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EFFECTS OF ORIENTATION OF THE ACCELERATION VECTOR ON BURNING-RATE AUGMENTATION

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16. Abstract

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EFFECTS OF ORIENTATION OF THE ACCELERATION VECTOR ON BURNING-RATE AUGMENTATION

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SUMMARY

The functional dependence of acceleration-induced burning-rate augmentation on the magnitude and orientation of the acceleration vector was determined for an aluminized composite propellant by using a slab motor mounted at various angles on a centrifuge. The rate augmentation was strongly dependent on the orientation of the acceleration vector with respect to the burning propellant surface.

INTRODUCTION

The flight performance of spin-stabilized and maneuverable rockets can be different from the static performance because of the effects of acceleration loading on the propellant burning rate. A number of studies have been conducted to characterize the acceleration-induced burning-rate augmentation of solid propellants (refs. 1 to 18), but little has been done to characterize the dependence of the rate augmentation on the orientation of the acceleration vector and to develop internal-ballistic programs that include acceleration effects.

The burning-rate augmentation is strongly dependent on propellant composition and reference (static) burning rate. For a given composition, the rate augmentation is a function of the acceleration level, orientation of the acceleration vector with respect to the burning surface, distance of propellant burned, or burning time, and pressure level.

The purpose of this investigation was to characterize the dependence of acceleration-induced rate augmentation on the magnitude and incidence angle of the acceleration vector with respect to the burning surface for an aluminized propellant over a wide acceleration range. These data were obtained by using a slab test motor mounted at various angles on a centrifuge and fired at centrifugal acceleration levels to 140g. A normalized orientation function that relates the rate augmentation to incidence angle was determined. This rate-augmentation-orientation function can be used in internal-ballistic calculations to account for nonisotropic burning due to acceleration loading on solid propellant grains.

SYMBOLS

$F(\theta)$	orientation function
$G(p,\alpha,t)$	burning-rate-augmentation function
p	pressure
r	burning rate
r_o	reference burning rate
t	time
α_n	centrifugal acceleration
θ	orientation angle

Subscripts:

θ	orientation angle
90	orientation angle measured normal into surface

Bars over quantities represent average of several tests.

APPARATUS AND PROPELLANT

Centrifuge

The centrifuge, located at the Langley Research Center, was previously described in reference 14. A photograph of the modified centrifuge with a test motor mounted on each arm is shown in figure 1. The motor on the right side of the photograph includes the extinction apparatus. The equipment on the other arm of the centrifuge is the test motor with the orientation apparatus. The test motor was mounted on the centrifuge with the nozzle pointed upward in a manner that eliminated speed changes due to motor thrust.

Test Motor and Orientation Apparatus

The orientation data were obtained with a 12.7-mm (0.5-inch) web version of the test motor shown in figure 2(a). (See ref. 14 for description.) The motor was mounted in an orientation apparatus in such a way that the angle between the propellant surface and the centrifugal acceleration could be varied in 1° increments as shown in figure 2(b).

The 12.7-mm (0.5-inch) web slabs were 96.5 mm (3.8 inches) wide by 144.8 mm (5.7 inches) long and were allowed to burn on the nozzle end. Since no aft-end restrictor was used in this motor, metallic particles were free to leave the burning surface as they were moved along by the tangential component of the acceleration force. This technique eliminated the uneven burning observed in the previous orientation study (ref. 13), during which the orientation was obtained by rotating the inserts within the motor case. Also, with the old technique, the tangential acceleration was across the propellant surface and perpendicular to the gas flow. The mounting of the test motor as shown in figure 2(b) better simulates the relationship between gas dynamics and the acceleration vector in operational rocket motors in that the tangential acceleration component and gas velocity are in the same plane.

Extinction Test Apparatus

A blowoff nozzle and water quench system, shown in figure 2(c), were employed so that the propellant could be partially burned under acceleration, extinguished, and then examined for surface geometry changes. The test-motor nozzle assembly was modified to accept two 6.4-mm-diameter (0.25-inch) explosive bolts for release of a plate holding the graphite nozzle insert. Upon activation of the explosive bolts during motor burning, the motor throat area was rapidly increased, and the solenoid valve released a small amount of water into the chamber through the modified head end plate and upper insert. The water cooled the chamber and prevented reignition without affecting the propellant surface.

Propellant

The aluminized polybutadiene acrylic acid (PBAA) propellant contained 16 percent of irregular aluminum with an average particle diameter of 7 μm and 70 percent of bimodal ammonium perchlorate (AP) oxidizer. The coarse-to-fine weight ratio of the AP was 70/30. The coarse and fine fractions had weight median diameters of 180 μm and 20 μm, respectively. The motor average burning rate as determined from static testing of these propellants was 7.8 mm/sec (0.307 inch/sec) at 3.45 MN/m^2 (500 psia), and the pressure exponent was 0.255.

DATA AND RESULTS

For a given propellant, knowledge of the functional dependence of acceleration-induced rate augmentation on orientation of the acceleration vector will allow the ballistician to predict pressure histories and grain profiles for complex grain designs and will also allow for the effects of longitudinal acceleration present in free flight.

The 12.7-mm (0.5-inch) web motor was used to measure the orientation dependence of the aluminized PBAA propellant used in the previous investigations (refs. 13 and 14). Tests were conducted at acceleration levels α_n from 0 to 140g in 20g increments at various orientation angles ($\theta = 90^\circ$, 85°, 80°, 75°, and 70°) to determine any coupling between acceleration level and orientation. The 90° orientation was normal and into the propellant surface.

The nominal chamber pressure was maintained between 3.45 and 4.83 MN/m^2 (500 and 700 psia) by varying the nozzle throat diameter as the augmentation changed. The average burning-rate augmentation (r/r_o) was determined from the average burning rate based on web burn time under acceleration divided by the reference (static) burning rate at the average pressure of the acceleration test.

The r/r_o data for each test are shown in figures 3(a) to 3(g) at the orientation angles evaluated at the given acceleration levels. There was more scatter in the r/r_o data at 70° and 75°, where the magnitude of r/r_o was reduced, than at higher orientation angles. Although the reason for this scatter is not understood, the average value of r/r_o from several tests was approximately 1.

The average burning-rate augmentation $\overline{r/r_o}$ (average of data from fig. 3) is shown in figure 4 as a function of centrifugal acceleration level with the orientation angle θ as a parameter. The value of $\overline{r/r_o}$ at $\alpha_n = 140g$ was 1.22 at $\theta = 90^\circ$, with significant change in $\overline{r/r_o}$ with acceleration occurring at and above 60g. To facilitate use of the orientation dependence in internal-ballistic calculations, the data in figure 4 were normalized and plotted as shown in figure 5 for 60g and above. The data below 60g indicated only a slight effect of acceleration loading and thus could be treated as unaffected. The normalized orientation function $F(\theta)$ was defined as follows:

$$F(\theta) = \frac{\left(\overline{r/r_o}\right)_\theta}{\left(\overline{r/r_o}\right)_{90}} \tag{1}$$

Since $F(\theta)$ is not strongly dependent on acceleration level, the following acceleration-induced transient burning-rate equation with a decoupled orientation-dependence term can be formulated:

$$r = G(p,\alpha,t)F(\theta) \tag{2}$$

where $G(p,\alpha,t)$ is the function describing the burning-rate augmentation as a function of pressure, acceleration level, and burning time, or distance burned, with the acceleration normal to the surface. The $G(p,\alpha,t)$ function for this propellant was previously determined (see ref. 12) at acceleration levels to 140g in 20g increments for web thicknesses of 50.8 mm (2.0 inches). Sufficient tests have not been conducted to verify decoupling between orientation and transient burning-rate augmentation for a wide range of test conditions. Pressure histories from tests using a similar propellant in the 50.8-mm (2.0-inch) web slab motor, reference 11, showed a strong dependence on orientation at the 140g acceleration level, as would be qualitatively predicted by $F(\theta)$ determined in the thin-web motors. Although there was a slight increase in the average rate, the large maximum in pressure, and thus burning rate, that occurred early in burning for the 90° orientation test was virtually eliminated when the acceleration vector was inclined just 10° from the normal.

