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TECHNICAL NOTE

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A PRELIMINARY INVESTIGATION ON THE DESTRUCTION OF SOLID-PROPELLANT ROCKET MOTORS BY IMPACT FROM SMALL PARTICLES

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
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SUMMARY

An investigation was conducted to determine whether solid-propellant rocket motors could be ignited and destroyed by small-particle impacts at particle velocities up to approximately 10,940 feet per second. Spheres ranging from 1/16 to 7/32 inch in diameter were fired into simulated rocket motors containing T-22 propellant over a range of ambient pressures from sea level to 0.12 inch of mercury absolute. Simulated cases of stainless steel, aluminum alloy, and laminated Fiberglas varied in thickness from 1/50 to 1/8 inch. Within the scope of this investigation, it was found that ignition and explosive destruction of simulated steel-case rocket motors could result from impacts by steel spheres at the lowest attainable pressure.

INTRODUCTION

Solid-propellant rockets utilized in current aircraft missiles or as retro-rockets on space vehicles and satellites may be subject to impact from particles ranging from moderate-velocity flak or machinegun bullets to extremely high-velocity meteorites. It is therefore of interest to determine whether destruction of a typical solid-propellant rocket could result from such impacts.

The present investigation was undertaken as a preliminary step toward a better understanding of the nature of this problem. In this investigation simulated-rocket-motor targets were impacted by spherical particles ranging in diameter from 1/16 to 7/32 inch with particle velocities as high as 10,940 feet per second (as limited by available equipment). Targets for the investigation were composed of T-22 propellant with simulated cases of steel, aluminum alloy, and laminated Fiberglas ranging from 1/50 to 1/8 inch in thickness. Impact tests were made over a range of ambient pressures from sea level to partial vacuums as low as 0.12 inch of mercury absolute.

APPARATUS AND PROCEDURE

Gun Description

Two .22-caliber Swift rifles and a helium gas gun were used in this investigation to fire spherical projectiles into simulated-rocket-motor targets. One of the rifles was mounted on a stand and used for atmospheric tests, whereas the other rifle was assembled so that the muzzle extended a few inches inside a small vacuum chamber and fired into targets located at the other end of the chamber; an overall view of this facility is shown in figure 1. The maximum velocity obtained with this facility was 7,800 feet per second. In order to achieve higher velocities a helium gas gun mounted to a large vacuum chamber was used; a photograph of this facility is shown in figure 2. A description of the operation of the helium gas gun is given in reference 1. Velocities on the order of 10,000 feet per second were readily achieved.

Instrumentation

Velocities were determined from the time required for a sphere to travel the distance between two timing screens. Each screen was 0.00025 inch thick and consisted of a thin aluminum coating on both sides of Mylar film. A potential of 250 volts was applied across each screen; the aluminum coating was dissolved from the edges of the screen to prevent arcing. Puncturing a screen completed the circuit which either started or stopped an electronic counter.

Camera coverage of the impacted targets consisted of a 16-millimeter Fastax camera using Tri-X film and operated at 1,000 to 1,500 frames per second. Also, as a supplement to the high-speed motion pictures, some 16-millimeter color motion pictures were taken at 64 frames per second.

Projectile Description

Projectiles were steel ball bearings having diameters of 1/16, 3/32, 1/8, and 7/32 inch, except for one 3/32-inch sapphire sphere. The 7/32-inch ball bearings were fired only in the .22-caliber Swift rifles. Since these spheres were almost .22 caliber in size, no sabot was required for firing. Spheres smaller than 7/32-inch diameter were fired by means of a nylon sabot. The nylon sabot was separated from the sphere either by splitting the sabot in two or by using a deflector plate. This plate was positioned in the path of the sabot so that only the edge of the sabot struck the top of the plate. With either method the small sphere which was held on the sabot by vacuum grease was separated from the sabot before impact.

Target Description

All targets contained a typical composite polysulfide ammonium perchlorate propellant, type T-22. The composition and related physical properties of T-22 propellant are given in reference 2.

Two types of targets were used to simulate solid-propellant motors. The first type, referred to as a cup-shaped target, consisted of thin target plates, ranging from 1/50 to 1/8 inch in thickness, bonded to propellant which had been cast into paper cups and then wrapped with tape. Target plates were of 301 and 347 stainless steel, 7075-T6 aluminum alloy, and phenolic laminated Fiberglas. A sketch of a cup-shaped target is shown in figure 3(a). Figure 4 shows a photograph of a cup-shaped target, a target holder, and a 1/4-inch-thick retaining collar. This collar had a $2\frac{1}{2}$-inch hole in the center and was used to prevent the thin target plates from being blown off the propellant just after impact. Figure 5 shows a cup-shaped target assembled in the small vacuum chamber just prior to a firing.

A second type of target, referred to as a cylindrical type, consisted of cylinders $3\frac{1}{2}$ inches in diameter and 4 inches long, with thin plates welded on one end and with propellant cast to a depth of about $3\frac{1}{2}$ inches. A sketch of a cylindrical target is shown in figure 3(b). The holder for these targets was machined so that the targets fitted snugly but were free to be ejected from the holder if a reaction force were developed by the target after impact.

RESULTS

The most significant results of tests conducted in this preliminary investigation are presented in tables I and II. Although these tests were limited to a moderate range of velocities, particle sizes, and partial vacuums, several conclusions may be made with some insight into impact ignition as gained from study of these results.

Results of Impacts at Sea-Level Atmospheric Pressure

The results of firings into cup-shaped targets simulating rocket motors at sea-level pressure (table I) indicate that ignition and explosive destruction could result from particle impact. As shown in this table, all targets impacted by 7/32-inch spheres were ignited and completely burned. Laminated Fiberglas plate targets as well as steel-plate targets were ignited and destroyed by impact from 1/8-inch steel spheres having velocities up to 6,620 feet per second, except for one target having a 1/8-inch-thick steel plate which was not pierced.

A number of cup-shaped targets impacted by 1/16-inch steel spheres were not completely burned, although ignition had been achieved. This phenomenon was observed for all targets with stainless-steel plates 1/32 inch thick for impact velocities up to 7,800 feet per second, the highest velocity attained in air. Two targets with thinner stainless-steel plates, 1/50 inch thick, were completely destroyed. Impacts into 1/40-inch-thick aluminum-plate targets showed the effect of propellant temperature and particle velocity. At a temperature of 60° F, one target impacted by a 1/16-inch sphere at a velocity of 6,180 feet per second burned completely whereas one impacted at a velocity of 5,900 feet per second ignited but ceased to burn. When the temperature of a similar aluminum target was raised to 100° F and the target was impacted at a velocity of only 5,500 feet per second it ignited and continued to burn until consumed.

Results of Impacts at Reduced Atmospheric Pressure

Firings into cup-shaped targets at reduced pressures from 1 to 3.3 inches of mercury absolute showed that two targets with 1/32-inch-thick stainless-steel plates were ignited by impact from 1/16-inch steel spheres at velocities above 9,500 feet per second but sustained burning was not achieved. Three similar targets impacted by 1/8-inch spheres at velocities from approximately 8,306 to 9,100 feet per second ignited and began to burn vigorously until combustion ceased. Burning ceased after the internal pressure forced the thin plates to strip away from the propellant and allowed the combustion gases to escape, and thereby relieve the pressure necessary for combustion. The same result was observed for a 1/16-inch-thick steel-plate target even though the depth of penetration was considerably less. Impact of the 1/8-inch laminated Fiberglas plate target resulted in a relatively deep penetration by the 1/8-inch sphere, but motion pictures indicated that ignition was not produced.

Impacts into cylindrical-type targets demonstrated the explosive type of destruction that could result from particle impact of actual rocket motors. All three firings with 1/8-inch spheres impacting targets of 1/32- and 1/16-inch-thick stainless steel at the lowest attainable pressure, 0.12 inch of mercury absolute, caused ignition followed by explosive destruction. One out of two firings with 3/32-inch steel spheres produced the same effect. A 3/32-inch sapphire sphere fired at the highest velocity, 10,940 feet per second, produced a bright flash on impact but ignition was not achieved.

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DISCUSSION OF RESULTS

The results of this investigation of small spherical particles impacting simulated solid-propellant motors can be divided into four classes, defined as follows:

Class 1 Projectile imbedded in the target plate but did not pierce it. An example of this class is firing 7.

