NASA TECHNICAL NOTE

NASA TN D-6708

c.1

NASA TN D-6708

STATISTICAL ANALYSIS OF LANDING CONTACT CONDITIONS FOR THREE LIFTING BODY RESEARCH VEHICLES

by Richard R. Larson

Flight Research Center

Edwards, Calif. 93523

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • MARCH 1972

1. Report No. NASA TN D-6708	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle STATISTICAL ANALYSIS OF LANDING CONTACT CONDITIONS FOR THREE LIFTING BODY RESEARCH VEHICLES		5. Report Date March 1972
		6. Performing Organization Code
7. Author(s) Richard R. Larson		8. Performing Organization Report No. H-684
		10. Work Unit No. 727-01-01-00-24
9. Performing Organization Name and Address NASA Flight Research Center P. O. Box 273 Edwards, California 93523		11. Contract or Grant No.
		13. Type of Report and Period Covered Technical Note
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D. C. 20546		14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

The landing contact conditions for the HL-10, M2-F2/F3, and the X-24A lifting body vehicles are analyzed statistically for 81 landings. The landing contact parameters analyzed are true airspeed, peak normal acceleration at the center of gravity, roll angle, and roll velocity. Ground measurement parameters analyzed are lateral and longitudinal distance from intended touchdown, lateral distance from touchdown to full stop, and rollout distance. The results are presented in the form of histograms for frequency distributions and cumulative frequency distribution probability curves with a Pearson Type III curve fit for extrapolation purposes.

17. Key Words (Suggested by Author(s)) Lifting body Landing contact conditions		18. Distribution Statement Unclassified - Unlimited	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 31	22. Price* $3.00

*For sale by the National Technical Information Service, Springfield, Virginia 22151

STATISTICAL ANALYSIS OF LANDING CONTACT CONDITIONS FOR THREE LIFTING BODY RESEARCH VEHICLES

Richard R. Larson
Flight Research Center

INTRODUCTION

Statistical studies (for example, refs. 1 to 4) of landing conditions for various types of aircraft have been used by designers to compare predicted with actual landing conditions and, therefore, more accurately determine the landing load requirements for the aircraft studied and similar aircraft. The studies have also aided in designing future aircraft and in improving the overall safety of flight operations.

A new type of aircraft—wingless, lifting bodies—was developed recently for which no landing study had been made. The use of these vehicles as piloted reentry aircraft is being studied. One important advantage offered by this type of vehicle would be the capability of landing at a predetermined landing strip, which would eliminate the need for a costly ocean recovery operation and permit reuse of the vehicle. Three lifting body configurations have been tested by the NASA Flight Research Center— the HL-10, M2-F3, and the X-24A. Sufficient touchdown data were obtained for a statistical analysis to be made. Results of the analysis are presented in this report. The landing contact parameters examined were true airspeed, peak normal acceleration at the center of gravity, roll angle, and roll velocity. The ground measurement parameters examined were lateral and longitudinal distance from the intended touchdown point, lateral distance from touchdown to full stop, and rollout distance. Vertical velocity at touchdown is not presented in this report because instrumentation was not provided.

Physical quantities in this report are given in the International System of Units (SI) and parenthetically in U.S. Customary Units. Measurements and calculations were made in Customary Units. Factors relating the two systems are presented in reference 5.

DESCRIPTION OF VEHICLES

The three lifting body vehicles (fig. 1) are generally similar in planform shape and have blunt noses, thick stabilizing control surfaces, and thick, squared-off bases. Sixteen M2-F2 flights were made before a center fin was installed to improve the handling qualities. The vehicle was then redesignated the M2-F3.

Figure 2 shows pertinent geometric characteristics of the three vehicles. A planform area of 14.86 square meters (160 square feet) was used as a basis for construction on the M2-F2/F3 and HL-10 vehicles, whereas a planform area of 17.74 square meters (191 square feet) was used for the X-24A vehicle. Interesting features of these vehicles are the half-cone shape of the M2-F2/F3, the negative camber of the HL-10, and the positive camber of the X-24A.

The vehicles are air-launched from a B-52 airplane at an altitude of 13,700 meters (45,000 feet). Either powerless glide flights or flights consisting of a powered climb followed by a glide phase are made. For powered flights, altitudes up to 24,400 meters (80,000 feet) and speeds in excess of Mach 1.5 can be attained, depending on the flight plan. The primary propulsion system is an XLR11-13 rocket engine which produces 35,600 newtons (8000 pounds) of thrust for approximately 100 seconds. In addition, a landing rocket engine which generates 2200 newtons (500 pounds) of thrust for up to 40 seconds is available, if needed, for the final approach.