The reason for the strong orientation dependence is illustrated by photographs, shown in figure 6, of the extinguished propellant surface from tests of 50.8-mm (2.0-inch) web slab motors. The two grains shown in figure 6 were machined so that when the motors were acceleration tested, approximately one-half the length of each grain was exposed to normal acceleration and the other half inclined at 5° and 15°, respectively. These motors were fired at 100g for 2.5 sec and extinguished to show the effect of orientation on the propellant pitting that is associated with the burning-rate augmentation of aluminized propellants. At 5° there was a slight change in the pitting characteristics of the incline, but at 15° there were very few pits on the inclined surface, and the slab cross section showed a definitely lower burning rate for the inclined surface. The depression formed at the inhibitor end of the 15° incline was due to the residue that "rolled" down the incline and was retained; an increase in local burning resulted from the presence of this residue.

Thus, the presence of the tangential component of the acceleration vector alters the force balance of the metallic residue particles that are responsible for the rate augmentation. When these particles are no longer held on or near the surface, their perturbing effect on the burning rate is diminished.

CONCLUDING REMARKS

The functional dependence of the burning-rate augmentation on the magnitude and orientation of the acceleration vector was determined under properly simulated flow and acceleration conditions for an aluminized composite propellant. The propellant contained 16 percent aluminum, 70 percent bimodal ammonium perchlorate, and 14 percent polybutadiene acrylic acid. This propellant was used in a 12.7-mm (0.5-inch) web slab test motor mounted on a centrifuge and tested at various orientations and accelerations to 140g.

The normalized function for the relation between burning rate and orientation was found to be strongly dependent on orientation of the acceleration vector and independent of acceleration level. Thus, for this propellant, orientation dependence can be treated as a decoupled multiplier in burning-rate calculations that allow for acceleration-induced non-isotropic burning.

An off-normal orientation of the acceleration vector with respect to the propellant surface results in a tangential force component that enhances removal of metallic residue particles from the burning surface. When the particles are no longer held on or near the surface, their perturbing effect on the burning rate is diminished. Thus, the alteration of the acceleration vector of a spinning rocket motor due to longitudinal acceleration in flight can result in different performance from that obtained in ground spin tests.

Langley Research Center,
National Aeronautics and Space Administration,
Hampton, Va., September 25, 1972.

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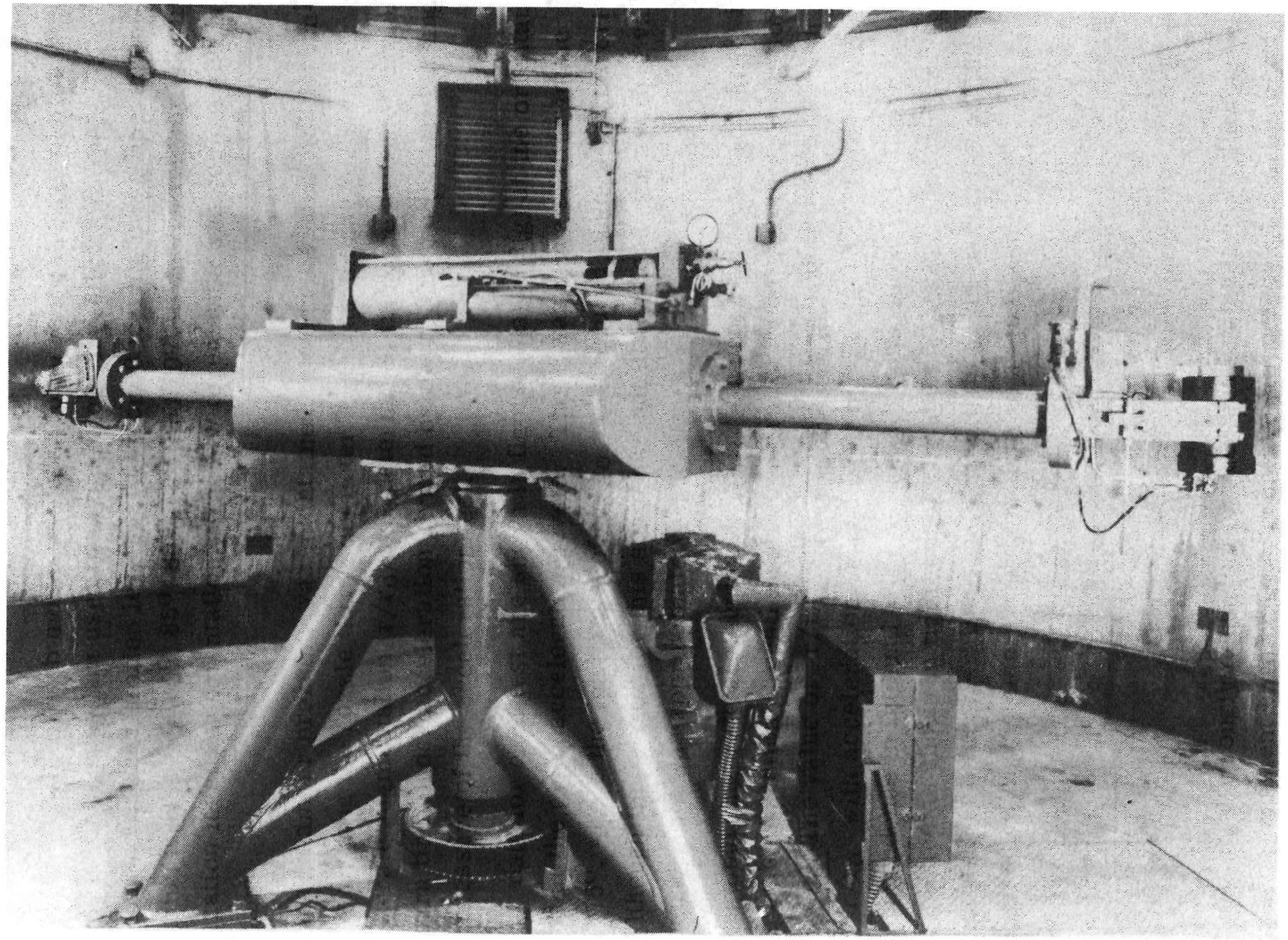

