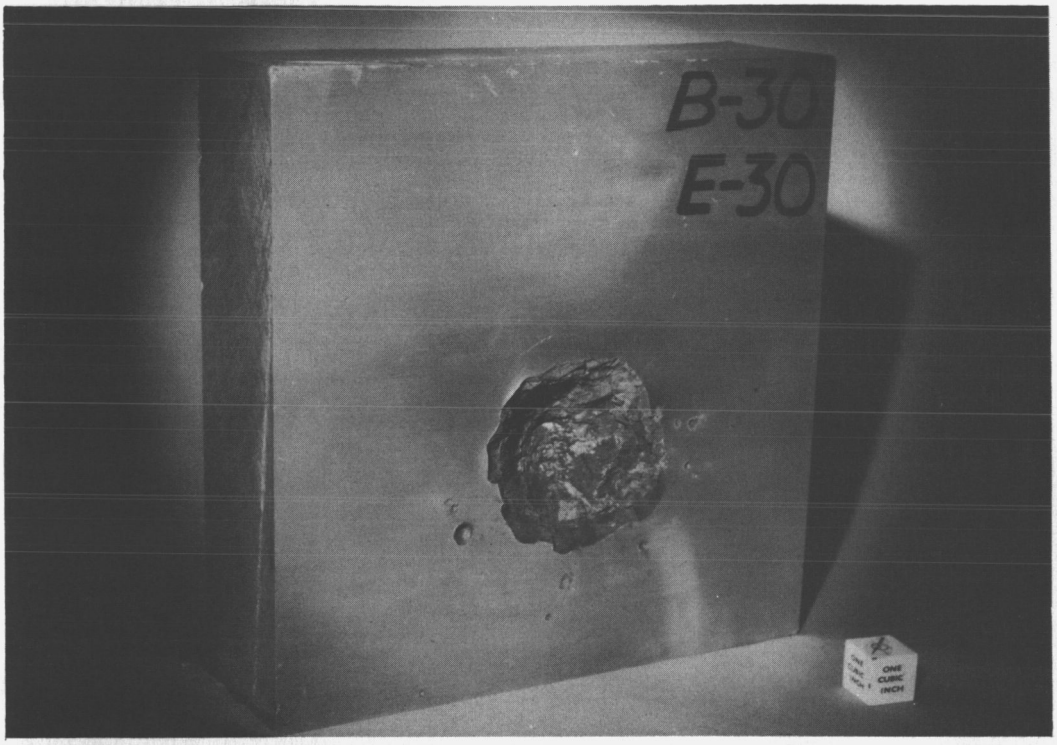
PROJECTILE MATERIAL AND MASS: ALUMINUM SPHERE: 10.38 gm, IMPACT VELOCITY: 7.27 kmps, BUMPER THICKNESS: 0.498 IN., TARGET THICKNESS: 0.388 IN., SPACING: 22.60 IN.

