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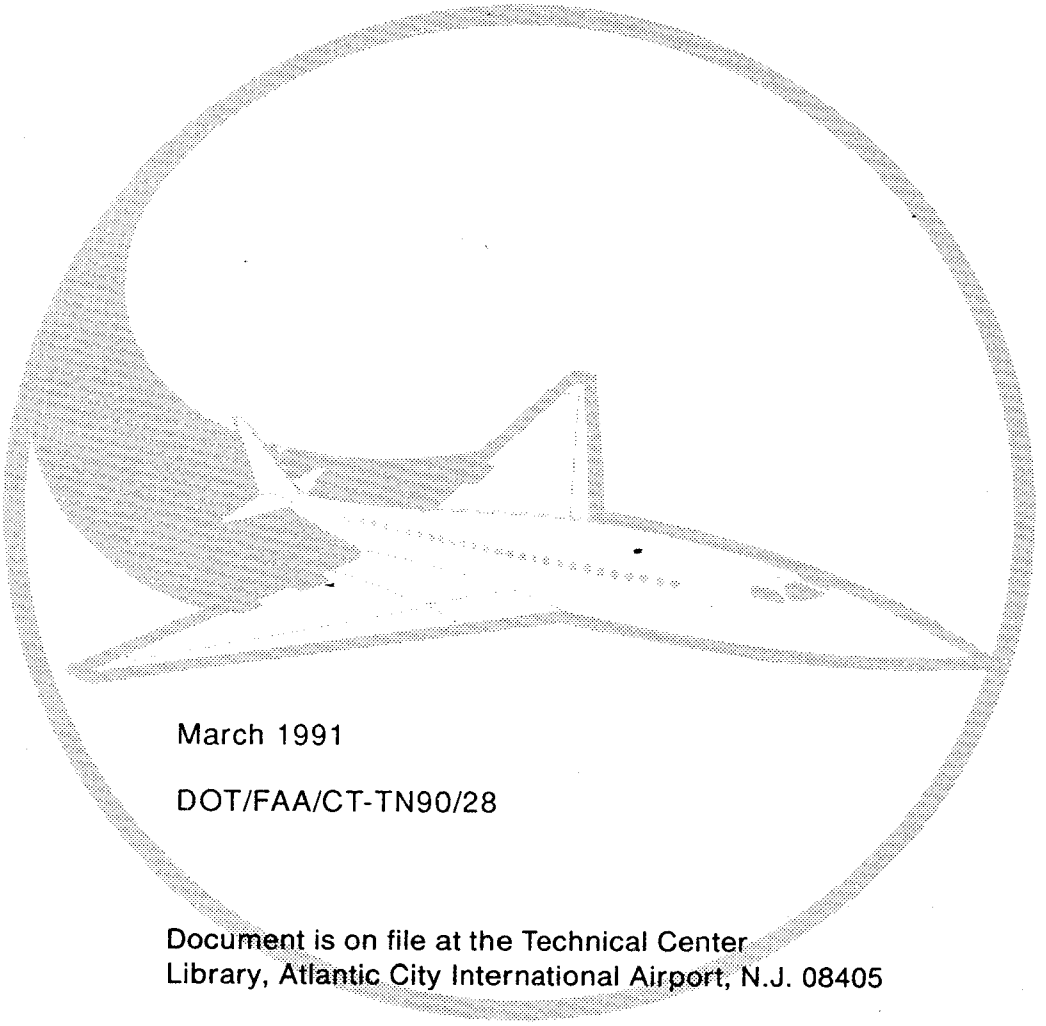
Model Rocketry Hazard Study



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16. Abstract

This study evaluates the potential hazard to an approaching or departing aircraft from a collision with a model rocket. Typically, these rockets have a gross weight of 1.5 kilograms (53 ounces) or less and carry a maximum of 0.125 kilograms (4.4 ounces) of propellant. The potential damage to jet transports, commuter aircraft, general aviation aircraft and rotorcraft resulting from an impact with these rockets is determined.

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Executive Summary

This report evaluates the potential hazard to an approaching or departing aircraft resulting from a collision with a model rocket. Under the proposed regulations, these model rockets have a gross weight ranging up to 1.5 kilograms (53 ounces) including 0.125 kilograms (4.4 ounces) of propellant and can achieve an altitude of 4000 feet and a theoretical velocity of up to 600 knots.

Although the probability of a collision is remote, the data base search into the Service Difficulty Report (SDR) and the Accidents and Incidents Data System (AIDS) verified that no previous incidence of this type has been reported in the past 6 years. However, the potential for damage in the unlikely event of a collision does exist. Therefore, for the purposes of this analysis a collision was assumed and the proposed regulatory changes were evaluated.

The proposed weight increase of the model rocket is 230 percent, from 16 to 53 ounces. However, after evaluation, the structural analysis indicates that a model rocket under present and proposed rules has the capability to damage aircraft in the event of a collision. Some operational limits for model rockets should be specified.

1. INTRODUCTION.

The use of unmanned rockets is governed by Federal Aviation Regulations (FAR) Part 101. This regulation applies to rockets that are larger than model size and to certain kites and balloons. Specifically,

(3) Any unmanned rocket except -
- (i) Aerial firework displays; and
- (ii) Model Rocket -
  - (a) Using not more than 4 ounces of propellant;
  - (b) Using slow-burning propellant;
  - (c) Made of paper, wood or breakable plastic, containing no substantial metal parts and weighing not more than 16 ounces, including the propellant; and
  - (d) Operated in a manner that does not create a hazard to person, property or other aircraft.

The National Association of Rocketry (NAR) has petitioned the Federal Aviation Administration (FAA) to allow rockets with marginally higher propellant weight and substantially greater total weight:

	Current Regulation	Proposed Regulation	Increase
Propellant Weight	4 ounces (0.113 kg)	4.4 ounces (0.125 kg)	10%
Total Weight	16 ounces (0.454 kg)	53 ounces (1.500 kg)	230%

This would be accomplished either through revision of the exemption in Part 101 or by granting a specific exemption for NAR's members. The effect of such a change on aviation safety must be assessed before a regulation can promulgate.