Class 2 Projectile penetrated the target plate but either did not ignite the propellant or ignition did not result in complete combustion. A typical example of this class is firing 12.

Class 3 Projectile penetrated deep enough into the propellant to produce a brief period of burning, but burning eventually ceased before all the propellant was consumed. A typical example of this class is firing 14.

Class 4 Projectile penetrated a sufficient distance into the propellant to cause sustained burning until all the propellant was consumed or until the target exploded. Examples of this class are firings 1 and 29.

Class 1 simply represents the case where the impacting particle lacks sufficient momentum to penetrate through the case of a rocket motor. Such impacts may cause a weak spot in the rocket case, but this should not seriously affect the performance of a rocket whose grain geometry is such that the propellant is bonded to the case, thus insulating it from the high-temperature combustion gases. An example of this type of grain design is the internal star configuration.

Class 2 represents the case where the particle penetrates into the propellant; however, the propellant is not ignited or the combustion pressure generated by ignition or partial burning is insufficient for steady burning and the burning ceases. One charactersitic of solid propellants is that, at a given temperature, there is a critical pressure below which burning is erratic or ceases entirely. A discussion of this phenomenon can be found in reference 3. For a given propellant at a certain temperature, the critical pressure mainly depends upon the propellant area ratio, that is, the ratio of the burning surface to the nozzle throat or flow-restriction area. This parameter is used extensively in the design of solid-propellant rockets since the magnitude of the propellant area ratio determines the chamber pressure for a given propellant at a given temperature. When a particle penetrates a rocket motor, the impact hole or throat is constant at ignition; therefore, for any particular propellant, the pressure generated depends upon the propellant temperature at the time of impact and the exposed surface area created by particle penetration. For class 2 impacts, it is believed that the surface exposed to burning is not large enough, relative to the impact hole, for sufficient pressure to build up to and beyond the critical level to sustain burning.

In a number of experimental firings at sea-level pressure, an intermittent spurting of combustion gases was observed. This phenomenon is referred to as chuffing which represents the intermediate condition between no burning and full or steady burning. Fluctuations in pressure result from a shifting from full burning to smoldering and back to full burning. If the pressure is below the critical level, the combustion gases escape from the reacting layer before sufficient heat is transferred to the sublayer. Thus, rapid oxidation eventually ceases and reverts to smoldering. As the surface layer of the propellant smolders, heat is generated which may be sufficient to cause the layer to burst into rapid oxidation. The cycle may or may not repeat. From experimental firings in partial vacuums, it appears that chuffing, resulting from impact, will not occur if the ambient pressure is less than 2 inches of mercury. Similar tests of targets which chuffed when impacted at sea-level pressure showed no signs of chuffing in partial vacuums even though the velocity and hence the energy at impact were greater.

Class 3 represents the case wherein the propellant is ignited by particle impact and penetration and a brief period of burning follows, but combustion eventually ceases. One type of class 3 impact was unexpected but reproducible. In three tests at sea-level pressure, targets burned momentarily, then chuffed, and finally stopped burning. One possible explanation for this phenomenon is offered in the following discussion: Consider the conditions just after a particle has come to rest in the propellant. The surface of propellant exposed by particle penetration is extremely irregular with small cracks extending into the grain and with many small, irregular propellant particles along the surface. Such a surface would produce a large surface area and possibly would result in a propellant area ratio above the critical value. As soon as the irregular particles have been consumed, the sudden decrease in burning area may lower the pressure to below the critical level required for combustion. Once this happens, chuffing may occur and eventually combustion may cease as was observed in firings 14, 15, and 16.

Figure 6 shows the cavities which resulted from a brief burning period where a small amount of propellant had been consumed. Inspection of all three cavities revealed smooth walls; no cracks were observed. This indicates that the irregular surface at ignition becomes a smoother surface as burning proceeds radially outward; this is typical for stable solid propellants which have burning-rate pressure exponents less than 0.85 (for T-22 propellant this pressure exponent is 0.372). An approximation of the surface of these cavities, the largest being about 1/2 inch in diameter and 1/2 inch deep, indicated that the propellant area ratios varied from about 94 to 106. Apparently, for T-22 propellant at a temperature of about 60° F, these area ratios are below the critical level.

Another type of class 3 impact resulted from some 1/8-inch spheres impacting cup-shaped targets under partial vacuums. Ignition was produced on impact and the propellant began to burn vigorously, and to develop higher and higher combustion pressure which forced the thin plates to strip away from the propellant, thus relieving the pressure necessary for combustion. This effect is illustrated in figure 7, which shows a series of sequence pictures selected from high-speed motion pictures of firing 25. In the upper left-hand corner of this figure is a sketch showing the target before impact, with the 1/4-inch retaining collar against the thin target plate. The projectile impacts the face of the target which appears as a bright elliptical surface from reflected light, frame 0. All frames are labeled relative to the impact frame. In frame 15 the face has darkened as a result of bulging. The pressure from the combustion gases has forced the plate to separate from the grain as it bulged outward. The following frames show the bright gases escaping from behind the target plate (held in place by the retaining collar), thus relieving the pressure necessary for combustion. It is realized that these impacts are classified as class 3, because the targets were inadequate to the extent that combustion pressure was vented. However, the results of firings 24 to 27 are interpreted as indicating destruction for an actual steel-case motor for which venting could not have occurred; the combustion pressure would have increased until the motor exploded.

Inasmuch as these cup-shaped targets burned momentarily but were not destroyed, some were sectioned for observation and measurement of the depth of particle penetration. A sketch of one of these cutaway targets is presented in figure 8 and shows the cracks caused by penetration of a 1/8-inch-diameter sphere. As a means of comparing penetration by spheres of different diameters, the depth of particle penetration was divided by sphere diameter to obtain a penetration ratio. It was found that, for nearly the same general impact conditions, the depth of particle penetration of a 1/32-inch steel-plate target was about 1.7 times that of the 1/16-inch steel-plate target. For the laminated Fiberglas plate target (firing 28) the penetration ratio was over 2.5 times as great as that of the 1/16-inch steel-plate target.

The main difference between firing 28 and firings 8 and 9 was the low ambient pressure of 1 inch of mercury absolute. At sea-level pressure such targets were destroyed after chuffing a number of times until full burning was established. Since chuffing was not observed at ambient pressures of less than 2 inches of mercury, conditions which lead to chuffing at sea-level pressure would not be expected to produce sustained burning at ambient pressure of 1 inch of mercury absolute.

Class 4 represents impacts resulting in immediate destruction. The impacting particle penetrates a substantial distance into the propellant so that sustained burning results. The pressure may drop after initial burning consumes the irregular surface layer, but it does not drop below the critical level. Since the surface burns radially outward generating increasing areas, the combustion pressure likewise increases. For an actual rocket, class 4 impacts will result in excessive pressures causing the motor to explode. Results of this nature were demonstrated by firings 29 to 31 and are illustrated in figures 9 to 12.

Figure 9 shows the result of firing 29, wherein a 1/32-inch stainless-steel-plate target was impacted by a 1/8-inch steel sphere, in a series of sequence pictures which are arranged in the same general manner as those in figures 7 and 11. The sketch in the upper left-hand corner represents the frame just before impact and is labeled -1. The target face again appears as a bright elliptical surface resulting from reflected light. Two other smaller bright spots are caused by light reflected off the front surface of the target holder. After impact, a bright jet issued from a darkened plate which had been forced to bulge under pressure. A well-established jet appears in frame 4. Several frames later other jets appeared, because the bulging plate provided a passageway for combustion gases to reach holes punctured in the plate by the split sections of the nylon sabot. However, despite the pressure-relieving effect caused by the sudden increase in area, the pressure reached explosive force as evidenced by plate failure in frame 11. Immediately thereafter, burning ceased as shown in frame 12. A photograph of this target, showing the extent of plate rupture, and of a 1/8-inch sphere mounted on a nylon sabot is presented in figure 10. The diameter of the impact hole was 1.44 times as large as the diameter of the sphere.

Figure 11 shows similar sequence pictures for targets with 1/16-inch-thick steel cases. The target face again appears as a bright elliptical spot just before impact. As in the case of the target with the thinner plate, the combustion pressure increased sharply, but with the thicker plate targets, destruction resulted from failure of the grain instead of the plate. In frame 15 the grain sheared out the back of the target, thus imparting a forward thrust and ejecting the target out of the holder. Pieces of propellant can be seen following the target. A photograph of a 1/16-inch-plate cylindrical target and grain fragments after impact from a 1/8-inch steel sphere is shown in figure 12. In view of the large surface of the grain fragments, it is not difficult to understand why rupturing the grain of an actual motor would quickly cause the motor to explode.