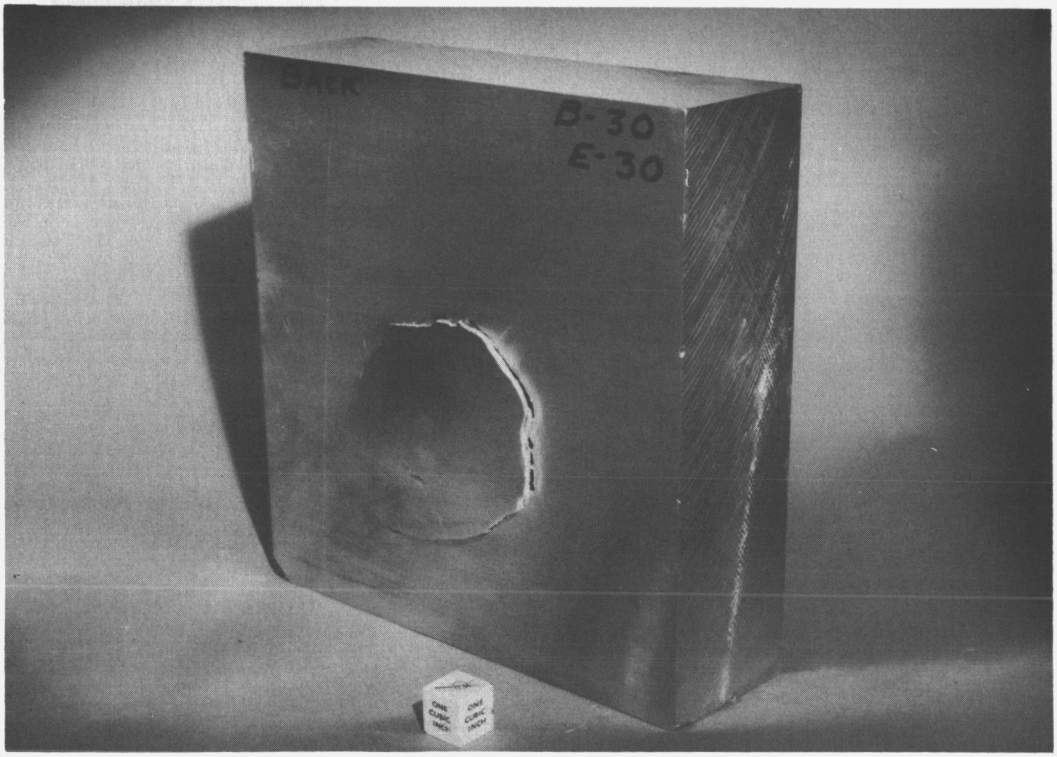
Plate 32. Dual-Sheet Target, Data No. 32



PROJECTILE MATERIAL AND MASS: SYNTACTIC FOAM SPHERE: 10.80 gm,