The velocity-altitude analysis model was set up to determine what speed and altitude the model rocket can achieve. The study also determined the velocity and altitude range of different types of aircraft during takeoff and landing.

Searches were performed on the Service Difficulty Report (SDR) and Accidents and Incidents Data System (AIDS) to assess the probability of collision.

The vulnerability analysis was carried out to determine the most vulnerable type of aircraft for each collision category, including fuselage, wing structure, windshield damage, and engine ingestion.

A ballistic limit model was used to determine if skin penetration would occur. Information on engine bird ingestion [1, 2] was also used to help in assessing the potential hazard resulting from engine ingestion of a model rocket.

2. VELOCITY AND ALTITUDE.

2.1 MODEL ROCKET.

A mathematical model was set up to calculate the altitude and velocity of a model rocket at each time increment from the Newtonian Laws of Motion and the basic equations of distance, velocity, and acceleration. With the assumption that it is in constant acceleration motion during each time interval, the model is presented as follows:

$$F_t - F_W - F_D = ma$$
$$F_W = mg$$
$$F_D = C_D(\tfrac{1}{2}\rho V_o^2)A$$
$$V_f = V_o + a\Delta t$$
$$h_f = h_o + V_o\Delta t + \tfrac{1}{2}a\Delta t^2$$

where

F_t is thrust produced by rocket motor
F_W is gravity force
F_D is drag force on the rocket
m is mass of the rocket
g is gravitational acceleration
C_D is drag coefficient
ρ is density of air
A is cross sectional area of rocket
a is acceleration of the rocket
Δt is time increment
V_o is velocity of rocket at the beginning of time interval
V_f is velocity of rocket at the end of time interval
h_o is altitude of rocket at the beginning of time interval
h_f is altitude of rocket at the end of time interval

The thrust-time curve of the rocket motor was taken from the 1989 North Coast Rocketry Catalog [3]. The results of velocity-altitude analysis with different model rocket masses are shown in figures 1, 2, 3, and 4 and summarized in table 1.

Figure 1 shows velocity-altitude curves for total mass equal 1.5 and 1.3 kilograms (kg) with proposed maximum propellant mass 0.125 kg (4.4 ounces). The drag coefficient (C_D) used here is 0.8. The diameter (d) is 4.0 inches for both cases.

For total mass = 1.1 and 0.9 kg with the same propellant mass as in figure 1, velocity-altitude curves are shown in figure 2 with C_D = 1.0 and d = 2.7 inches for both cases.

Figure 3 shows velocity-altitude curve for total mass = 0.7 and 0.5 kg with the same propellant mass as in figure 1. C_D = 1.0 and d = 1.88 inches for both cases.

Figure 4 shows velocity-altitude curve for maximum total mass 0.454 kg (16 ounces) and maximum propellant mass 0.113 kg (4.0 ounces) allowed by current rule. C_D = 1.0 and d = 1.88 inches for this case.

The maximum velocity, altitude at maximum velocity, and apogee (h_{MAX}) are summarized in table 1 for each model rocket total mass.

If the propellant mass is raised from 4.0 to 4.4 ounces, with all other conditions remaining the same, there are approximately 5 percent increases in both maximum velocity and maximum altitude.

2.2 AIRCRAFT PERFORMANCE.

The approach and departure phases of operation represent the most likely period for a potential impact because aircraft are at their lowest altitude and slowest velocity. Table 2 shows altitude and velocity of different category aircraft within a 5- and 10-nautical mile proximity to an airport.

For purposes of analysis, the aircraft is assumed to be on a 3° glide slope on approach with minimum altitude approximately 1600 feet above ground level (AGL) and takeoff and approach speed between 60 and 190 knots indicated air speed (IAS).

3. PROBABILITY OF COLLISION.

A thorough literature search was conducted to determine if any previous accidents or incidents had occurred between a model rocket and an aircraft on approach and departure. The Service Difficulty Report (SDR) and Accidents and Incidents Data System (AIDS) were interrogated to review the events of collisions between aircraft and model rockets. This data base search covered the years 1984-1989, and no accidents or incidents related to the subject were found. Therefore, the probability of an impact occurrence is considered remote.

TABLE 1. ROCKET VELOCITY-ALTITUDE SUMMARY

Total Mass (kg)	Propellant Mass (kg)	Drag Coefficient	Rocket Diameter (in)	Maximum Velocity (knots)	Altitude at Max. Vel. (ft)	Apogee (ft)
1.500	0.125	0.8	4.00	254	680	1760
1.300	0.125	0.8	4.00	273	700	1810
1.100	0.125	1.0	2.70	353	960	2560
0.900	0.125	1.0	2.70	385	1050	2590
0.700	0.125	1.0	1.88	543	1430	4000
0.500	0.125	1.0	1.88	599	1770	3810
0.454	0.113	1.0	1.88	606	1850	3780

TABLE 2. VELOCITY AND ALTITUDE OF AIRCRAFT DURING TAKEOFF AND APPROACH

	Take-Off				Approach[a]			
	Speed[c] (knots)	Rate of Climb (ft/min)	Altitude[d] at 5 nm[b] (ft)	Altitude[d] at 10 nm[b] (ft)	Speed[c] (knots)	Rate of Descent (ft/min)	Altitude[d] at 5 nm[b] (ft)	Altitude[d] at 10 nm[b] (ft)
Jet Transport	160 - 190	2,000 - 3,500	3,800 - 5,500	7,600 - 11,000	120 - 145	650 - 1,200	1,600 - 2,200	3,500 - 4,500
Commuter Aircraft	110 - 150	1,000 - 2,000	2,700 - 4,000	5,400 - 8,000	110 - 130	600 - 1,000	1,600 - 2,200	3,500 - 4,500
General Aviation Aircraft	60 - 120	600 - 1,400	3,000 - 3,500	6,000 - 7,000	60 - 120	350 - 900	1,600 - 2,200	3,500 - 4,500
Rotorcraft	60 - 100	500 - 1,200	2,500 - 3,500	5,000 - 7,000	60 - 100	350 - 750	1,600 - 2,200	3,500 - 4,500

[a] The approach is assumed to take 3° glide slope
[b] nm = nautical mile
[c] Indicated Air Speed (IAS)
[d] Above Ground Level (AGL)

4. VULNERABILITY ANALYSIS.

Two types of impact scenarios were considered for this analysis. Type A collision is the model rocket impacting the underside of the aircraft, namely, the fuselage, wings, tail surfaces, and engine pods. The critical parameters are the model rocket velocity and impact angle. Type B collision is the aircraft impacting the model rocket. The critical parameters are the aircraft velocity and impact location.