The results of firings 32 and 33 wherein 3/32-inch steel spheres were fired into similar cylindrical targets indicated that destruction could be achieved by a smaller sphere. However, this result might represent the marginal case for velocities on the order of 9,500 feet per second, other conditions being equal, since one target was destroyed while another target was ignited but burning was not sustained.

One 3/32-inch sapphire sphere was fired to represent a nonmetallic-particle impact. This relatively lightweight projectile had a velocity of 10,940 feet per second, the highest attained in this investigation. Slow-motion pictures of this test, firing 34, showed no sign of ignition although a very bright flash of light was produced on impact, an indication of particle breakup. The depth of penetration was still quite deep, 6.4 particle diameters.

The actual mechanism of ignition by impact and penetration has not been determined; however, sufficient heat can be generated by the energy-conversion processes during impact and penetration to successfully ignite a solid propellant as demonstrated by experimental firings. One of the main factors affecting the outcome of the impact is the propellant temperature. The effect of propellant temperature was indicated by two aluminum-plate targets impacted at sea-level pressure, firings 20 and 21. It was found that the target at 60° F was not destroyed, but the target heated to 100° F completely burned when ignited by impact from a sphere having even less velocity. The difference in temperature had a marked effect. The added heat produced a higher burning rate; also it lowered the resistance to particle penetration, thereby causing an increased propellant area ratio. More general effects of propellant temperature are discussed in reference 3.

Finally, what is the consequence of motors which are penetrated but not destroyed shortly after impact? Any performance short of that expected for a rocket might be considered just as detrimental as complete destruction. Therefore, other conditions such as the effect of penetration on ignition, burning, and direction of thrust must be considered when the motor is fired intentionally. If successfully ignited, the rocket might explode if a sufficient increase in burning surface were produced during particle penetration, and if catastrophic pressure were not reached, there would still be the unexpected thrust from the impact hole to affect rocket performance.

SUMMARY OF RESULTS

The results of this preliminary investigation of impacts of simulated solid-propellant (T-22) rocket motors by small steel spheres can be summarized as follows:

1. At sea-level ambient pressure, motors with cases of stainless steel, aluminum, or laminated Fiberglas can be ignited and destroyed by small steel particles which have sufficient momentum to penetrate the case and travel a substantial distance into the propellant.

2. Under the lowest ambient pressure attainable, 0.12 inch of mercury, simulated rocket motors with up to 1/16-inch-thick steel cases were ignited and exploded by 1/8-inch steel spheres having velocities on the order of 9,000 feet per second.

3. Under the ambient pressure of 0.12 inch of mercury, simulated 1/32-inch-thick steel-case rocket motors were ignited and destroyed by only one out of two impacts from 3/32-inch steel spheres having velocities on the order of 9,500 feet per second.

4. Under ambient pressures up to 2 inches of mercury absolute, simulated 1/32-inch steel-case rocket motors were ignited on impact by 1/16-inch spheres having velocities of approximately 10,000 feet per second but burning was not sustained.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Field, Va., May 24, 1960.

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1. Collins, Rufus D., Jr., and Kinard, William H.: The Dependency of Penetration on the Momentum Per Unit Area of the Impacting Projectile and the Resistance of Materials to Penetration. NASA TN D-238, 1960.

2. Anon.: Propellant Manual. SPIA/M2 (Contract NOrd 7386), Appl. Phys. Lab., The Johns Hopkins Univ., Apr. 1959.

3. Zucrow, M. J.: The Gas Turbine Power Plant, the Turboprop, Turbojet, Ramjet, and Rocket Engines. Vol. II of Aircraft and Missile Propulsion, John Wiley & Sons, Inc., c.1958.

TABLE I.- RESULTS OF CUP-SHAPED TARGETS IMPACTED AT SEA-LEVEL ATMOSPHERIC PRESSURE

Firing	Sphere diameter, in. (a)	Plate thickness, in.	Plate material	Velocity, ft/sec	Observations
1	7/32	1/32	347 stainless steel	4,720	Propellant ignited and burned completely - class 4.
2	7/32	1/8		5,770	Propellant ignited and burned completely - class 4.
3	7/32	1/8		3,380	Propellant ignited and burned completely - class 4.
4	1/8	1/32	347 stainless steel	6,620	Propellant ignited and burned completely - class 4.
5	1/8	1/32		3,760	Propellant ignited and burned completely - class 4.
6	1/8	1/16		5,400	Propellant ignited and burned completely - class 4.
7	1/8	1/8		[b]6,500	Sphere imbedded but did not pierce target plate - class 1.
8	1/8	1/8	Laminated Fiberglas	[b]6,500	Propellant ignited, chuffed, and then burned completely - class 4.
9	1/8	1/8		6,170	Propellant ignited, chuffed, and then burned completely - class 4.
10	3/32	1/32	347 stainless steel	[b]7,000	Propellant ignited, chuffed, and then burned completely - class 4.
11	1/16	1/32	347 stainless steel	[b]5,000	Propellant ignited, chuffed several times, and then stopped burning - class 2.
12	1/16	1/32		[b]6,000	Propellant ignited, chuffed several times, and then stopped burning - class 2.
13	1/16	1/32		[b]6,000	Propellant ignited, chuffed several times, and then stopped burning - class 2.
14	1/16	1/32		7,800	Propellant ignited and burned for a fraction of a second, then chuffed and stopped burning. Relatively large cavities resulted from burning - class 3.
15	1/16	1/32		[b]7,500	
16	1/16	1/32		[b]7,500	
17	1/16	1/50	301 stainless steel	7,740	Propellant ignited and burned completely - class 4.
18	1/16	1/50		5,250	Propellant ignited and burned completely - class 4.
19	1/16	1/40	7075-T6 aluminum	6,180	Propellant ignited and burned completely (temp. = 60° F) - class 4.
20	1/16	1/40		5,900	Propellant ignited but stopped burning (temp. = 60° F) - class 2.
21	1/16	1/40		[b]5,500	Propellant ignited and burned completely (temp. = 100° F) - class 4.

[a] All spheres were of steel.

[b] Estimated velocity based on powder charge when timing system malfunctioned.

TABLE II.- RESULTS OF TARGETS IMPACTED AT REDUCED ATMOSPHERIC PRESSURES

Firing	Sphere diameter, in. (a)	Plate thickness, in.	Plate material	Velocity, ft/sec	Absolute pressure, in. Hg (b)	Penetration ratio (c)	Observations
Cup-shaped targets							
22	1/16	1/32	347 stainless steel	[d]10,000	1	7.2	Propellant ignited but stopped burning - class 2.
23	1/16	1/32		9,640	2	6.4	Propellant ignited but stopped burning - class 2.
24	1/8	1/32	347 stainless steel	[d]9,060	3.3	12.0	Propellant ignited and burned until combustion gases escaped from between plate and grain and caused burning to cease - class 3.
25	1/8	1/32		8,500	1	11.2	
26	1/8	1/32		9,060	2	11.8	
27	1/8	1/16		8,250	2	6.8	
28	1/8	1/8	Laminated Fiberglas	8,400	1	19.2	Severe penetration but no ignition - class 2.
Cylindrical targets							
29	1/8	1/32	347 stainless steel	9,280	0.12		Propellant ignited and burned until plate ruptured - class 4.
30	1/8	1/16		[d]9,060	.12		Propellant ignited and burned until grain ruptured - class 4.
31	1/8	1/16		[d]9,060	.12		Propellant ignited and burned until grain ruptured - class 4.
32	3/32	1/32	347 stainless steel	9,500	.12	6.0	Propellant ignited but stopped burning - class 2.
33	3/32	1/32		[d]9,900	.12		Propellant ignited and burned until plate ruptured - class 4.
34	3/32 Sapphire	1/32		10,940	.12	6.4	Bright impact flash but no ignition - class 2.

[a] All spheres were of steel except one sapphire as indicated.

[b] Ambient pressure indicated in the vacuum chamber.

[c] Ratio determined from penetration depth divided by sphere diameter.

[d] Estimated velocity based on powder charge when timing system malfunctioned.