IMPACT VELOCITY: 7.03 kmps, TARGET THICKNESS: 4.00 IN.

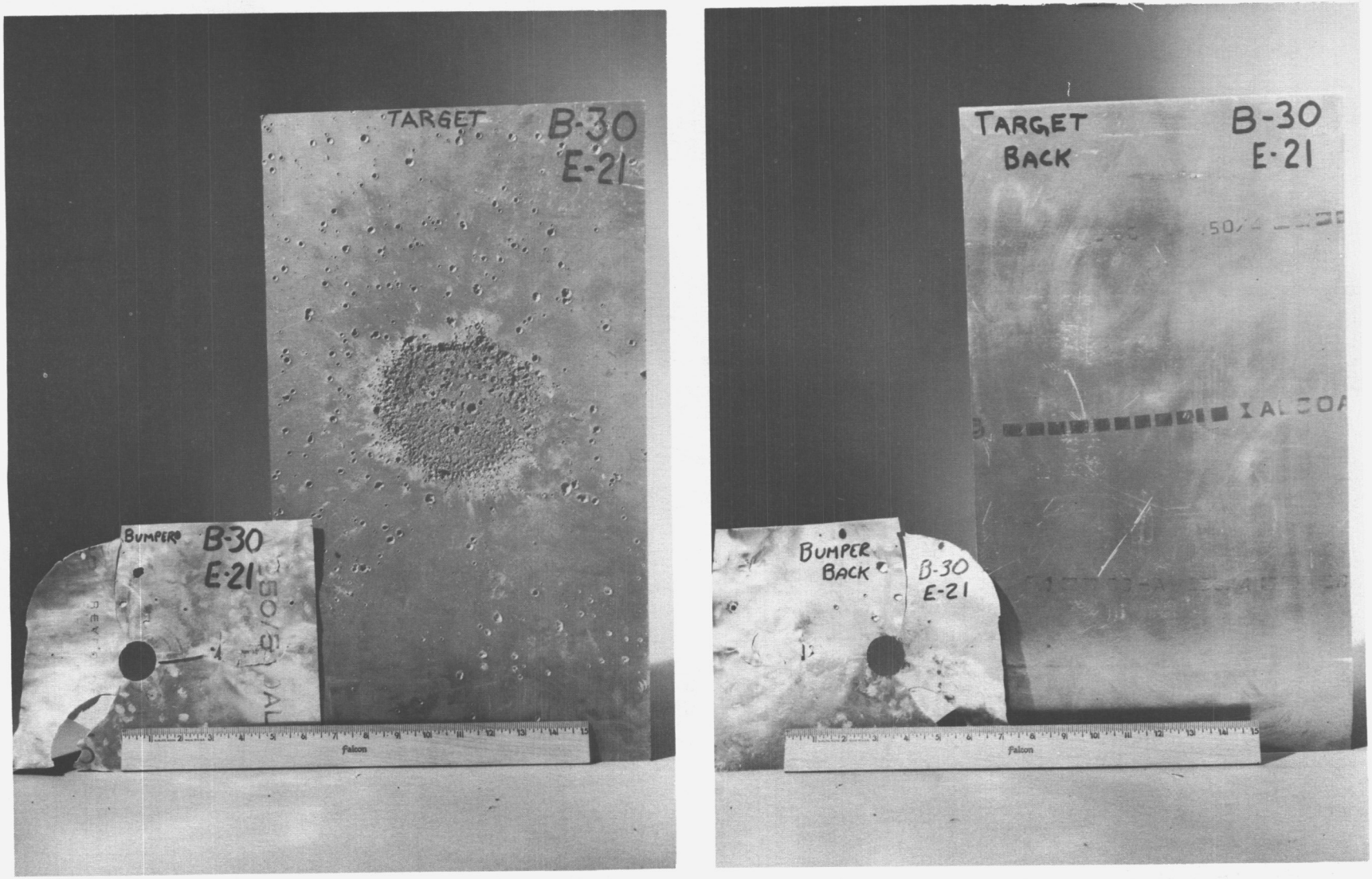
Plate 33. Semi-Infinite Target, Data No. 33