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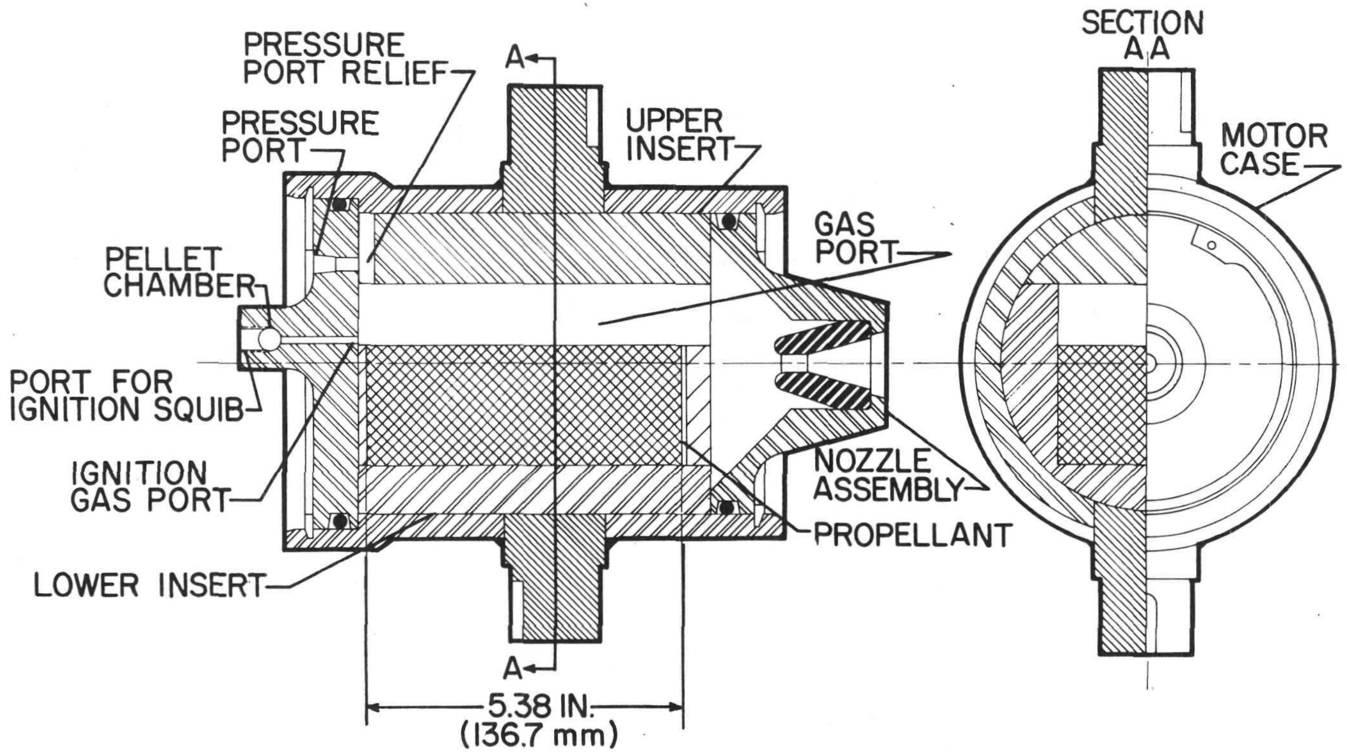
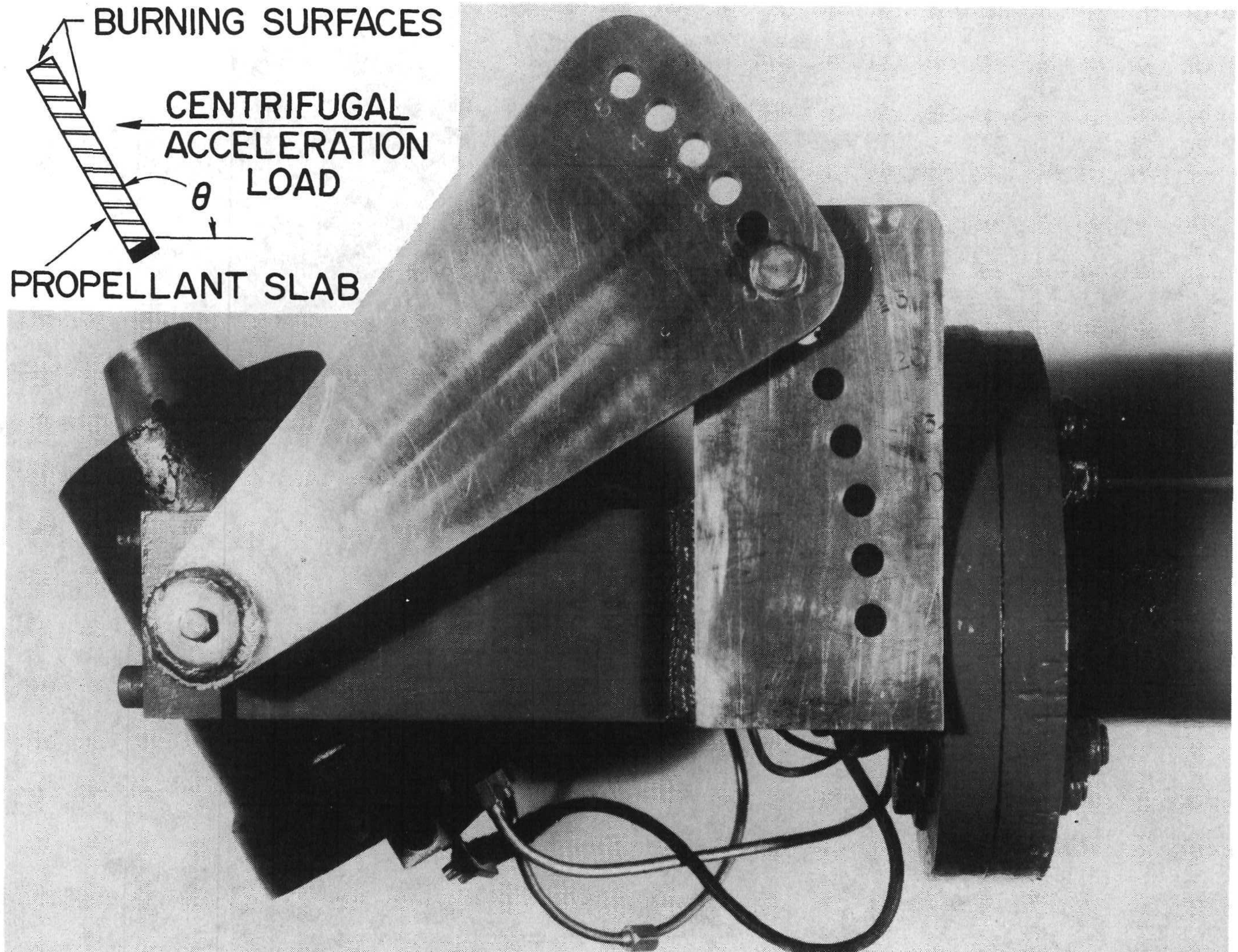
Figure 1.- Centrifuge.



(a) Slab test motor.

Figure 2.- Test apparatus.



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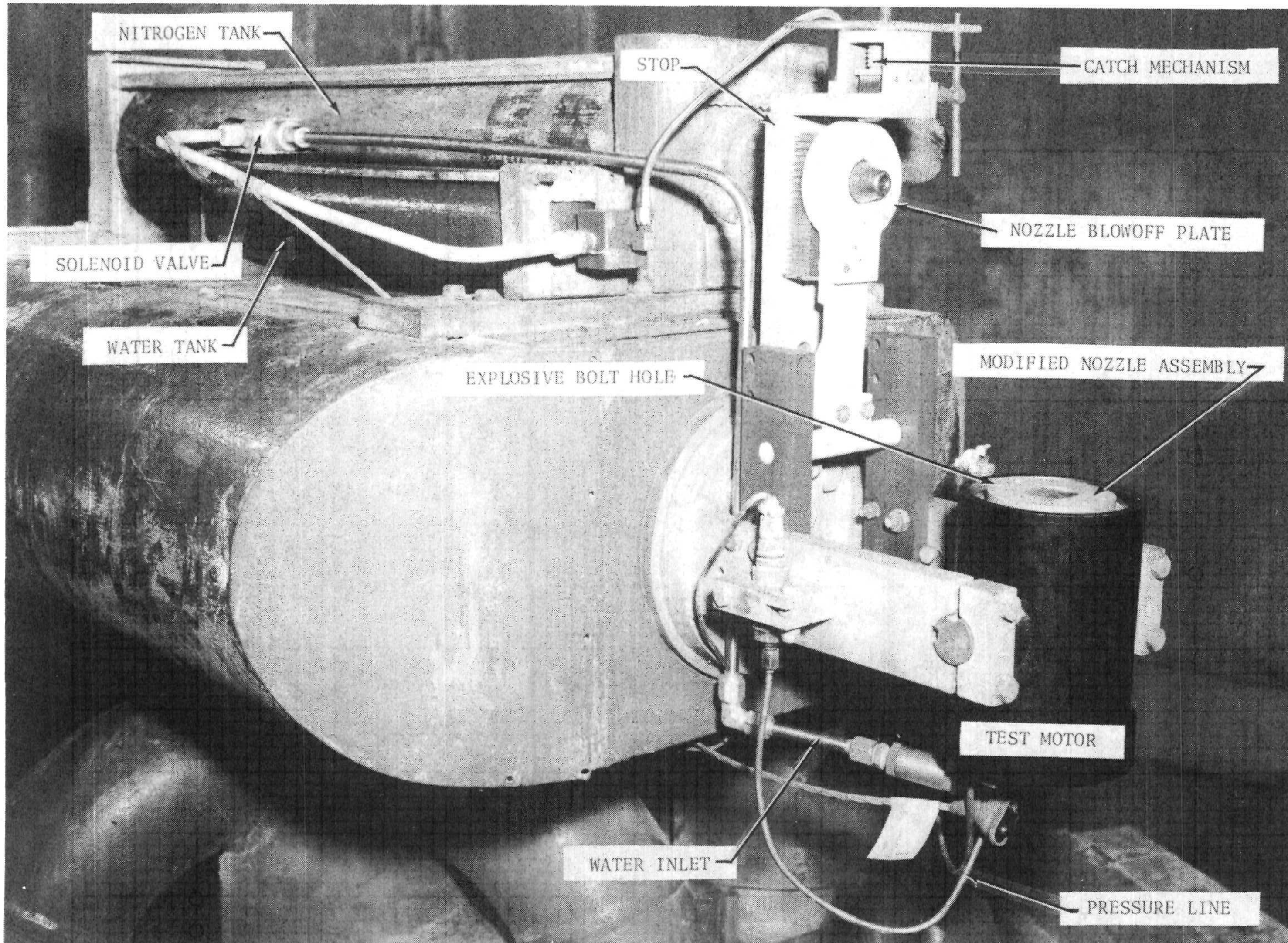
(b) Orientation apparatus.