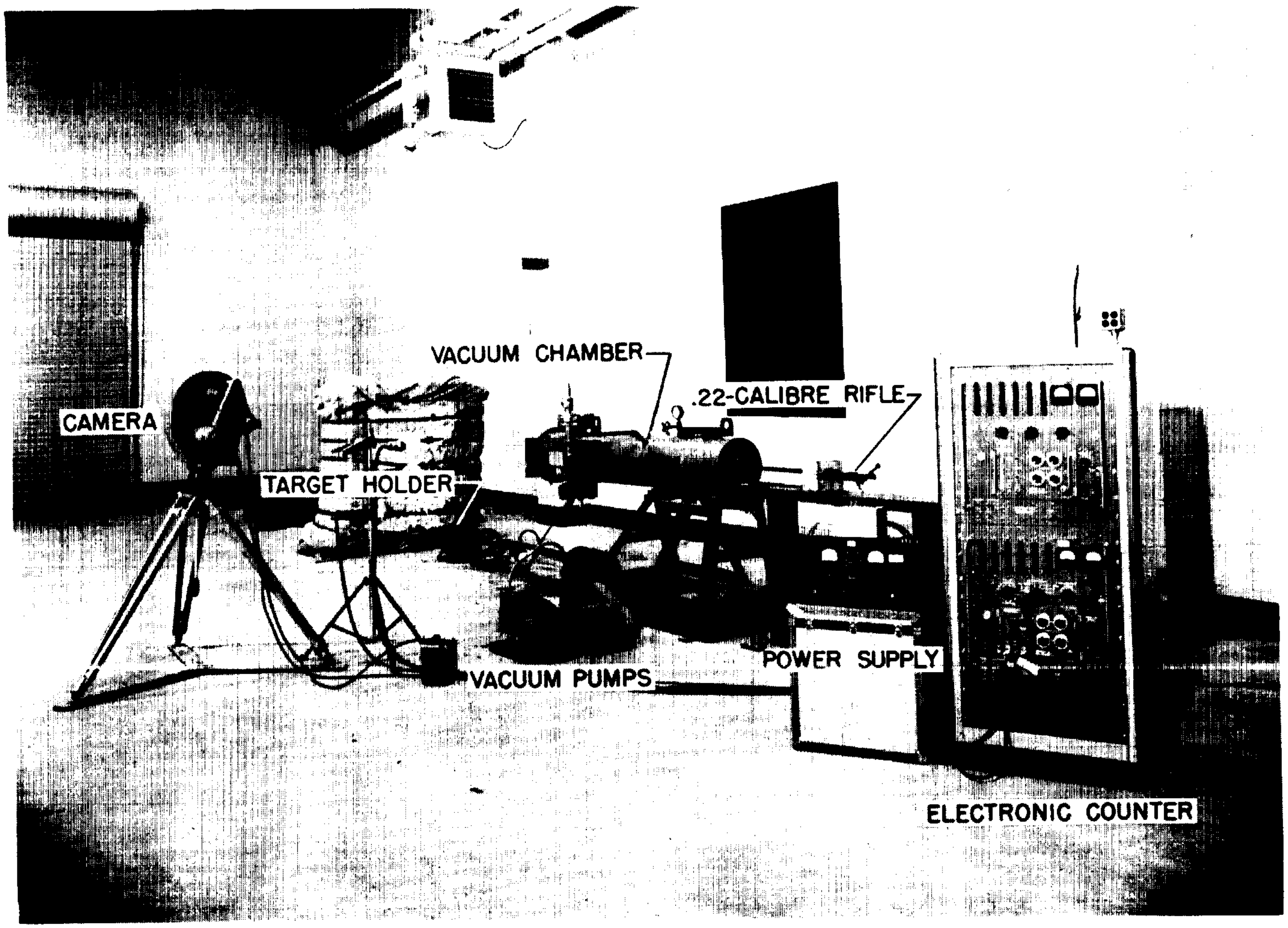

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Figure 1.- Overall view of .22-caliber Swift rifle and small vacuum chamber with related equipment.