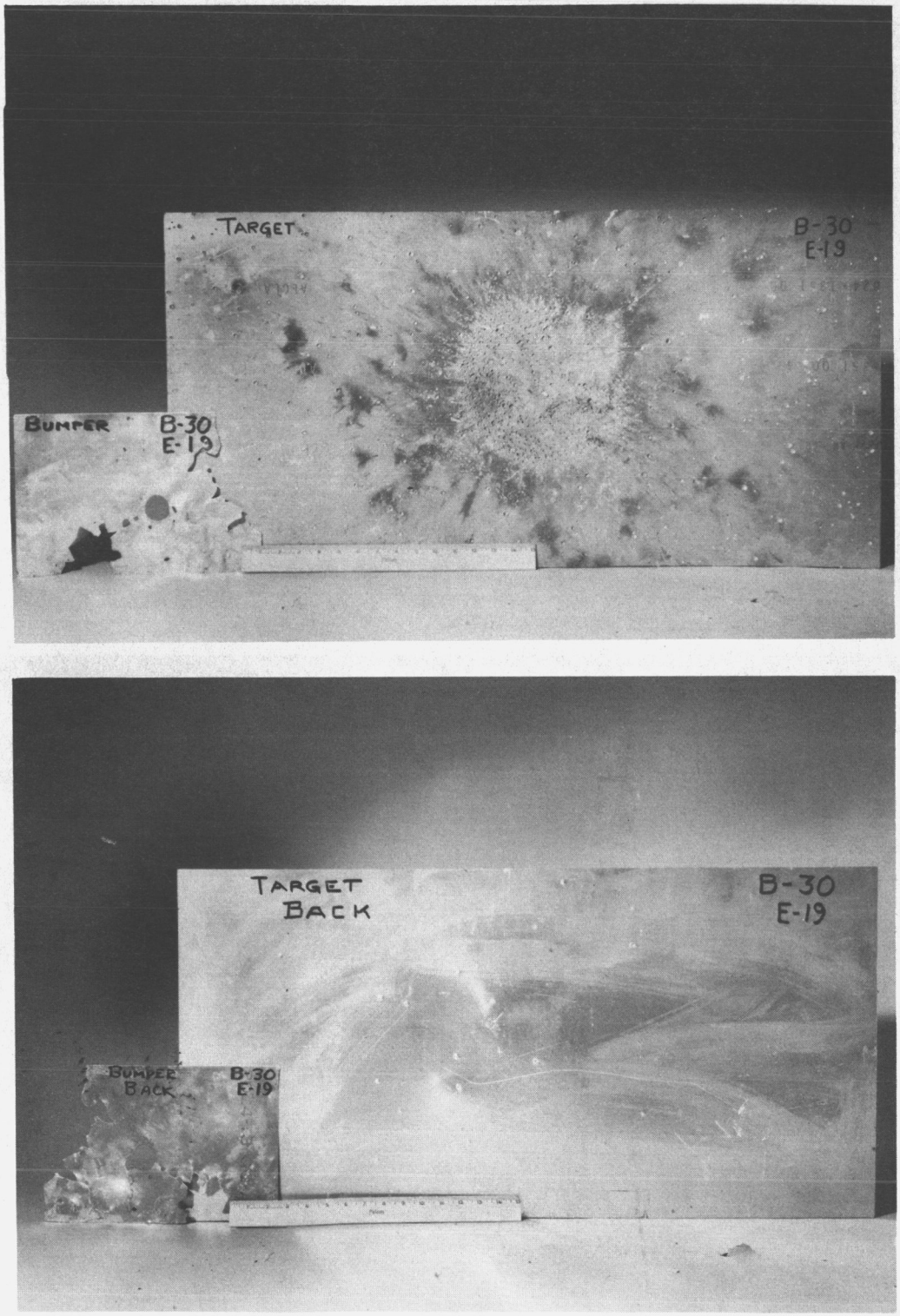
PROJECTILE MATERIAL AND MASS: SYNTACTIC FOAM SPHERE: 10.80 gm,
IMPACT VELOCITY: 7.03 kmps, TARGET THICKNESS: 3.60 IN.