Figure 2.- Continued.



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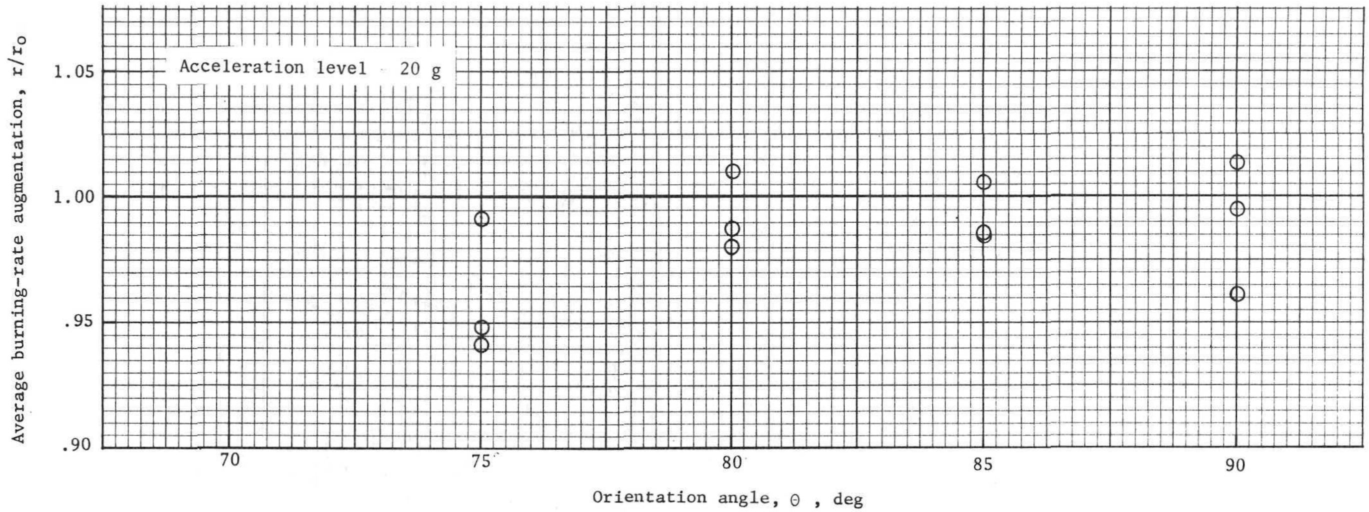
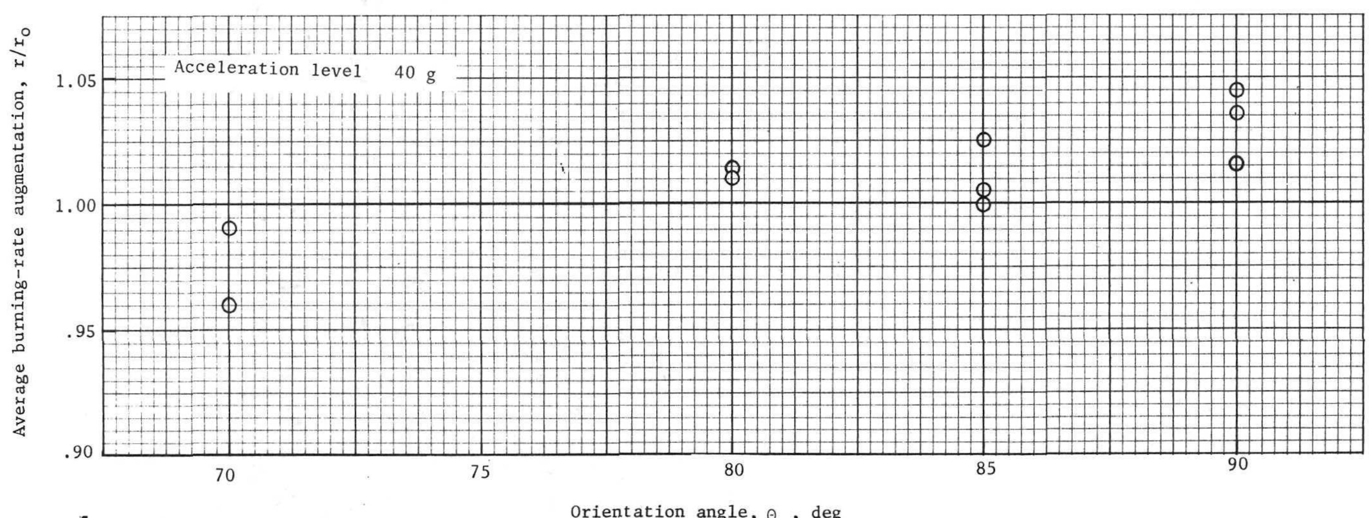
(c) Extinction apparatus.

Figure 2.- Concluded.

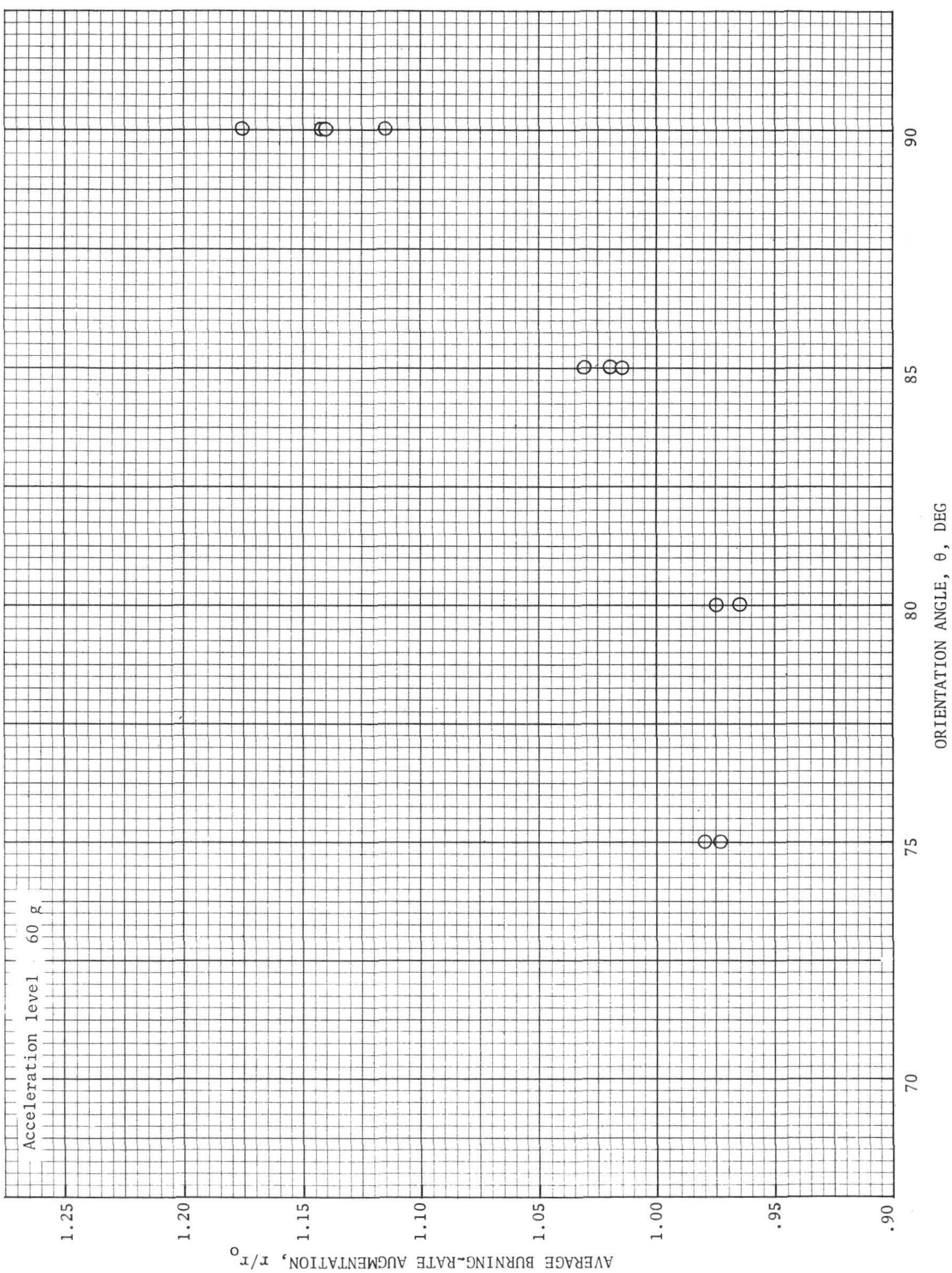


(a) 20g.