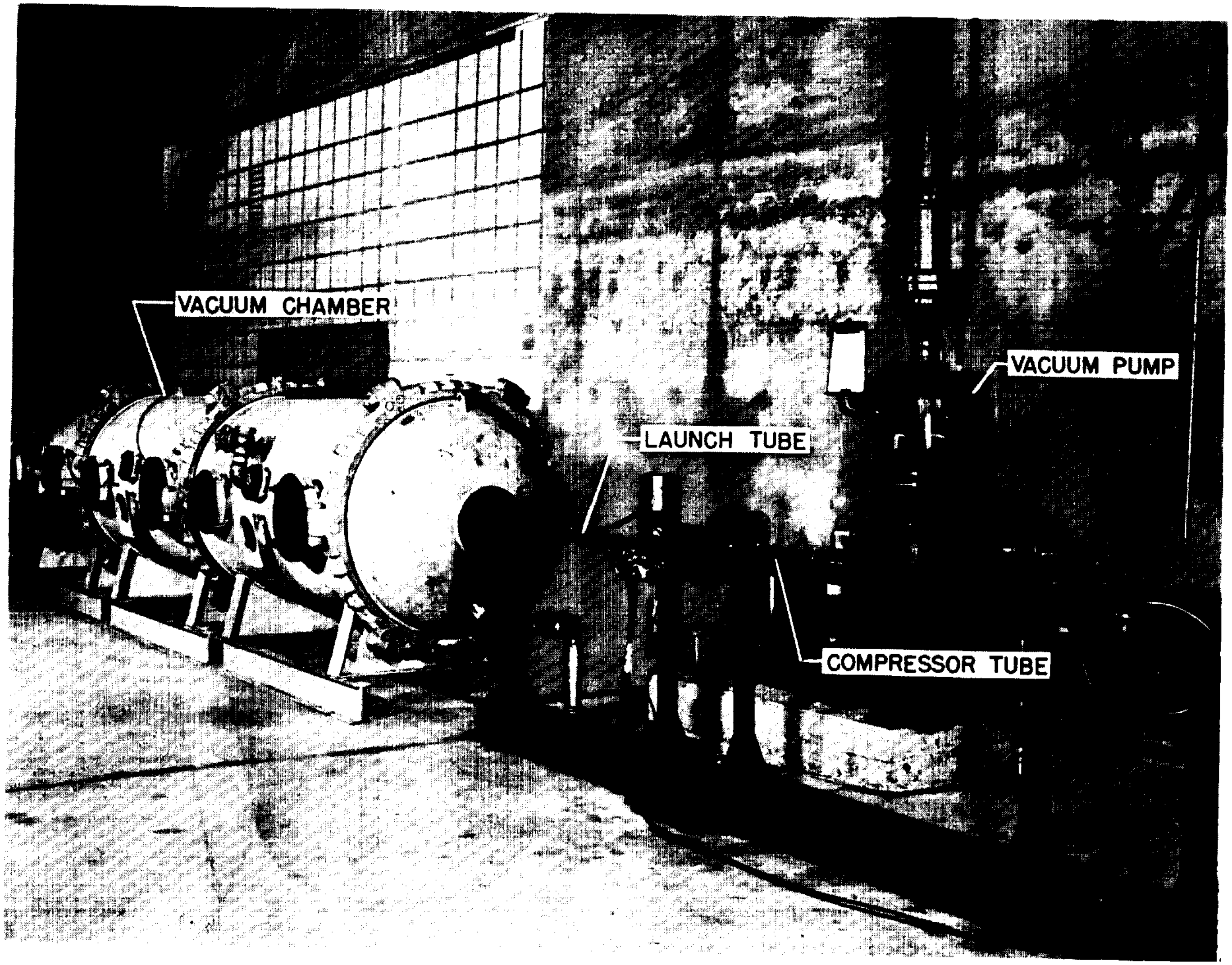

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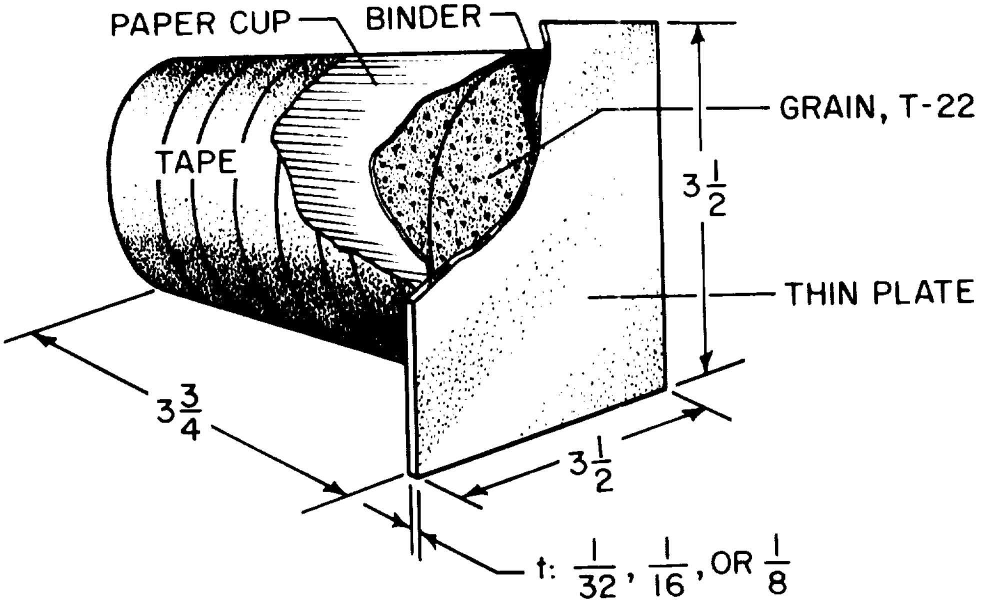
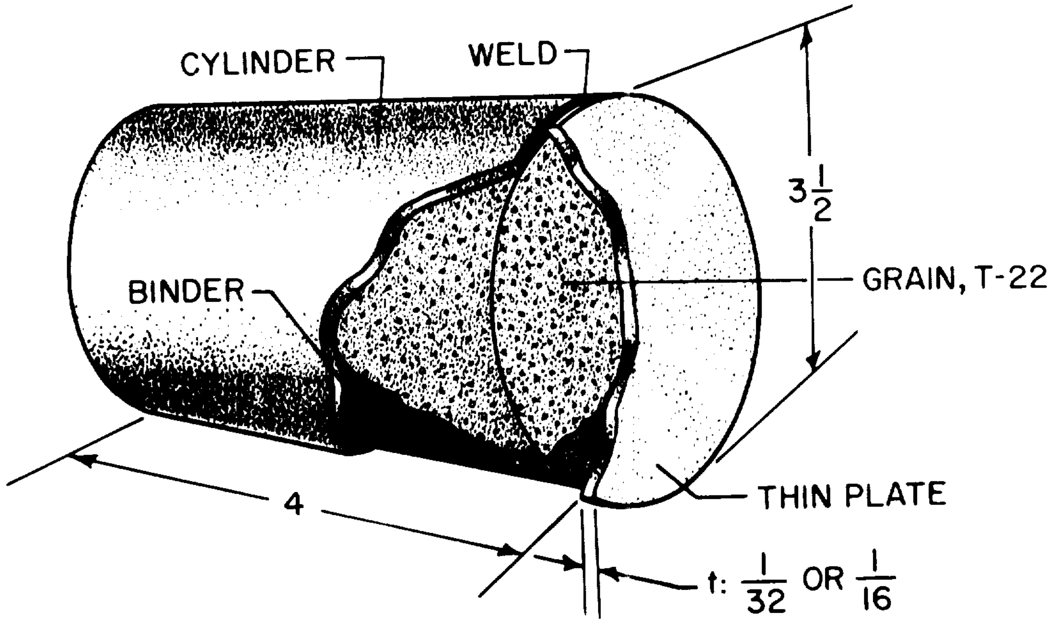
Figure 2.- View of the helium-gas-gun facility with large vacuum chamber.



(a) Cup-shaped target.



(b) Cylindrical target.

Figure 3.- Sketches of targets used to simulate solid-propellant rocket motors. All dimensions are in inches.