Plate 34. Finite-Sheet Target, Data No. 34



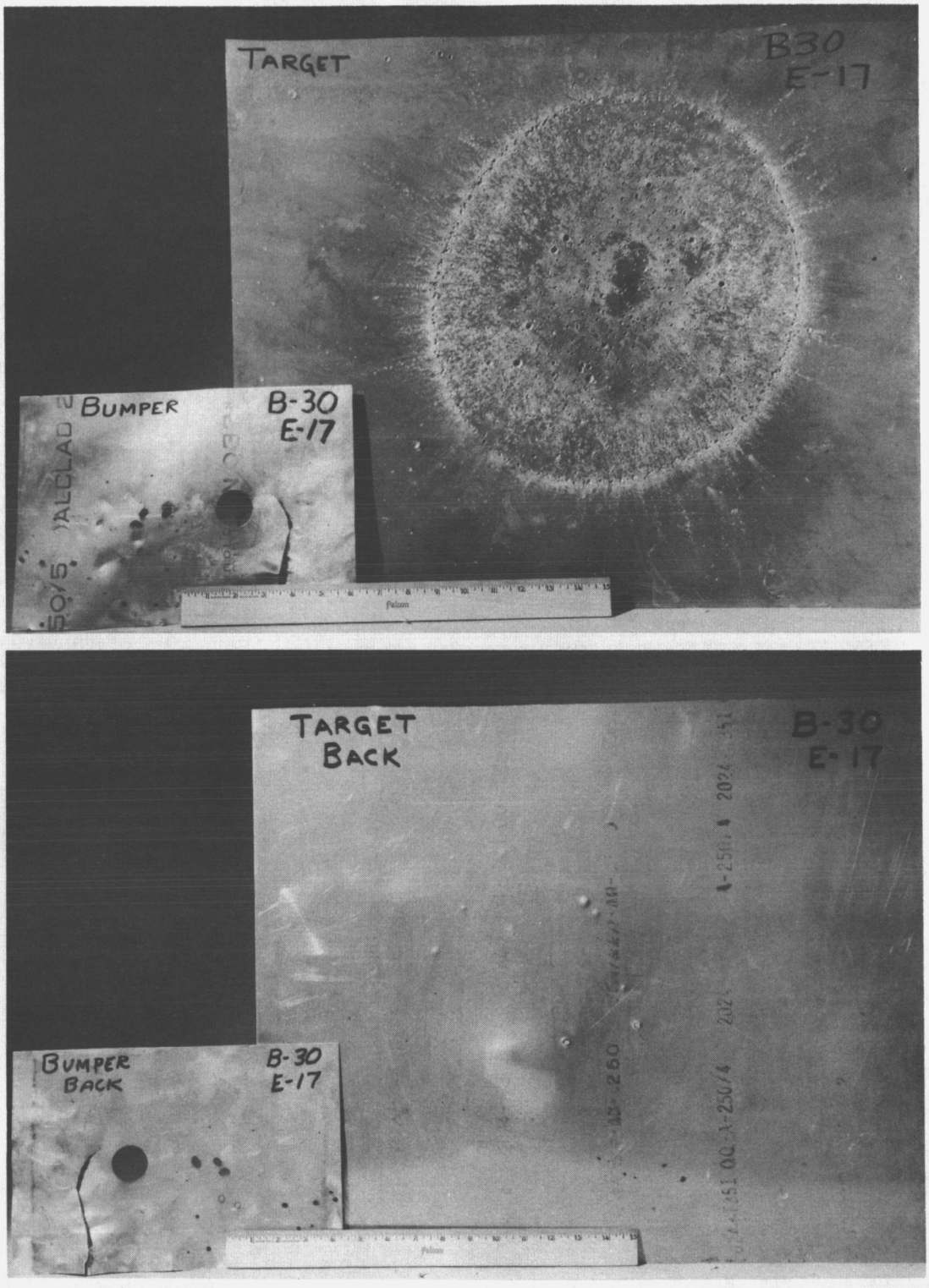
PROJECTILE MATERIAL AND MASS: SYNTACTIC FOAM SPHERE: 10.83 gm, IMPACT VELOCITY: 7.03 kmps,
BUMPER THICKNESS: 0.032 IN., TARGET THICKNESS: 1.498 IN., SPACING: 17.80 IN.