The failure mechanism characterized by each impact is skin puncture in Type A collisions, and windshield breakage or engine ingestion and subsequent turbine and/or propeller blade failure in Type B collisions.

The most threatened type of damage is the model rocket impacting and penetrating the wing fuel tank. This type of impact can cause fuel ignition and threaten the safety of flight.

According to the analysis, the aircraft most vulnerable to impact are general aviation aircraft and rotorcraft because of lower operational altitude and speed, and different structural design considerations. The primary concern for the jet transport is engine ingestion of the model rocket and the potential subsequent engine damage, loss of thrust, and other secondary damage that can threaten the safety of flight.

5. STRUCTURAL ANALYSIS.

5.1 STRUCTURAL PENETRATION.

A ballistic limit model [4] was used to determine whether the model rocket will penetrate the aircraft skin. Ballistic limit is defined as that velocity below which an object or projectile will fail to penetrate a protective barrier.

5.1.1 Ballistic Limit Model.

The following equation is used to calculate ballistic limit.

$$V_L=1.944ku[L/d]^{0.15}\sqrt{f(z)d^3/M}$$

where

$z=[T/d](\sec\theta)^{0.75}$
$f(z)=z+e^{-z}-1$
T is thickness of target plate (cm)
d is diameter of model rocket (cm)
θ is impact angle
u = 1750

M is mass of model rocket (g)
L is length of model rocket (cm)
k = 3
V_L is ballistic limit (knots)

The correction factor, k = 1, is for a long rod impacting single aluminum plate. To account for the material difference with a model rocket made of plastic, wood, or paper impacting a single aluminum alloy plate, a correction factor k = 3 was used. This model predicts the speed at which the model rocket will penetrate the aircraft skin.

Ballistic limit versus skin thickness curves were calculated for three sizes of rockets. These curves are shown in figures 5 and 6 for the proposed regulation and in figure 7 for the existing regulation. The propellant mass was excluded from the total mass for these three sets of curves to obtain maximum velocity. Four impact angles (0°, 30°, 45°, and 60°) were considered for each case.

Figure 5 shows ballistic limit versus skin thickness curves for the four impact angles and for a rocket mass of 1.375 kg (48.5 ounces), diameter of 4 inches, and length of 60 inches. In general, the skin thickness for jet transport aircraft is in the range 0.03 to 0.1 inch and the ballistic limit is 71 and 236 knots, respectively, for zero impact angle. For general aviation aircraft, the skin thickness is in the range 0.03 to 0.06 inch and the ballistic limit is 71 and 142 knots, respectively, for zero impact angle. Referring to figure 1, the theoretical maximum velocity that the model rocket can reach is 254 knots for total mass of 1.5 kg. Therefore, assuming the occurrence of an impact, the model rocket will penetrate the aircraft skin.

Figure 6 shows ballistic limit versus thickness curves for the four impact angles and for a rocket mass of 0.375 kg (13.2 ounces), diameter of 1.28 inches, and length of 420 inches. The skin thickness for general aviation aircraft is in the range of 0.03 to 0.06 inch and the ballistic limit is 99 and 197 knots, respectively, for zero impact angles. Figure 3, shows that the theoretical maximum velocity for this model rocket is 599 knots. Assuming that a collision will occur, the model rocket will penetrate the aircraft skin.

Figure 7 shows ballistic limit versus skin thickness curve for a rocket mass of 0.341 kg (12 ounces), diameter of 1.88 inches, and length of 42 inches for four impact angles. In this case, the rocket mass 0.341 kg (12 ounces) is the maximum mass 0.454 kg (16 ounces) less the maximum propellant mass of 0.113 kg (4 ounces) as allowed by the present rule. The ballistic limit for general aviation aircraft with skin thickness in the range of 0.03 to 0.06 inch is 103 and 206 knots, respectively, for zero impact angle. The theoretical maximum velocity for this model rocket as indicated in figure 4 is 606 knots.

5.2 ENGINE INGESTION.

The engine ingestion problem is a dynamic high speed impact problem. The geometrical and material nonlinearities and dynamical and high strain rate effects need to be considered. To perform a detailed analysis of this problem, a sophisticated analytical tool, such as a finite element program, is needed.

The purpose of this project is to assess the potential damage on aircraft caused by an impact with a model rocket. Use of engine bird ingestion data [1, 2], will serve the purpose of this project relative to engine ingestion problems without using a sophisticated finite element program.

On January 28, 1988, a Boeing 737 aircraft taking off from Lihue Airport, Kauai, Hawaii, ingested a 2-ounce bird. This bird ingestion resulted in damage to three fan blades.

On August 29, 1988, at the O'Hare Airport, Chicago, Illionis, two birds weighing 3 ounces each were ingested into a turbine engine of a departing Boeing 737 aircraft with a speed of 145 knots. The leading edge of a fan blade was damaged, and one twisted fan blade was found.

On February 10, 1988, at Rio de Airport, Rio de Janeiro, Brazil, a bird weighing 11.25 ounces was ingested into a turbine engine of a departing Boeing 737 aircraft with a speed of 128 knots. It caused severe damage and involuntary power loss to the engine. Transverse fracture on fan blade, flange separation, and damage on acoustic panel were found.

On July 21, 1987, at Traverse City Airport, Michigan, a bird weighing 16 ounces was ingested into a turbo-propeller engine of a departing Metro III. It caused a severe bending damage to the compressor blades.

Some bird ingestion damage is an economic impact only (Hawaii and Chicago incidents cited above) while others with more severe damage threaten the aircraft safety of flight (Rio incident). Generally, single bird ingestions into turbine engines with weights of 4 ounces or less that result in flight safety

threatening damage are very rare. However, single bird ingestions above 4-ounce bird weights can result in safety of flight damage that is rare but with various degrees of probability [1, 2, 5].