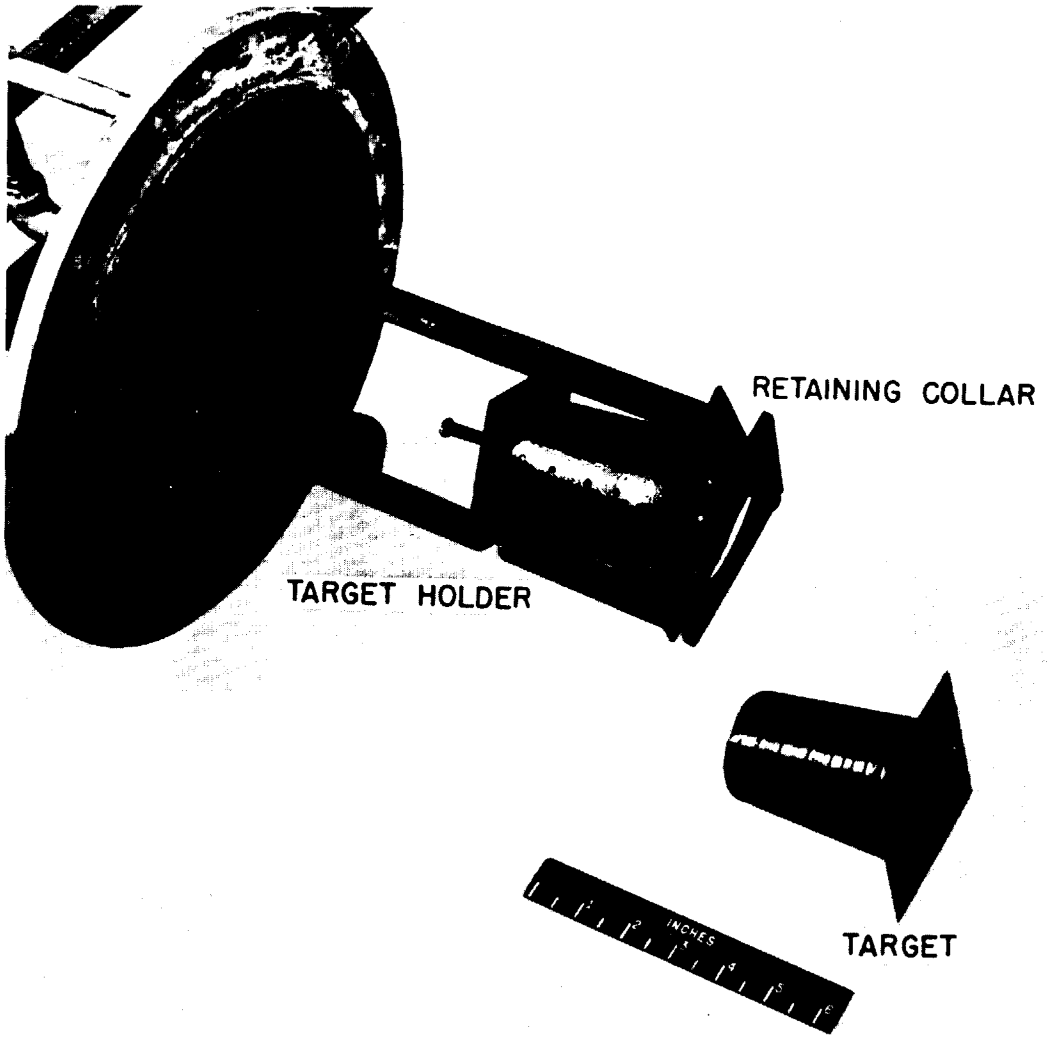


Figure 4.- View of cup-shaped target and perforated target holder. L-59-2076.1

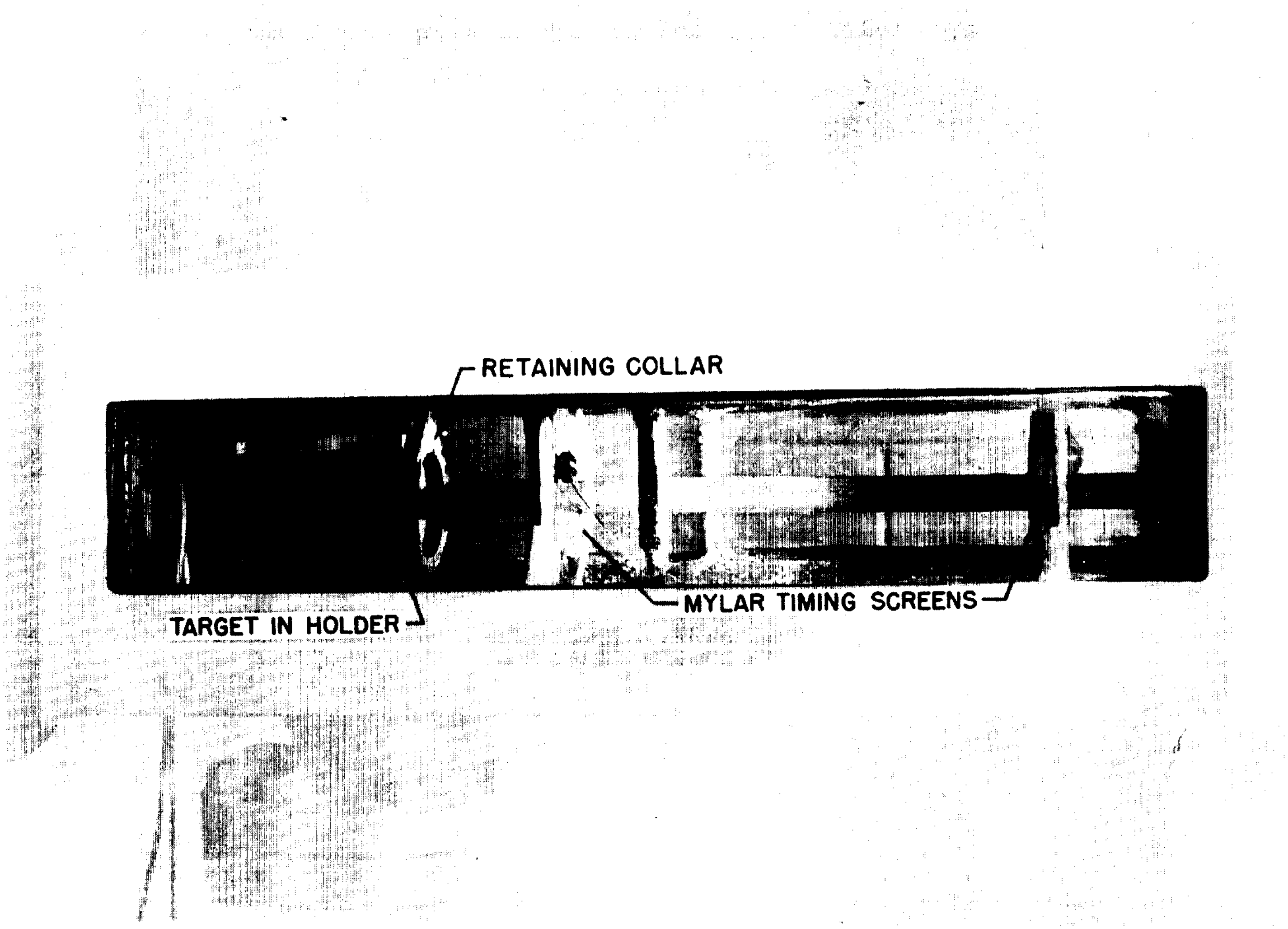


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Figure 5.- Photograph of cup-shaped target prior to firing in small chamber.

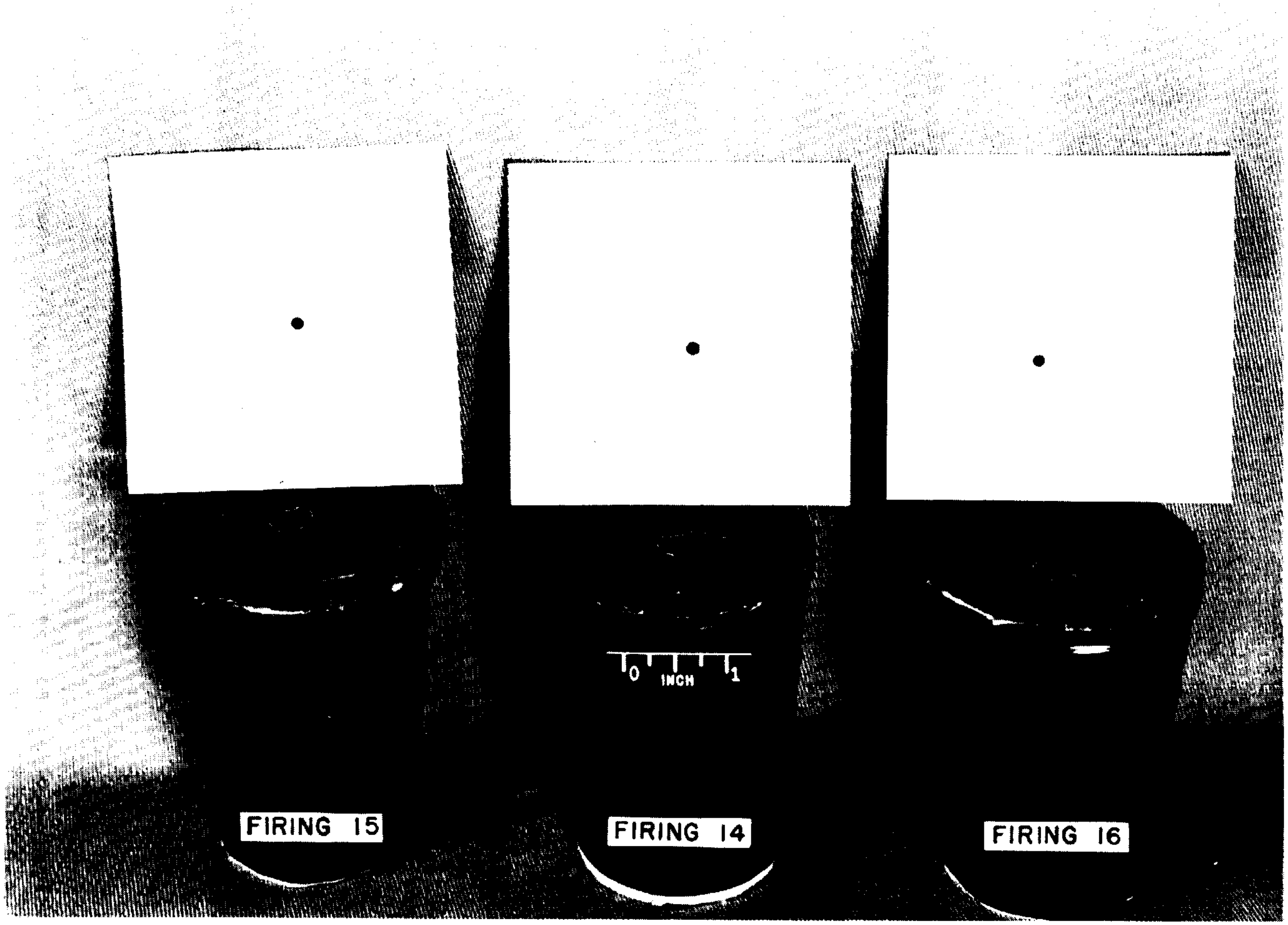

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Figure 6.- Photographs of targets which ignited, burned momentarily, and then stopped burning. Note impact holes in target plates which were removed to show the general size of cavities in the propellant.