Plate 35. Dual-Sheet Target, Data No. 35



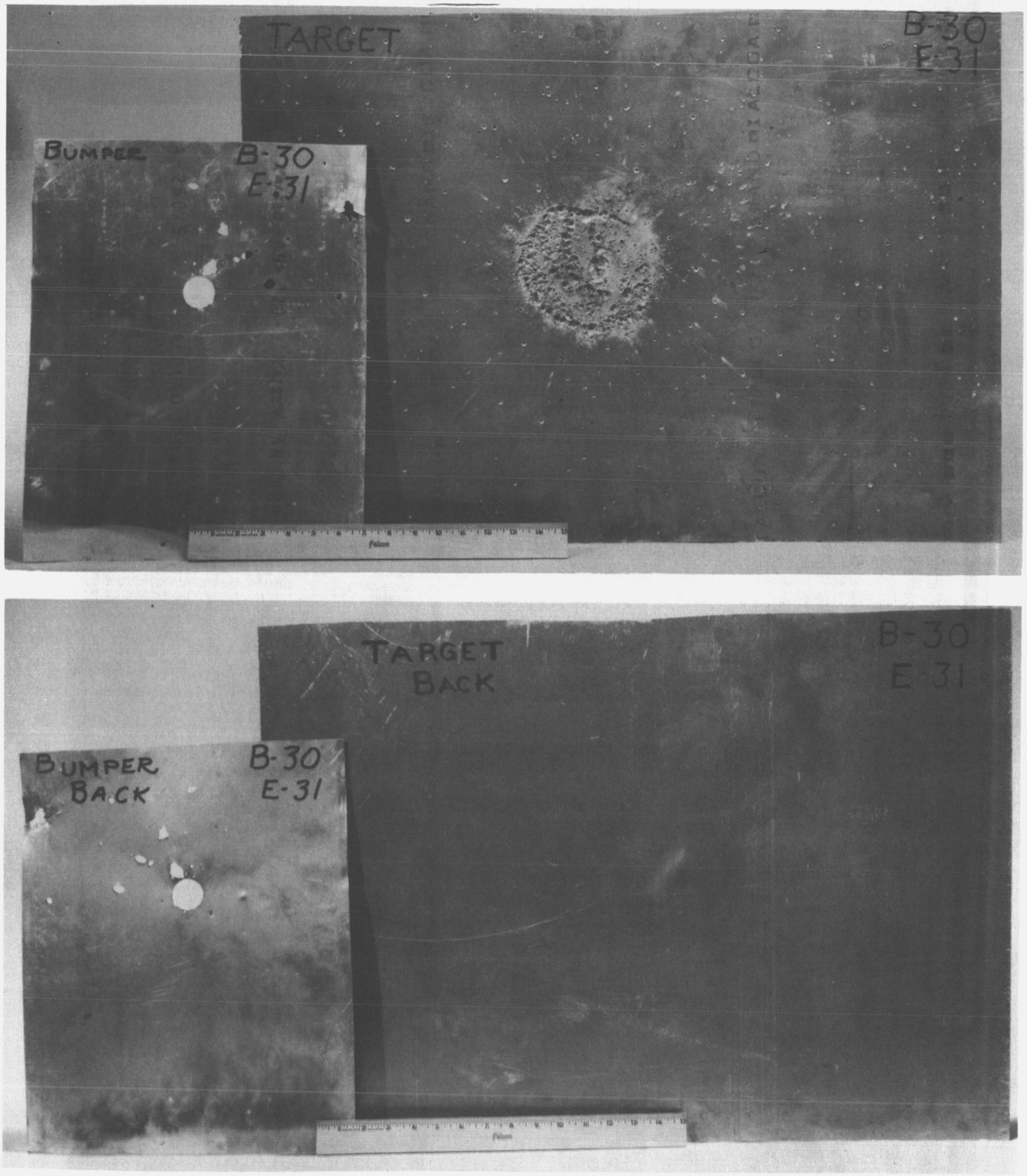
PROJECTILE MATERIAL AND MASS: SYNTACTIC FOAM SPHERE: 10.80 gm, IMPACT VELOCITY: 7.03 kmps, BUMPER THICKNESS: 0.032 IN., TARGET THICKNESS: 0.243 IN., SPACING: 35.60 IN.