By reviewing the available engine bird ingestion data, the following statement can be made: The model rockets, even under the present rule, have the potential to cause damage to aircraft engines.

6. CONCLUSIONS.

- The model rockets have the capability to reach the theoretical speed of 600 knots and an altitude of 4000 feet based on the calculation performed for this report.
- Searches on the Service Difficulty Report and Accidents and Incidents Data System during the years 1984-1989 indicate that the probability of collision between model rocket and aircraft is remote.
- The two most vulnerable types of aircraft are general aviation aircraft and rotorcraft, due to lower operational altitude and velocity and different structural design conditions.
- The results of structural analysis show that model rockets under present and proposed rules have the capability to damage the aircraft, assuming that a collision occurs.
- Some operational limits for model rockets should be specified, e.g., not operating the model rocket in controlled airspace or within at least 5 miles of the boundary of any airport would limit the operations of model rockets at least 5 to 10 nautical miles from the airports and further reduce the chance of collision between a model rocket and an aircraft.

7. REFERENCES.

1. Frings, Gary, A Study of Bird Ingestion Into Large High Bypass Ratio Turbine Aircraft Engines, DOT/FAA/CT-84/13, Department of Transportation, Federal Aviation Administration, September 1984.

2. Hovey, Peter H., and Skinn, Donald A., Study of the Engine Bird Ingestion Experience of the Boeing 737 Aircraft, DOT/FAA/CT-89/16, Department of Transportation, Federal Aviation Administration, October 1989.

3. Advanced Rocketry Products, North Coast Rocketry Catalog, 1989.

4. Zukas, J. A., Nicholas, T., Swift., H.F., Greszczuk, L.B., and Curran, D.R., Impact Dynamics, John Wiley & Sons Inc, New York, 1982.

5. Martino, Joseph P., and Skinn, Donald A., Study of Bird Ingestion into Small Inlet Area, Aircraft Turbine Engines, DOT/FAA/CT-89/17, Department of Transportation, Federal Aviation Administration, December 1989.

8. BIBLIOGRAPHY.

Jane's All the World's Aircraft 1988-89, Janes Information Group Inc.

Stine, G. Harry, Handbook of Model Rocketry, fifth edition, Prentice Hall Press, New York, 1987.

------, Thirty years of Model Rocketry: A Safety Report, The National Association of Rocketry and The Hobby Industry Association, 1988.