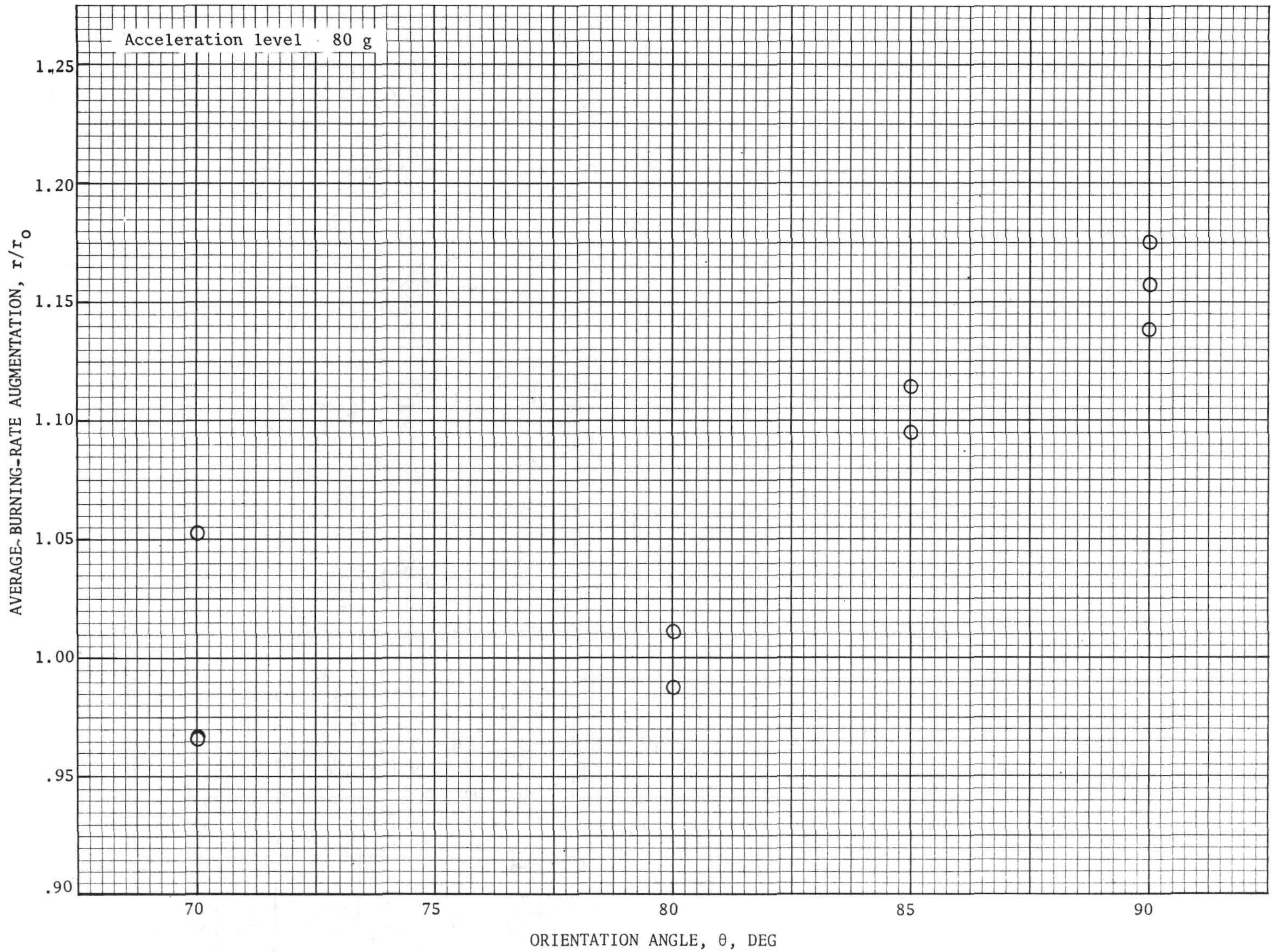
(b) 40g.

Figure 3.- Average burning-rate-augmentation data as a function of orientation.



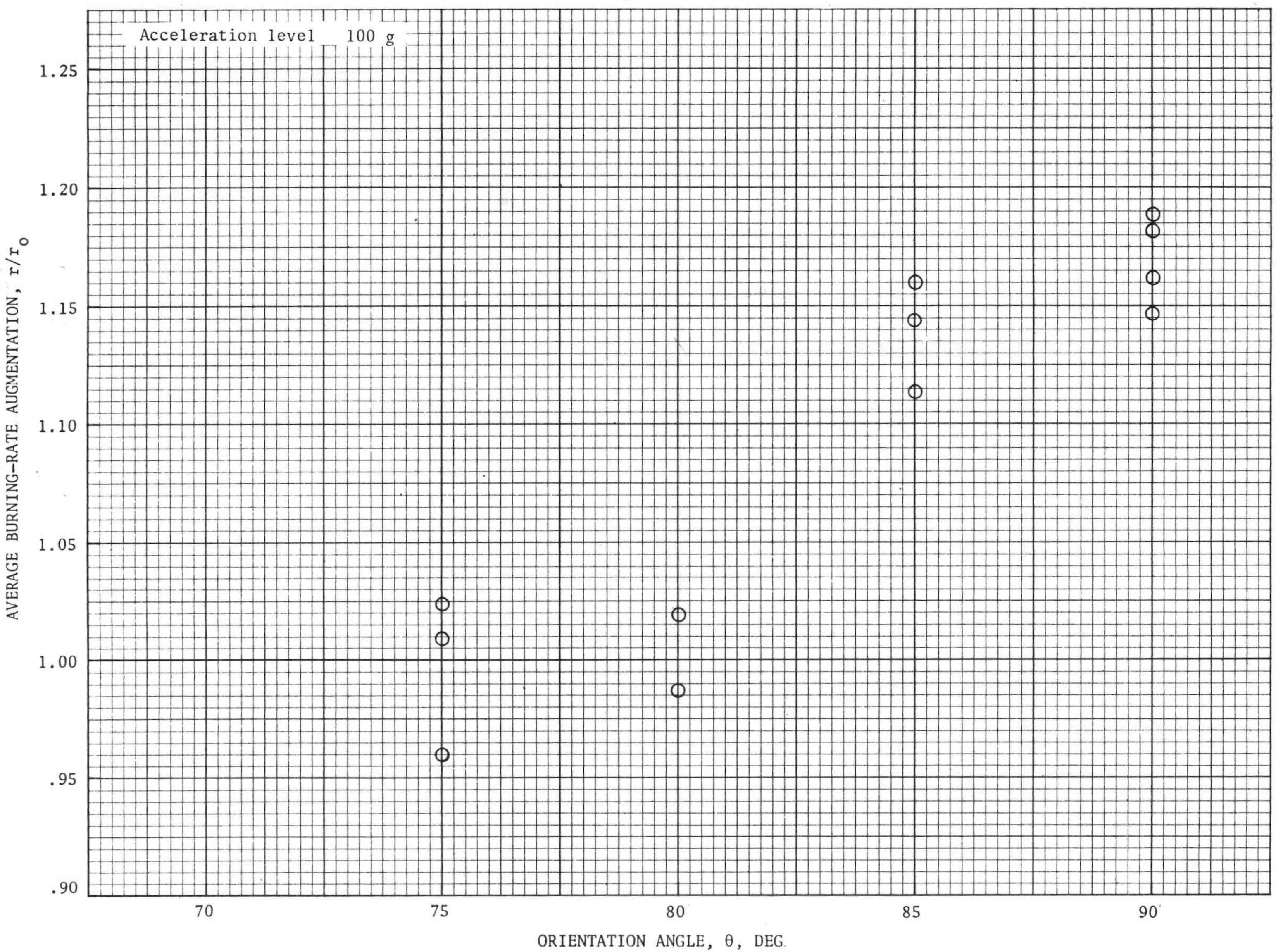
(c) 60g.