Plate 36. Dual-Sheet Target, Data No. 36



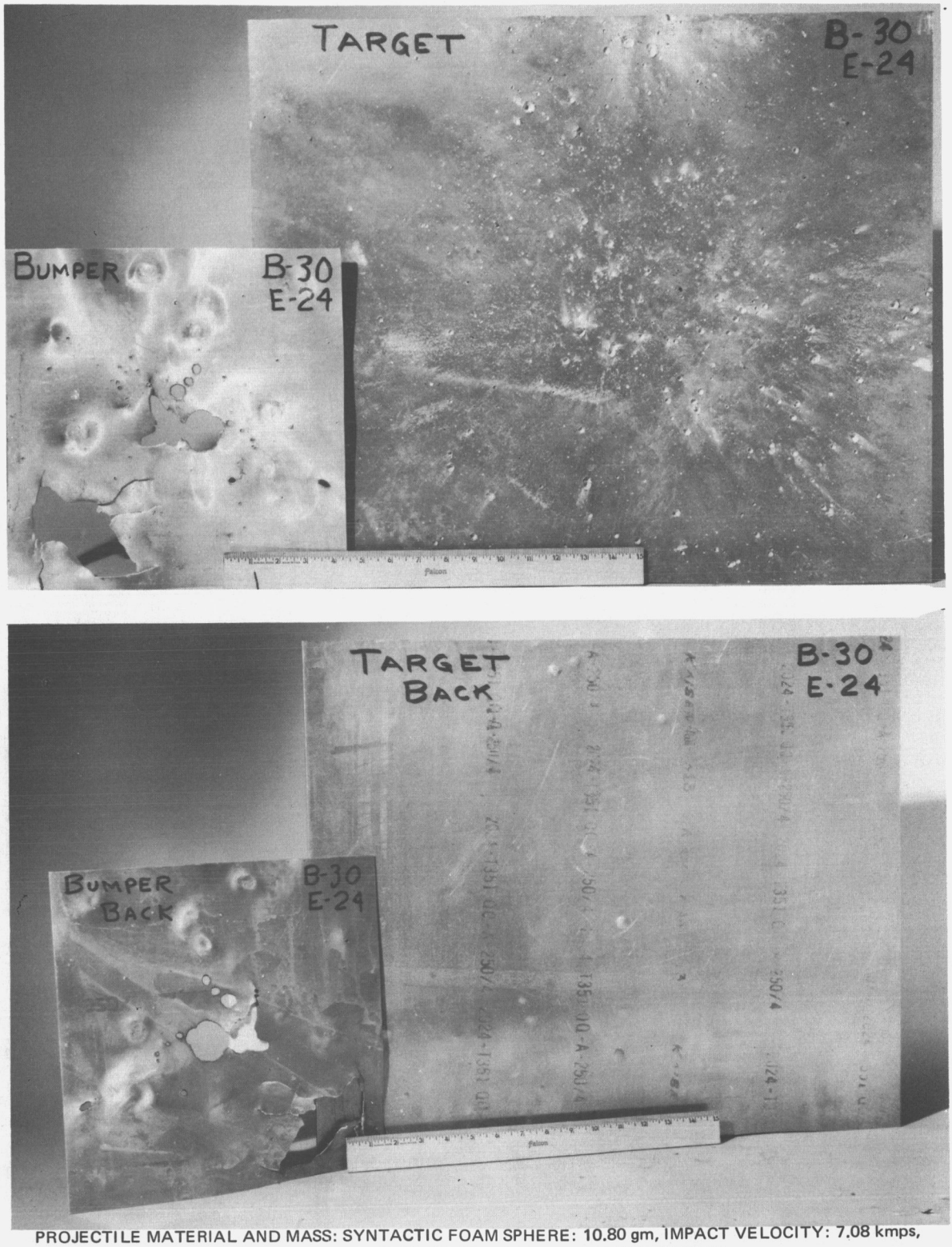
PROJECTILE MATERIAL AND MASS: SYNTACTIC FOAM SPHERE: 11.05 gm, IMPACT VELOCITY: 7.03 kmps, BUMPER THICKNESS: 0.032 IN., TARGET THICKNESS: 0.255 IN., SPACING: 47.40 IN.