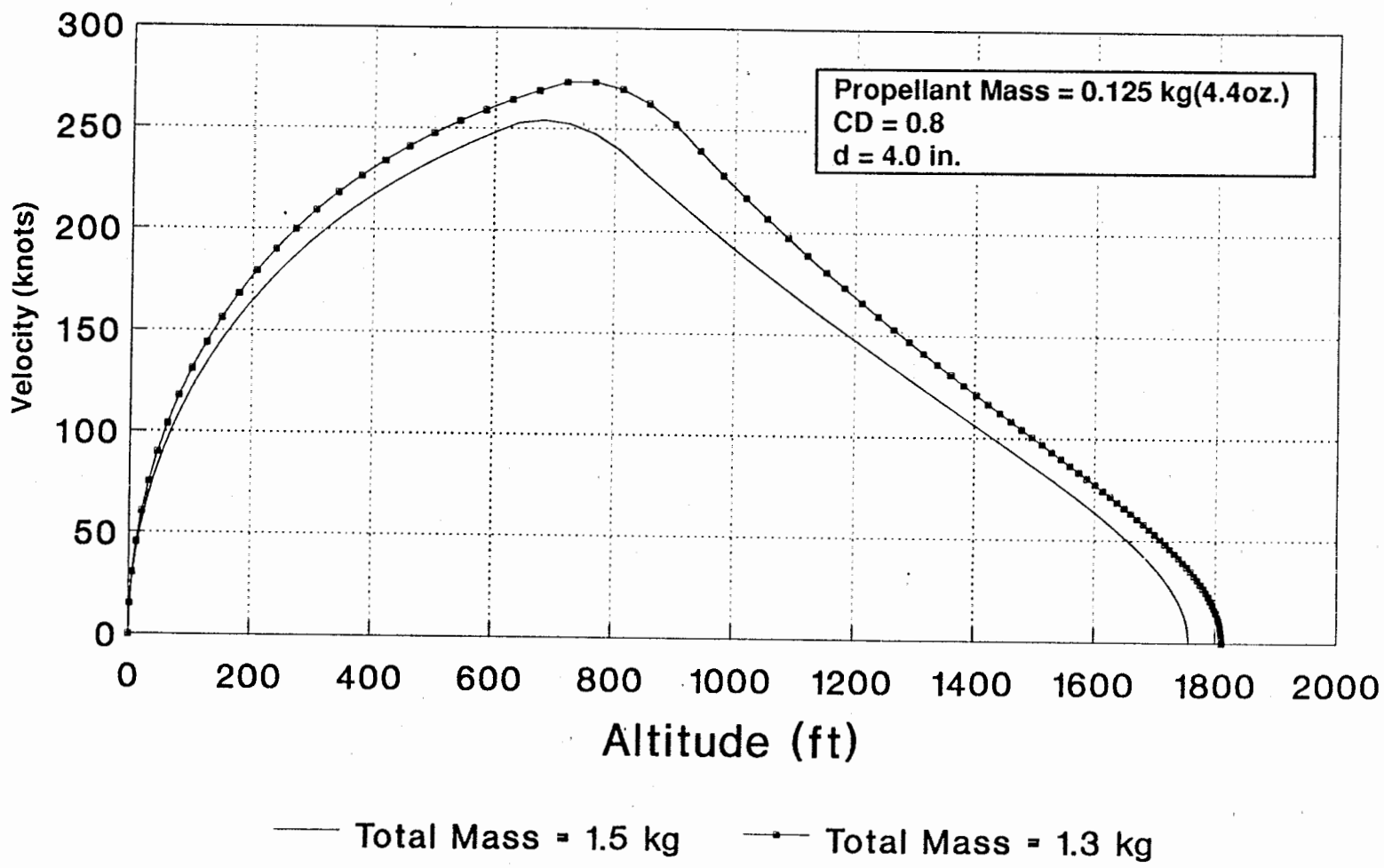

FIGURE 1. VELOCITY-ALTITUDE CURVE FOR ROCKET TOTAL MASS = 1.5 AND 1.3 KILOGRAMS

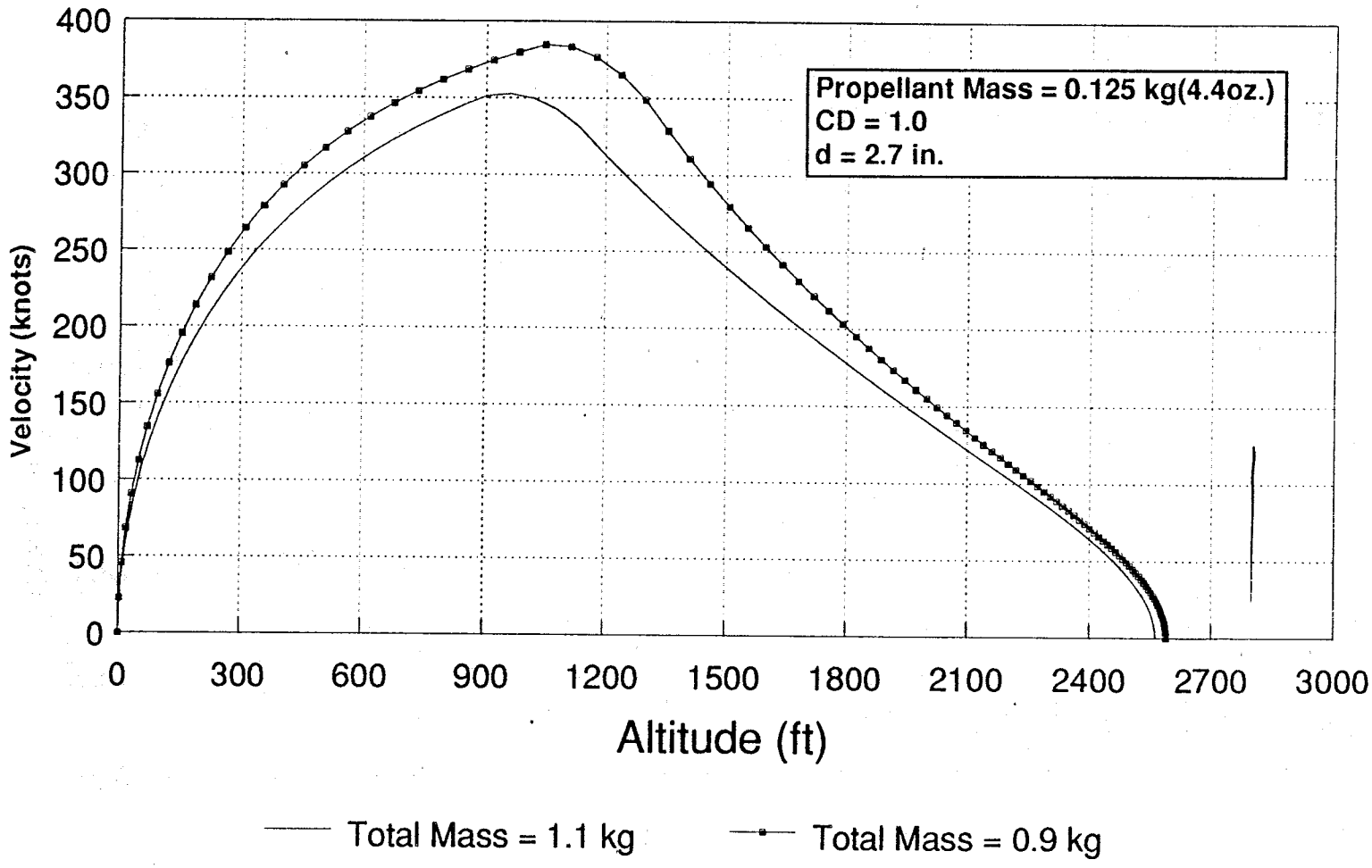

FIGURE 2. VELOCITY-ALTITUDE CURVE FOR ROCKET TOTAL MASS = 1.1 AND 0.9 KILOGRAMS