Figure 3. - Continued.



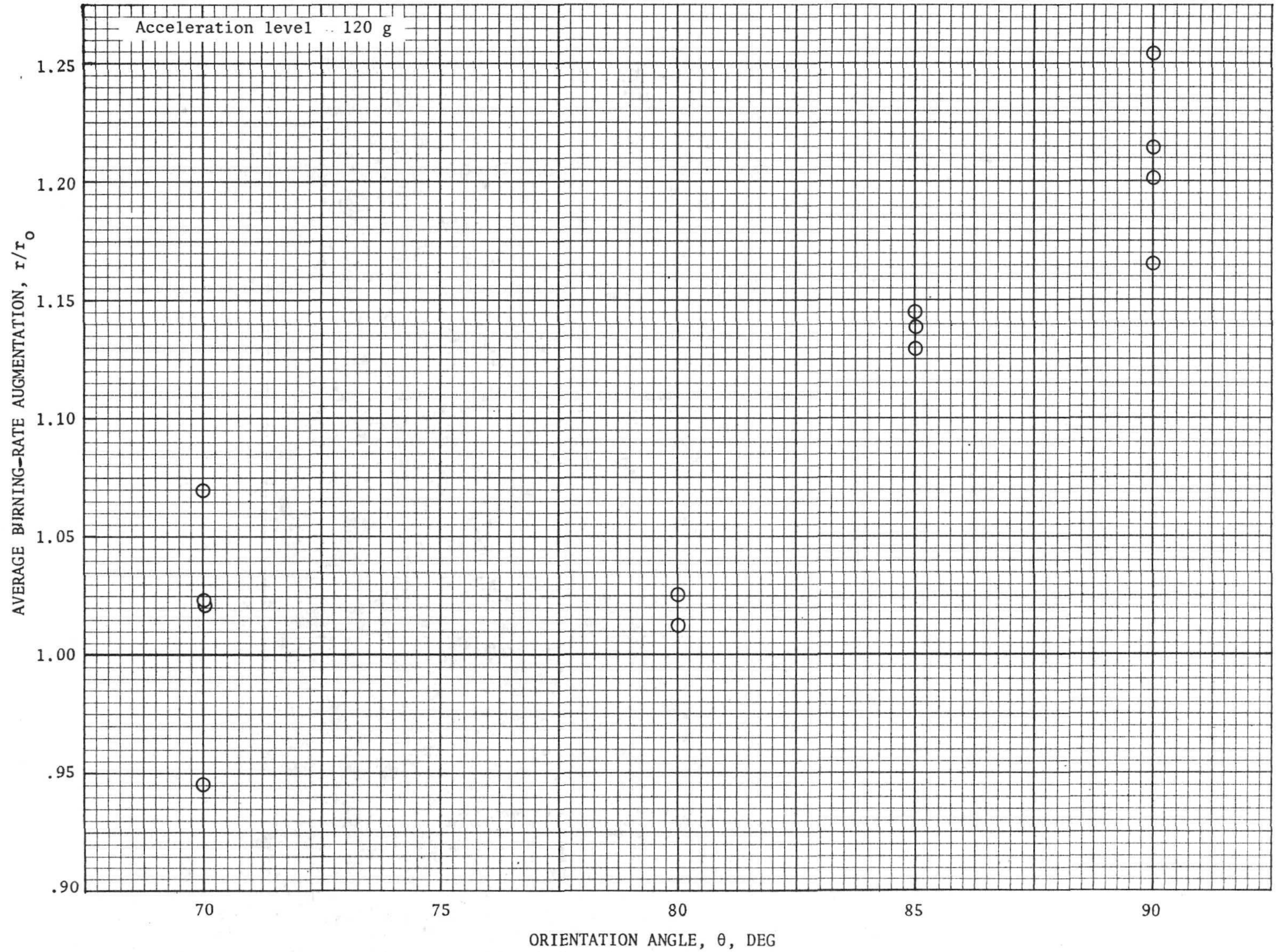
(d) 80g.

Figure 3.- Continued.



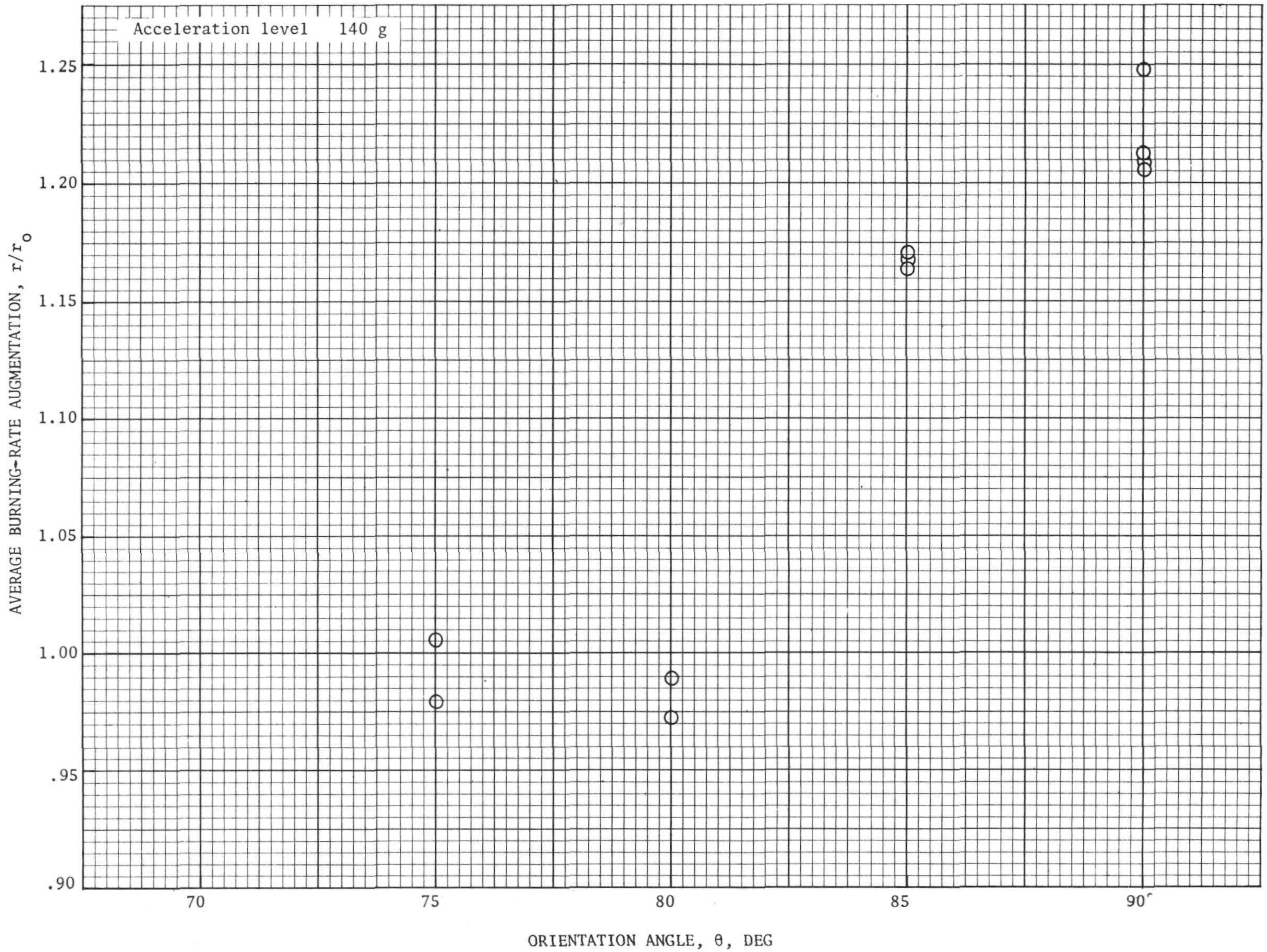
(e) 100g.