Plate 37. Dual-Sheet Target, Data No. 37



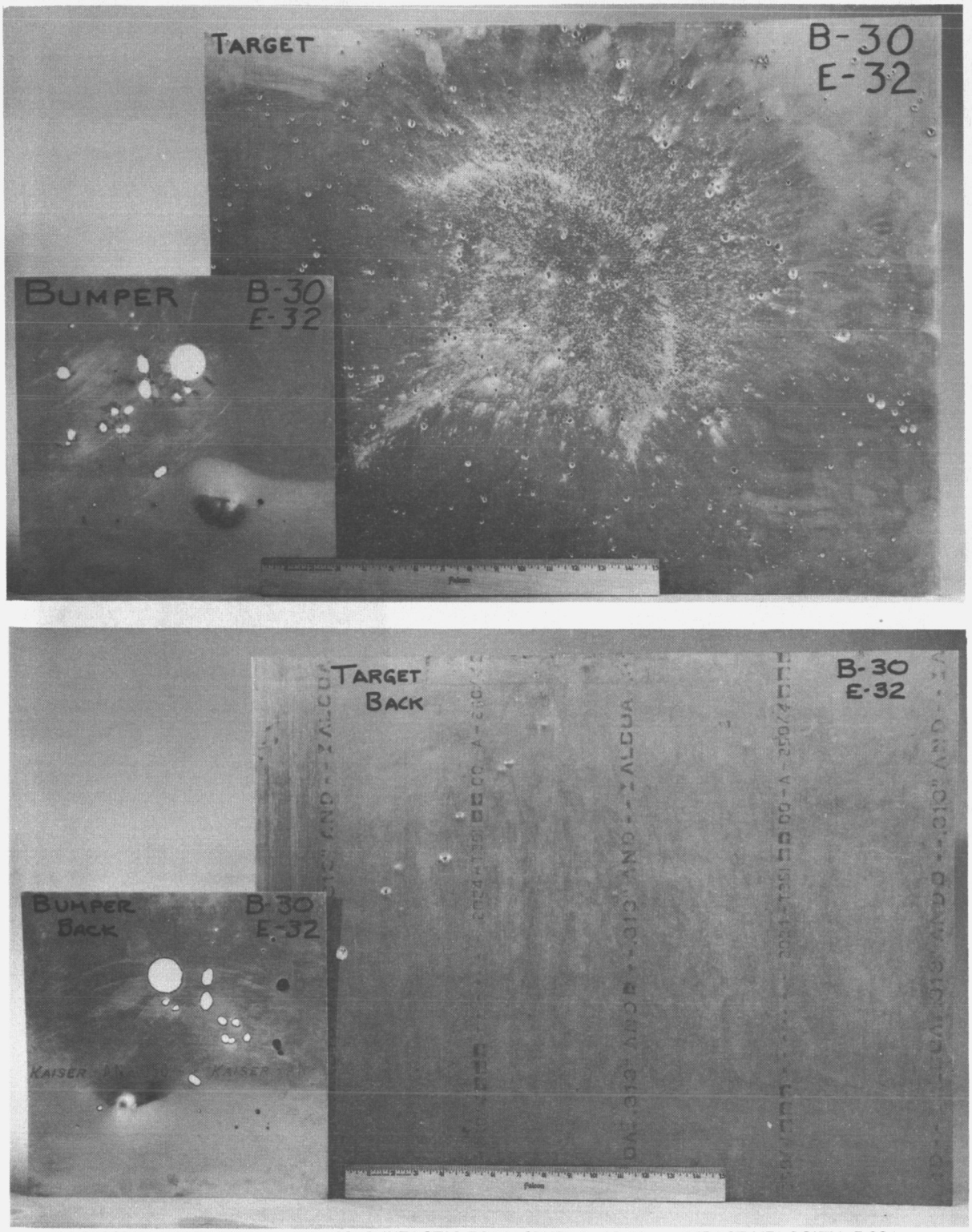
PROJECTILE MATERIAL AND MASS: SYNTACTIC FOAM SPHERE: 10.84 gm, IMPACT VELOCITY: 7.08 kmps, BUMPER THICKNESS: 0.020 IN., TARGET THICKNESS: 1.25 IN., SPACING: 35.60 IN.

Plate 38. Dual-Sheet Target, Data No. 38.



PROJECTILE MATERIAL AND MASS: SYNTACTIC FOAM SPHERE: 10.80 gm, IMPACT VELOCITY: 7.08 kmps,
BUMPER THICKNESS: 0.063 IN., TARGET THICKNESS: 0.323 IN., SPACING: 35.60 IN.

Plate 39. Dual-Sheet Target, Data No. 39.



PROJECTILE MATERIAL AND MASS: SYNTACTIC FOAM SPHERE: 10.76 gm, IMPACT VELOCITY: 7.03 kmps, BUMPER THICKNESS: 0.050 IN., TARGET THICKNESS: 0.323 IN., SPACING: 35.60 IN.

Plate 40. Dual-Sheet Target, Data No. 40