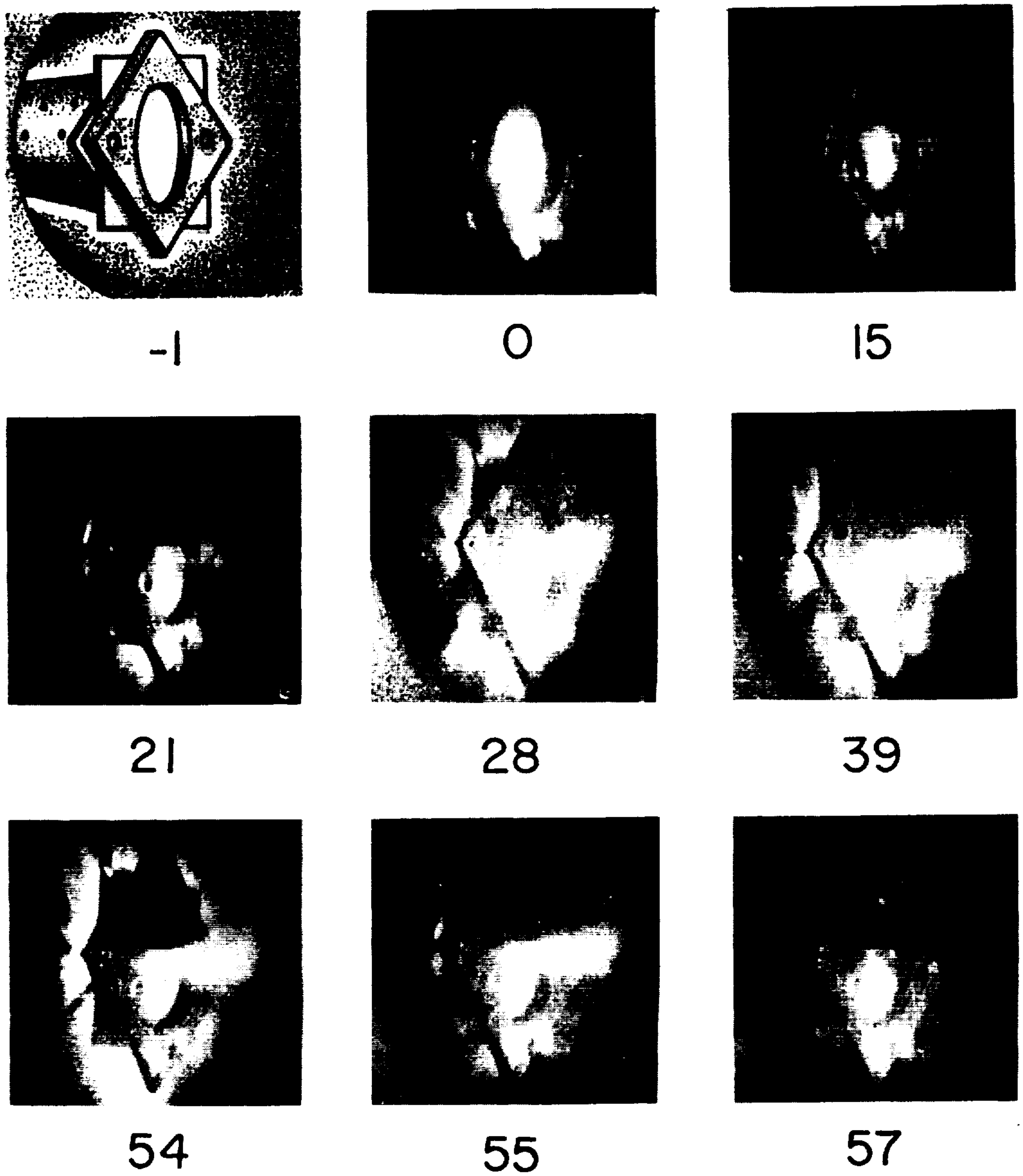

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Figure 7.- Frames from motion picture of firing 25, showing a 1/32-inch-plate cup-shaped target impacted by a 1/8-inch steel sphere. Under each frame is time to the nearest millisecond relative to the impact frame.

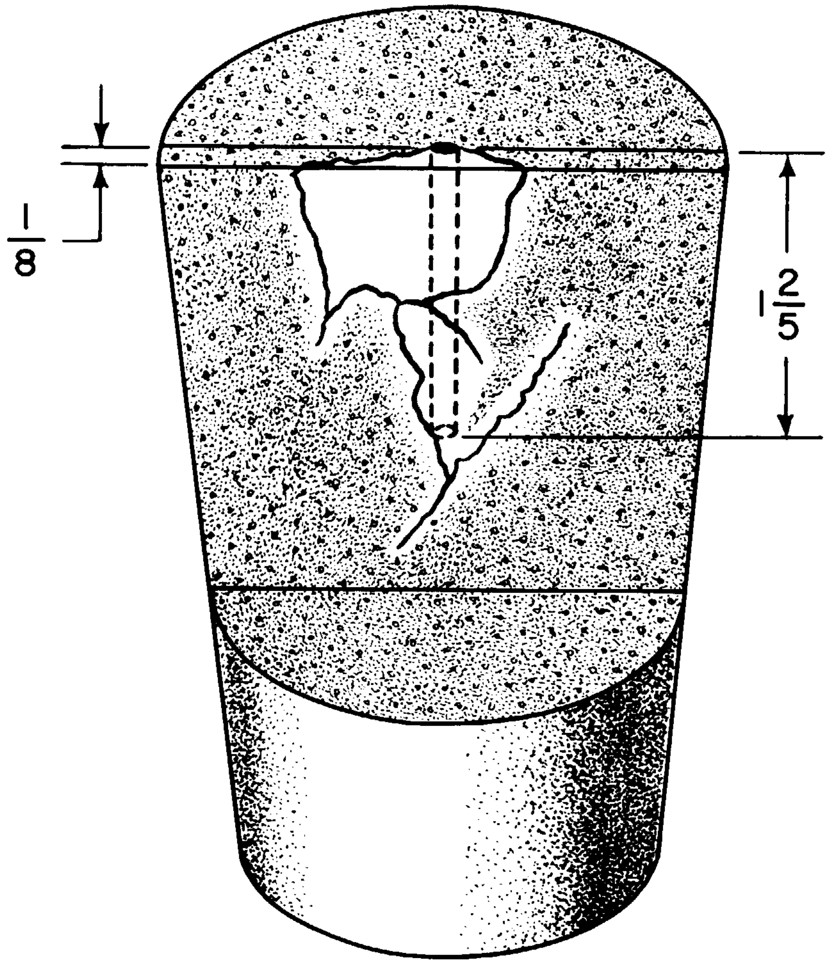

Figure 8.- Cutaway sketch showing cracks in the target grain of firing 25 after penetration by a 1/8-inch steel sphere.