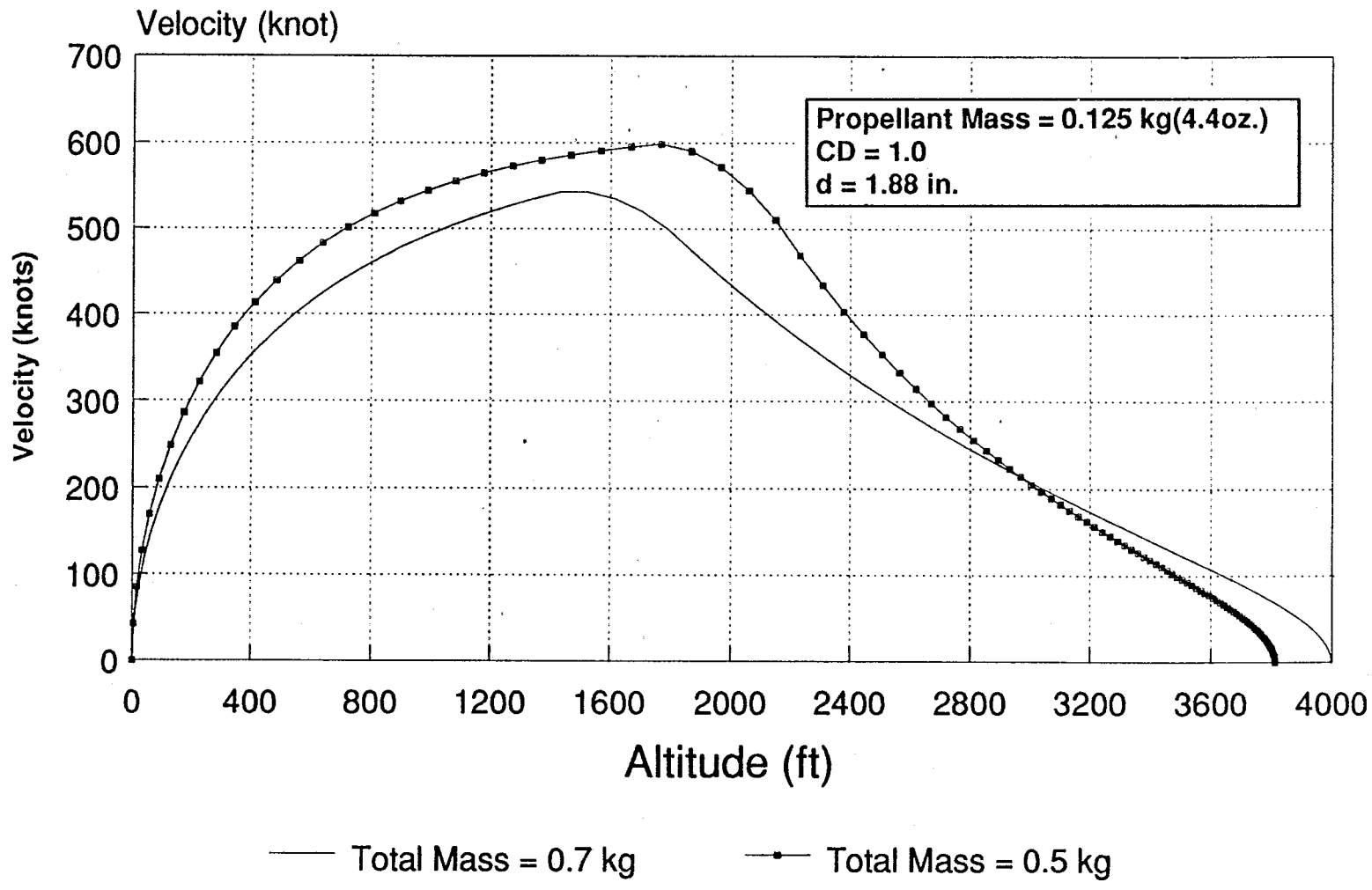

FIGURE 3. VELOCITY-ALTITUDE CURVE FOR ROCKET TOTAL MASS = 0.7 AND 0.5 KILOGRAMS

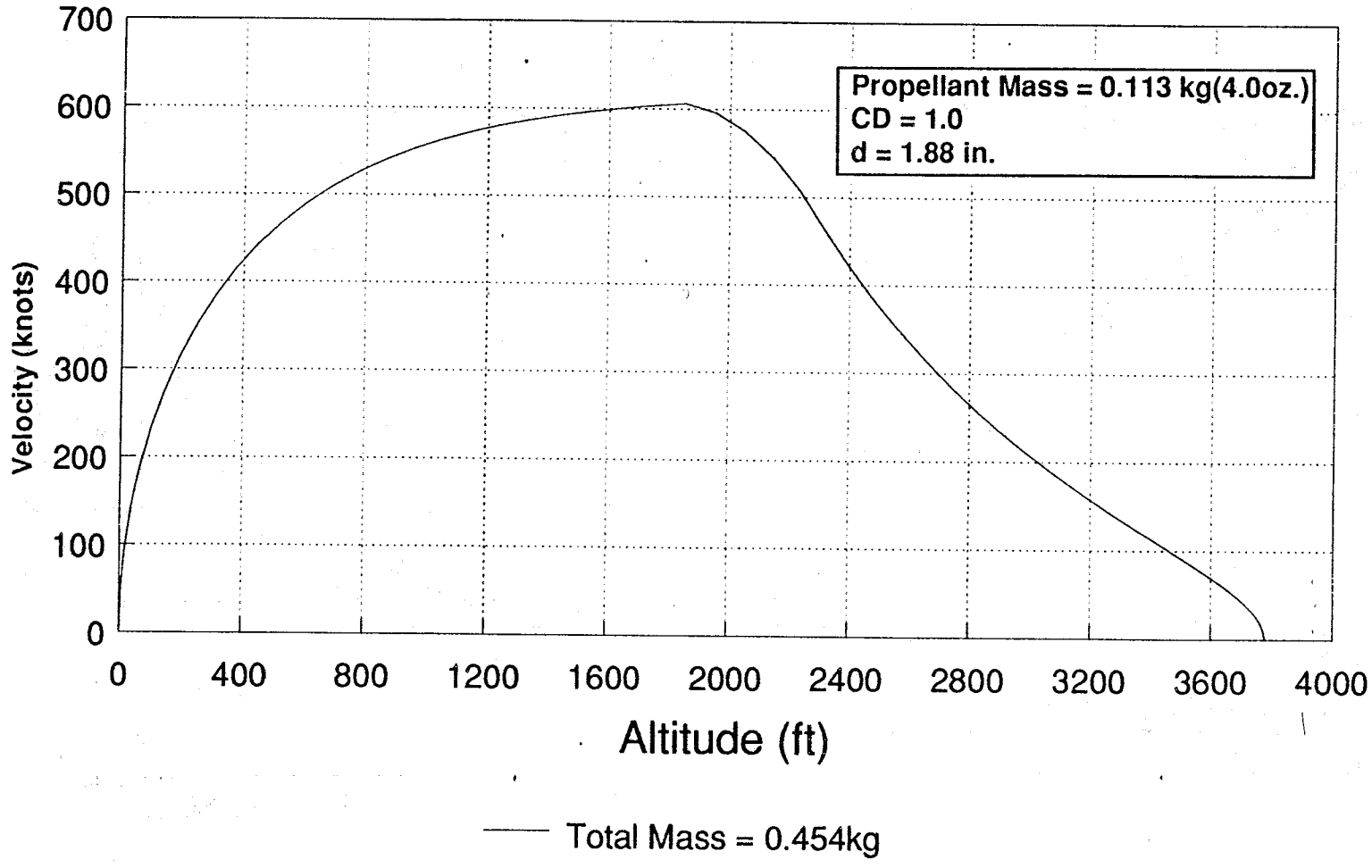

FIGURE 4. VELOCITY-ALTITUDE CURVE FOR ROCKET TOTAL MASS = 0.454 KILOGRAMS