Figure 3.- Continued.



(f) 120g.

Figure 3.- Continued.



(g) 140g.

Figure 3.- Concluded.

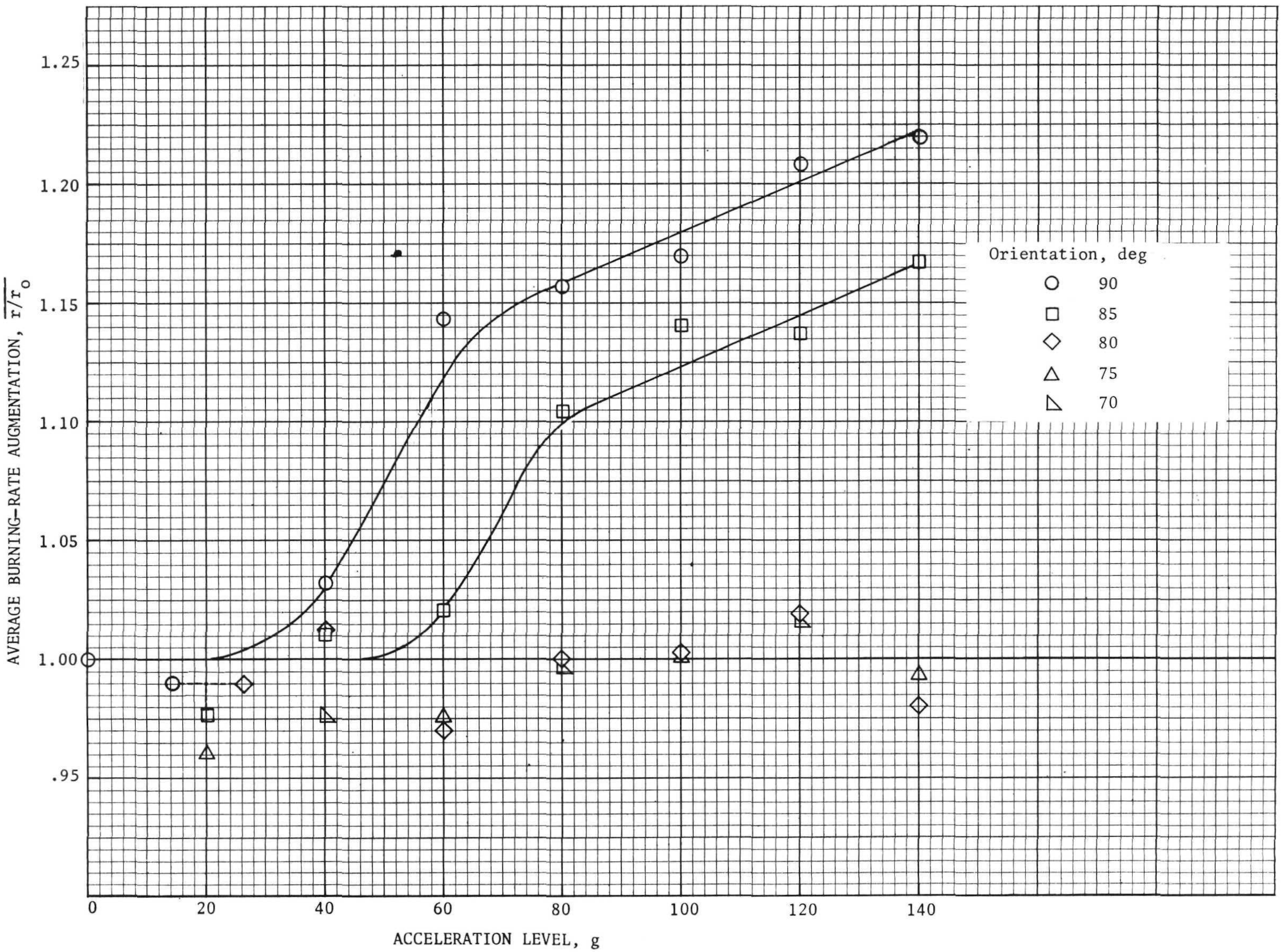


Figure 4.- Summary of orientation test results with 12.7-mm-thick (0.5-inch) web propellants.