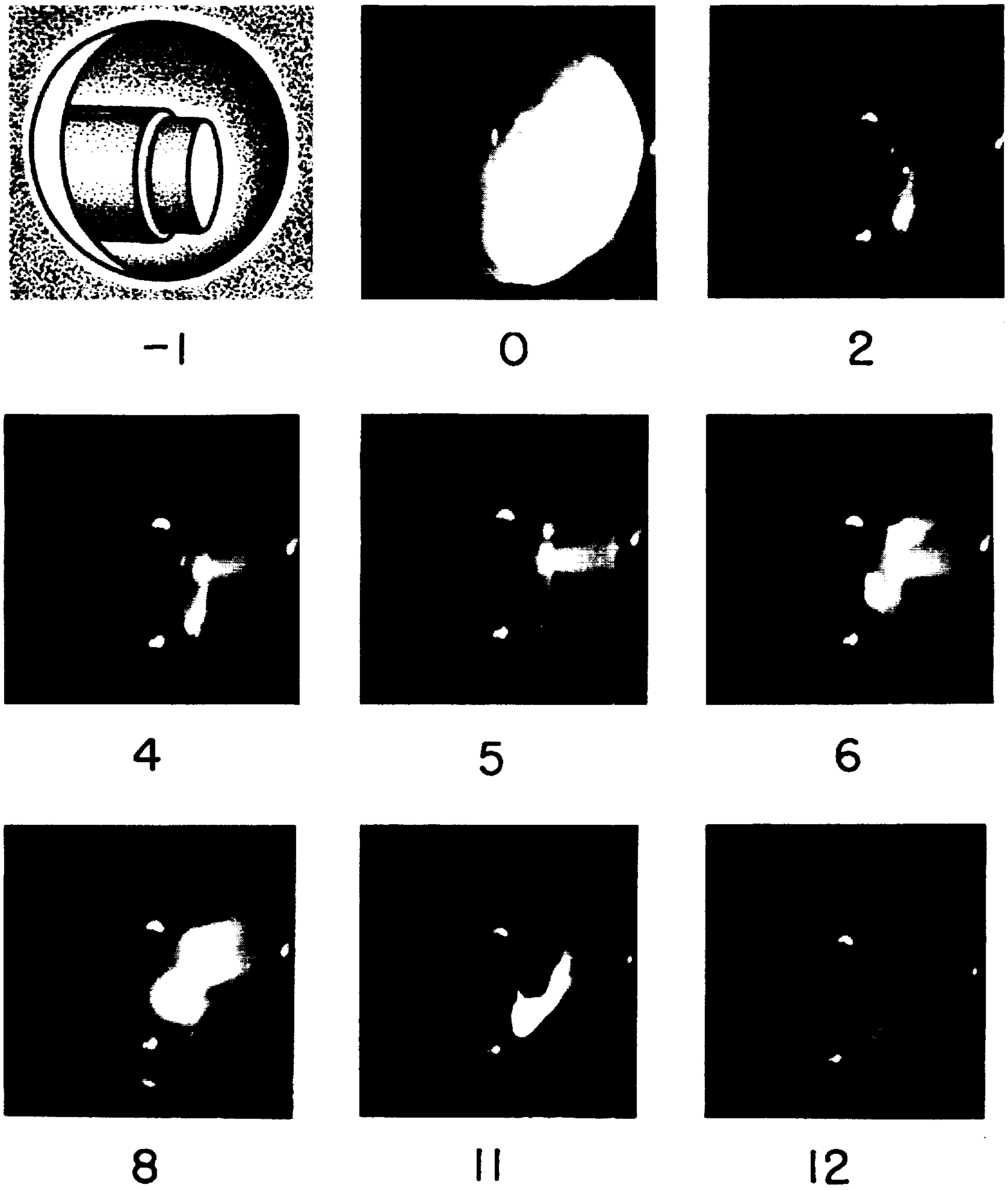

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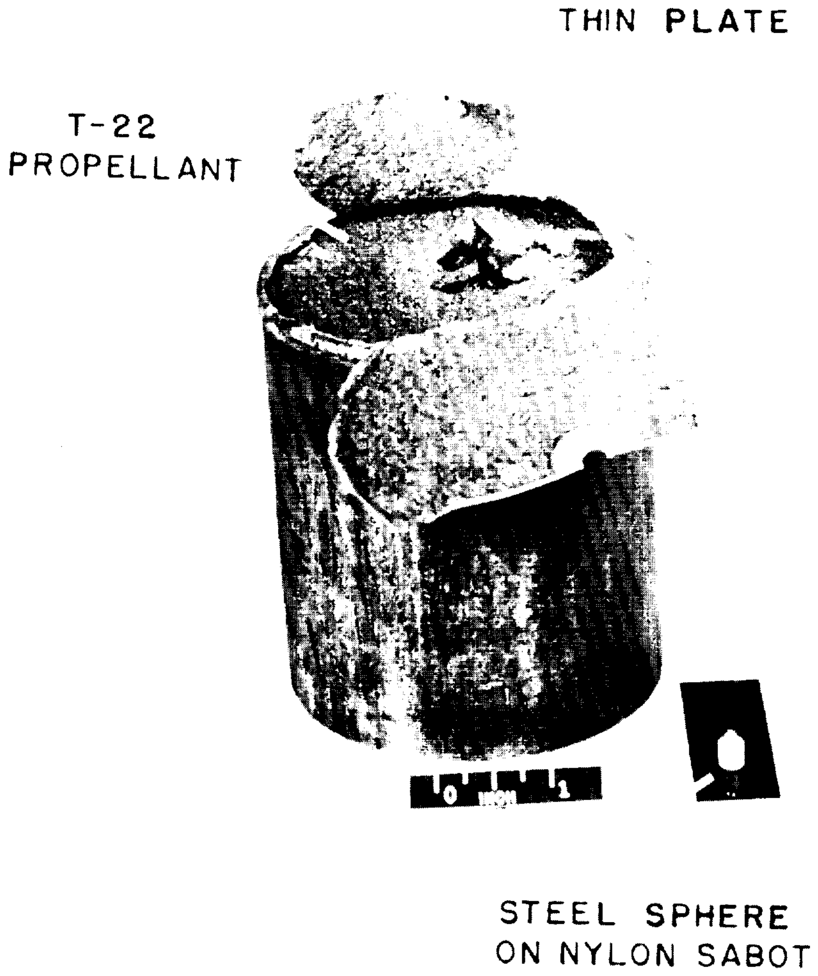
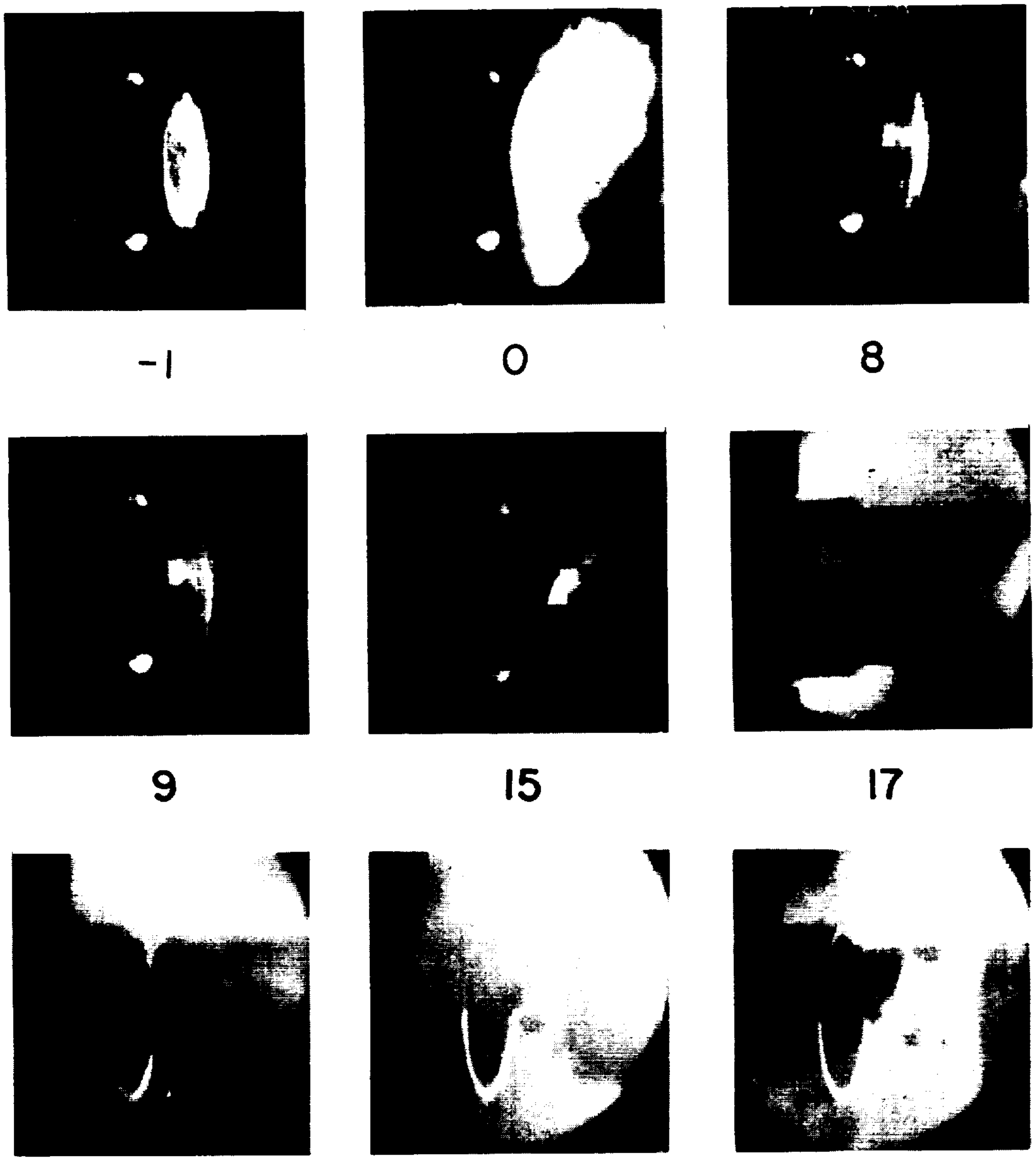
Figure 9.- Frames from motion picture of firing 29, showing a 1/32-inch-plate cylindrical target impacted by a 1/8-inch steel sphere. Under each frame is time to the nearest millisecond relative to the impact frame.

L-994



L-59-3107.1

Figure 10.- Photograph of firing 29 after impact by a 1/8-inch steel sphere. Note that propellant remained bonded to the 1/32-inch plate.



-1 0 8

9 15 17

19 20 21

L-954

L-60-2447

Figure 11.- Frames from motion picture of firing 30, showing a 1/16-inch-plate cylindrical target impacted by a 1/8-inch steel sphere. Under each frame is time to the nearest millisecond relative to the impact frame.

L-59-3109

Figure 12.- Photograph of grain fragments after impact of a 1/16-inch-plate cylindrical target by a 1/8-inch steel sphere. Firing 30.

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