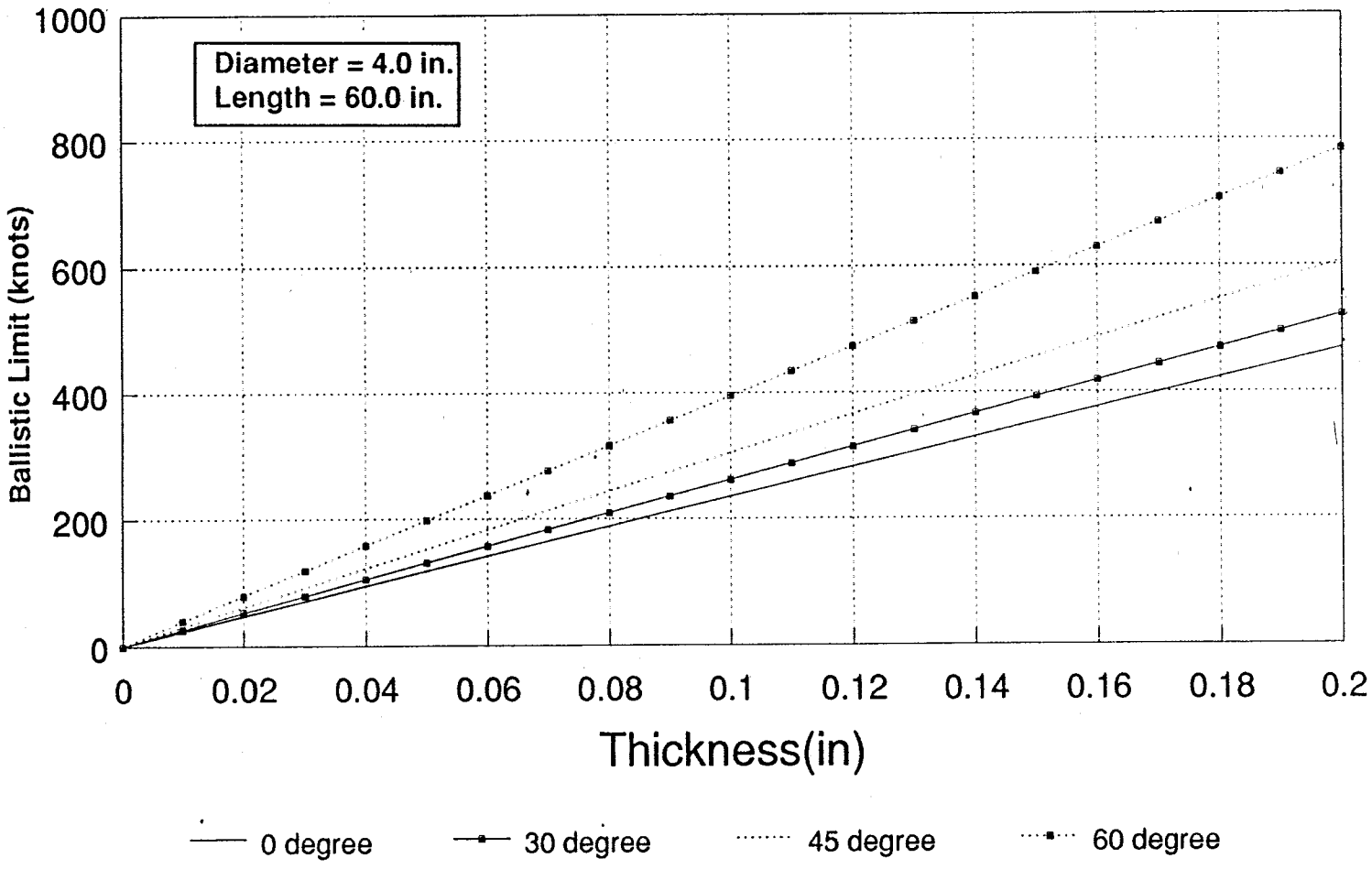

FIGURE 5. BALLISTIC LIMIT - THICKNESS CURVE FOR DIFFERENT IMPACT ANGLE WITH TOTAL MASS = 1.375 KILOGRAMS

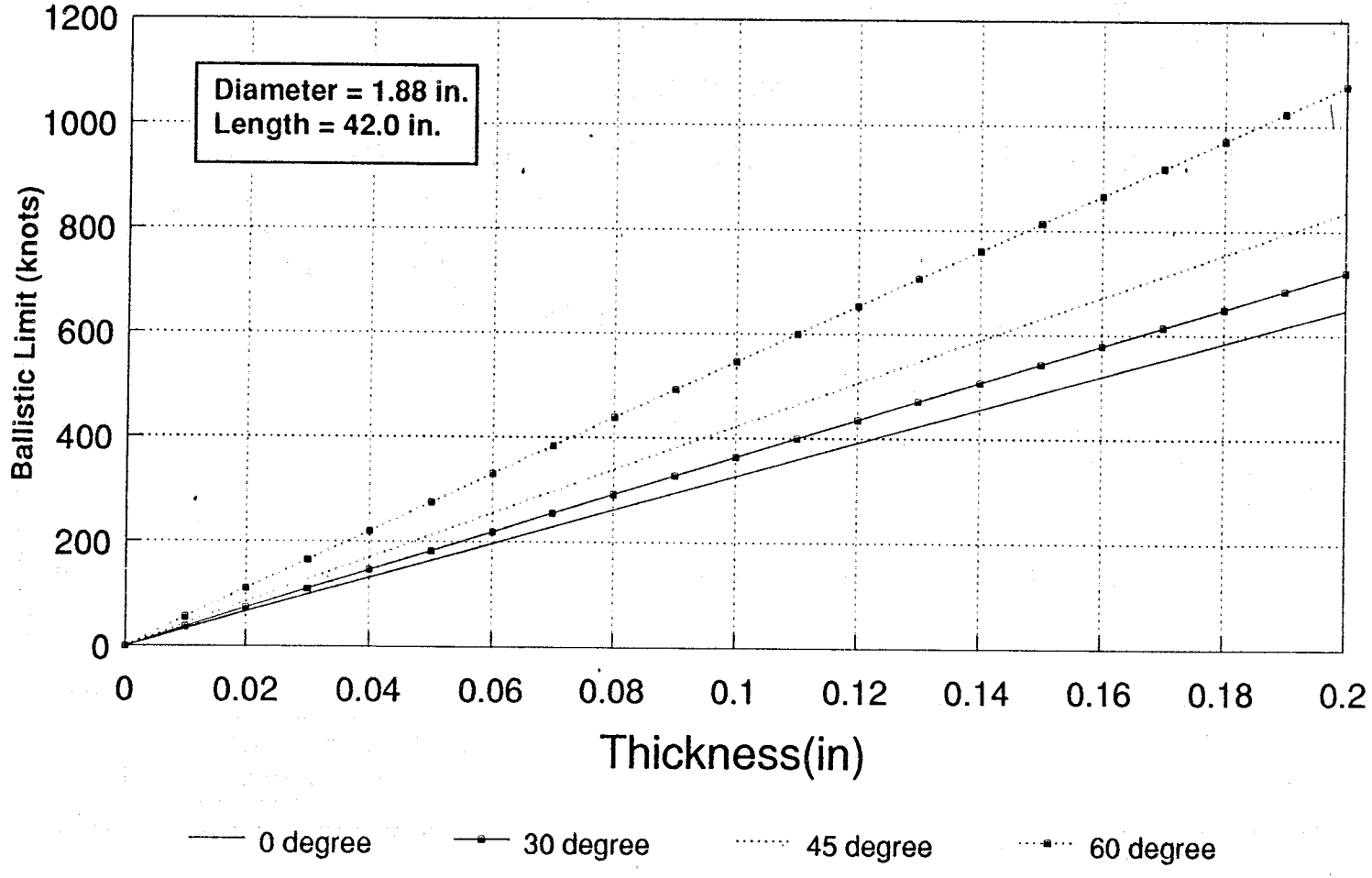