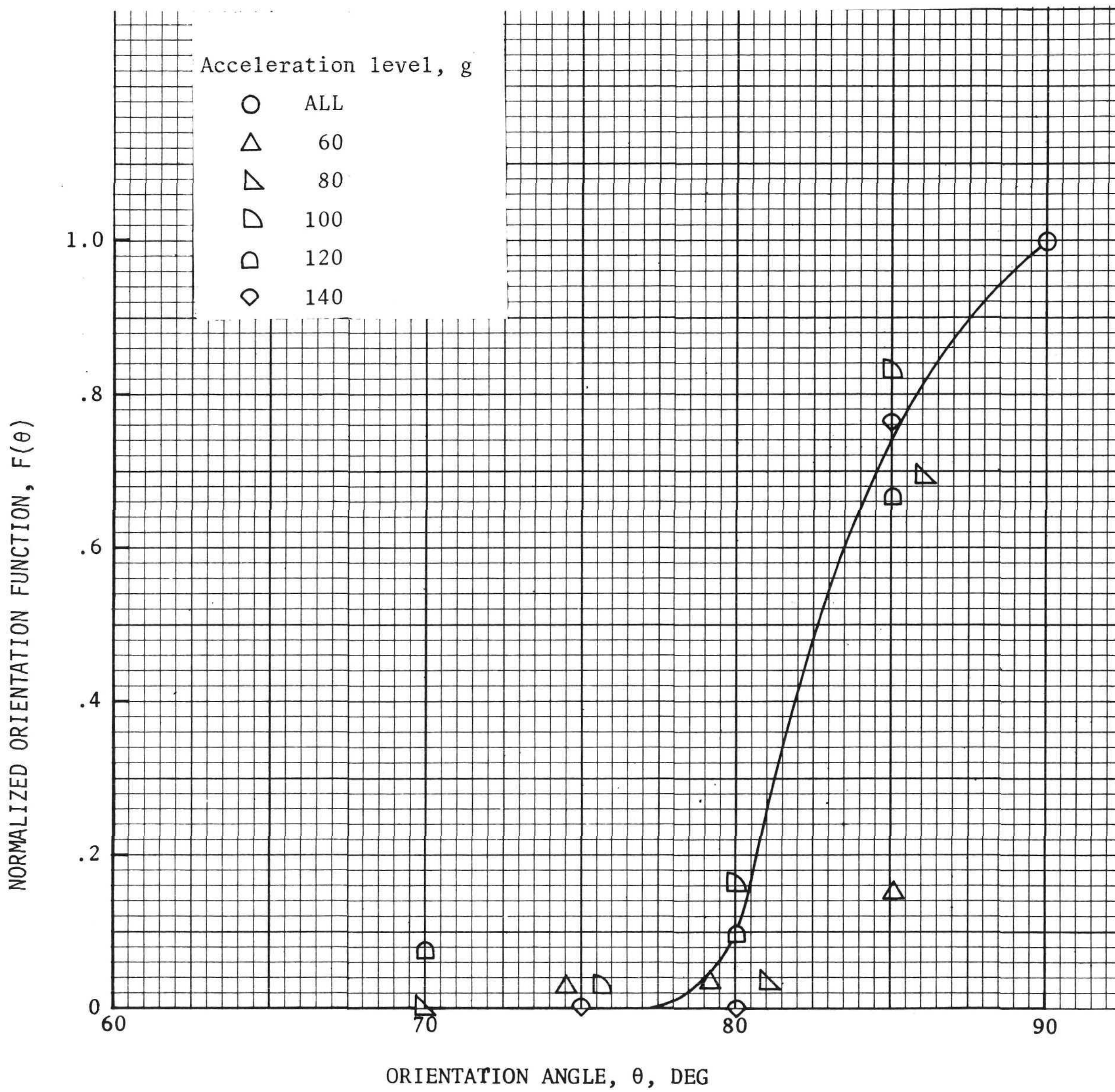
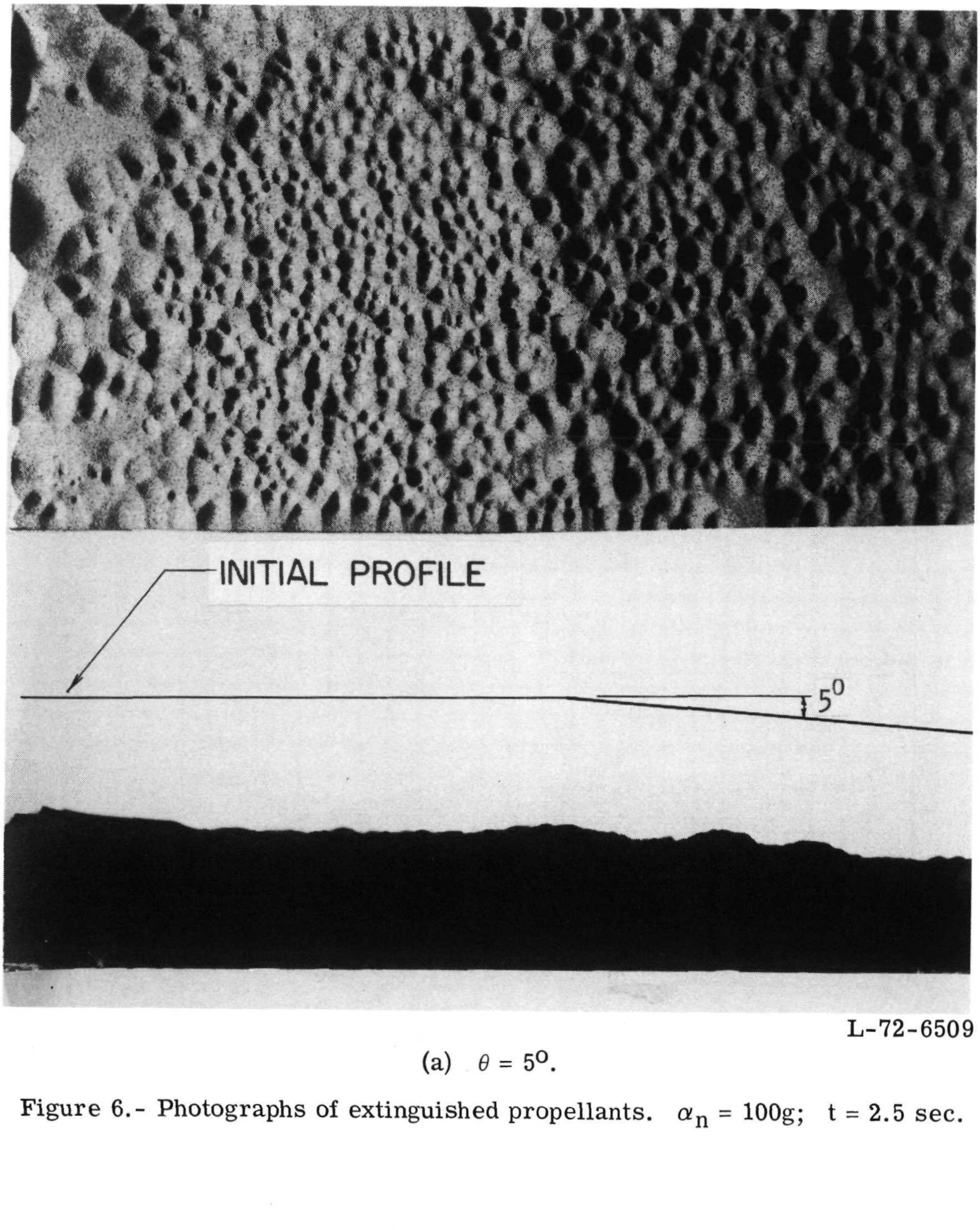


Figure 5.- Normalized orientation function for accelerations from 60g to 140g.



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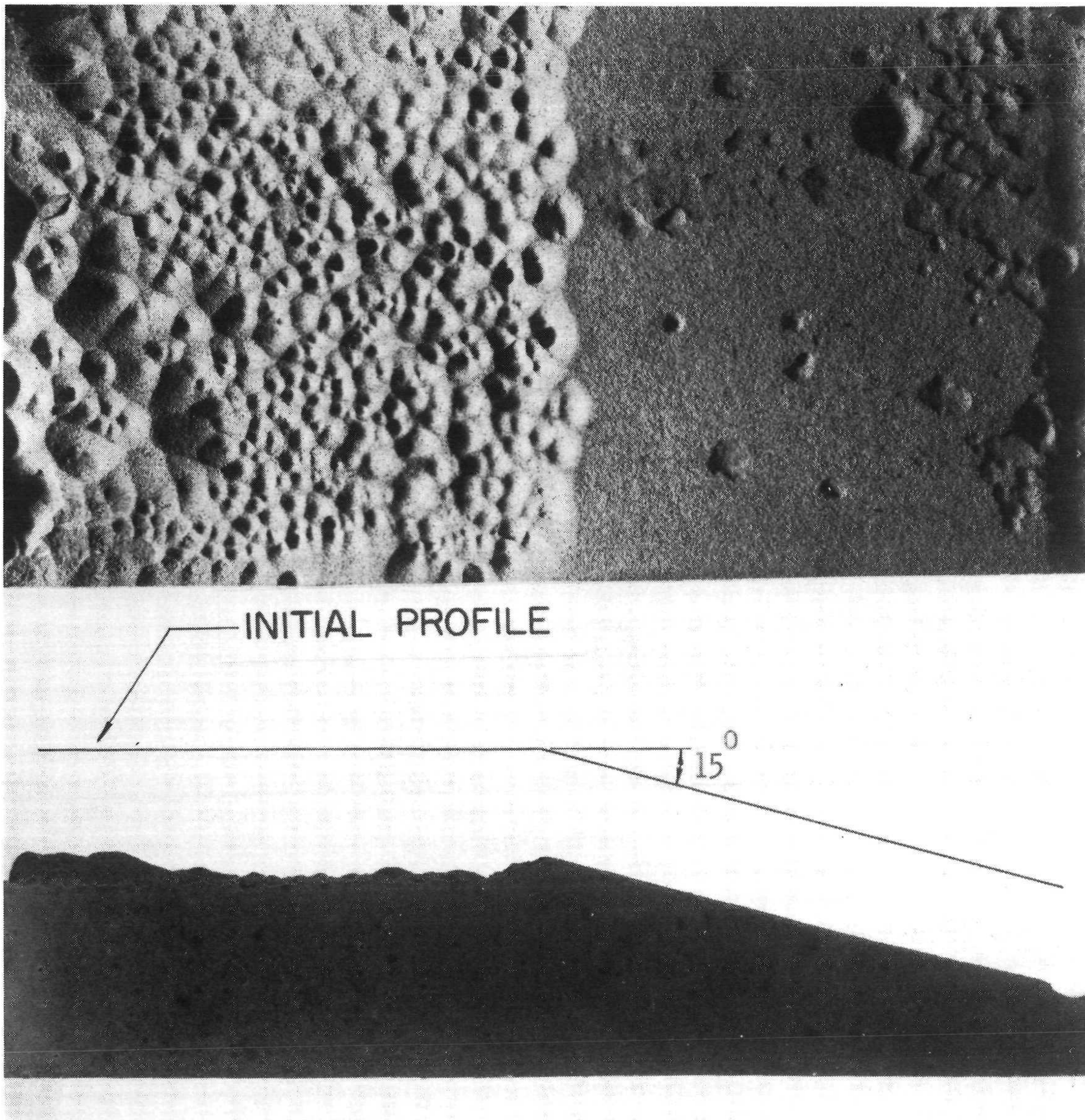
(a) $\theta = 5^{\circ}$.

Figure 6.- Photographs of extinguished propellants. $\alpha_n = 100g$; t = 2.5 sec.



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(b) $\theta = 15^{\circ}$.

Figure 6.- Concluded.

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