FIGURE 6. BALLISTIC LIMIT - THICKNESS CURVE FOR DIFFERENT IMPACT ANGLE WITH TOTAL MASS = 0.375 KILOGRAMS

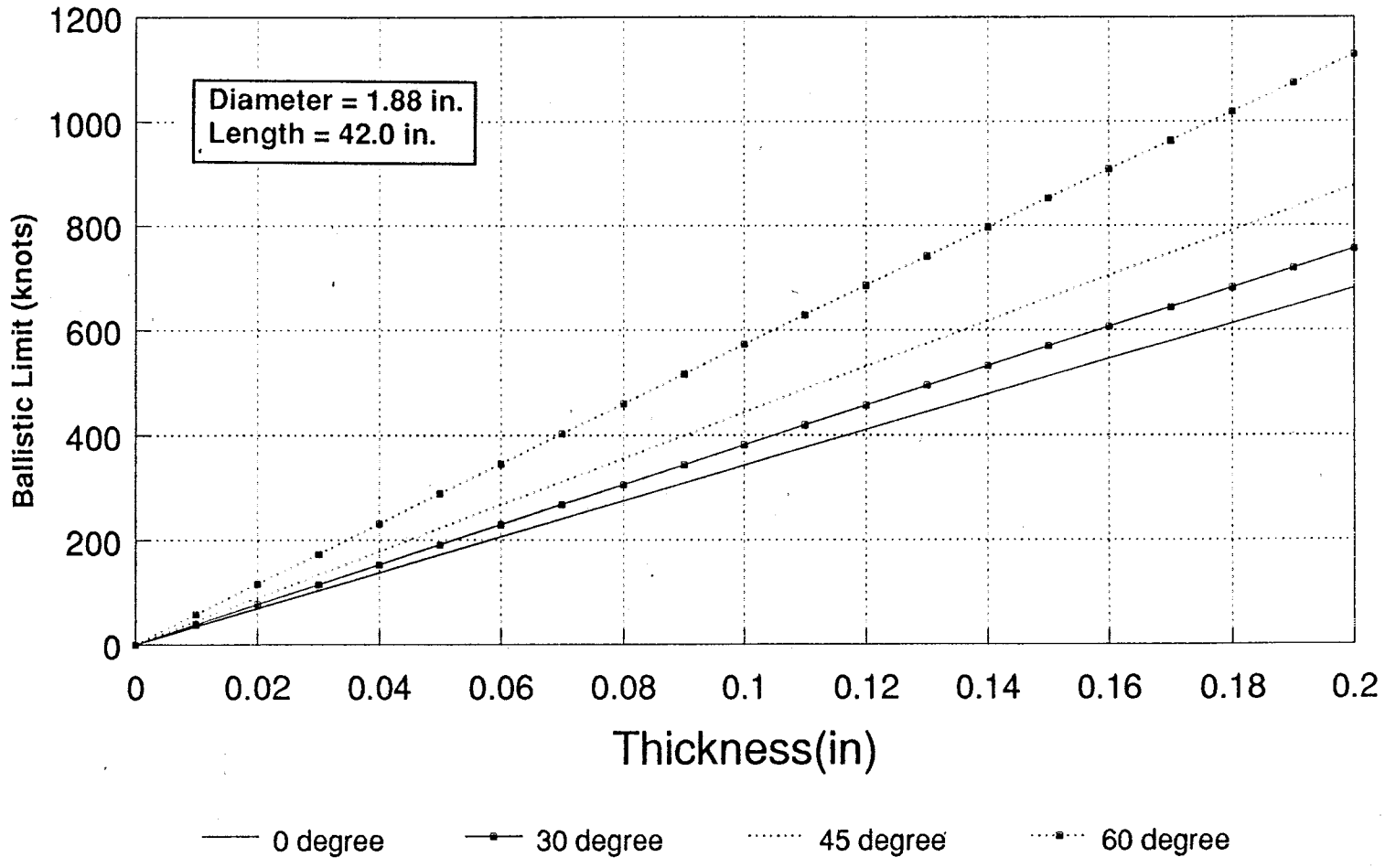

FIGURE 7. BALLISTIC LIMIT - THICKNESS CURVE FOR DIFFERENT IMPACT ANGLE WITH TOTAL MASS = 0.341 KILOGRAMS