The conventional tricycle-type landing gear system is basically the same in all three vehicles. However, the full-castering, dual, co-rotating nose gear is nonsteerable. Also, the landing gear is nonretractable once deployed in flight and is manually stowed on the ground. The main gear is fabricated from Northrop F-5 components and the nose gear is of North American Rockwell T-39 components.

The physical characteristics of the vehicles are described in more detail in references 6 to 8.

INSTRUMENTATION AND DATA REDUCTION

The quantities pertinent to this investigation are true airspeed, peak normal acceleration at the center of gravity, roll angle, and roll velocity. Their ranges, frequency responses, and accuracies are summarized in table 1. A standard NASA pitot-static tube, mounted on a nose boom ahead of each vehicle, was used to measure total and static pressure for the calculation of true airspeed. Normal acceleration was measured by a sensitive accelerometer mounted close to the vehicle's center of gravity. Roll angle and roll velocity were obtained from attitude and rate gyros, respectively. All data were telemetered to a ground station by means of a pulse code modulation data acquisition system.

Calibrations and corrections were applied to the raw data, and the results were recorded in engineering units on a digital magnetic tape at 50 samples per second. The data were then listed at 50 samples per second, except for the M2-F2 flights, for which the sampling rate was 10 samples per second.

The exact touchdown time was determined on all the M2-F2/F3 and X-24A flights by examining the left and right main gear oleo strut displacement data. However, oleo displacements were not recorded on the HL-10 flights; the touchdown time was determined by examining normal acceleration data from a 50-sample-per-second plot.

A surveyor's wheel was used to measure the lateral and longitudinal distance from the intended touchdown point, lateral distance from touchdown to full stop, and rollout distance. However, at the beginning of the program only the rollout distance was measured and an odometer was used for all the M2-F2 flights and for HL-10 flights 3, 4, 5, 7, and 15. The additional measurements began with M2-F3 flight 17, HL-10 flight 16, and X-24A flight 1. (See tables 2 to 4.)

APPROACH AND FLARE PATTERN

The basic approach pattern used for the lifting body vehicles is shown in figure 3 for a left-hand turn beginning at an altitude of 6100 meters (20,000 feet). This pattern is a carryover from the X-15 program (ref. 9). A different pattern, using a 360° approach, was flown on flight 5 of the M2-F2 (table 2) and flights 15, 17, and 18 of the HL-10 (table 3). Positioning was accurately determined from radar tracking during flight by mission control. Heading and altitude corrections were transmitted to the pilot when necessary.

The final landing approach and flare technique is illustrated in figure 4. An indicated airspeed of approximately 300 knots with an approach angle of 18° was maintained. The pilot's normal preflare aim point was the end of the runway. At an altitude of 305 meters (1000 feet) above the ground a 1.5g flare was initiated to bring the vehicle to a shallow glide slope 30.5 meters (100 feet) above the ground with an indicated airspeed of about 230 knots. A more detailed description of the approach is given in reference 10.

A different landing approach pattern was used on HL-10 flights 36 and 37 as indicated in table 3. This technique is described in reference 11. Briefly, the 35,600-newton- (8000-pound-) thrust engine was replaced by three rocket engines, which each produced 2200 newtons (500 pounds) of thrust for 90 seconds during the approach. The approach angle was reduced from 18° to 6°, with an indicated airspeed of 300 knots. At an altitude of 61 meters (200 feet) above the ground, the engines were shut down and the flare was initiated. This type of landing approach resulted in a much higher pilot workload than the steeper approach, and the touchdown aim point was more difficult to determine.

GEAR EXTENSION

All three lifting body vehicles experienced a substantial nose-down pitching motion at landing gear extension (ref. 12). This gear transient caused a large decrease in lift-to-drag ratio, as shown in figure 5, which was adapted from references 7, 8, 13, and 14. The curves are presented for a low-speed, trimmed condition. To retrim the vehicle, the pilot applied aft stick motion at gear extension.

Higher sinking speeds resulted with the gear down; consequently, the pilot preferred to delay gear extension until just prior to touchdown. The landing gear took from 0.5 to 1 second to fully extend and lock. Escort pilots provided gear extension information and altitude cues during this critical phase of the flight.

LANDING CONDITIONS

The 81 landings of the lifting-body vehicles considered in this report (tables 2 to 4) were made on marked strips on the hard surface of Rogers Dry Lake at Edwards Air Force Base, Calif., with the exception of one emergency landing on Rosamond Dry

Lake, an alternate landing site, caused by a rocket engine failure. The landings were made following general research flights of the vehicles; no flights were made specifically to obtain landing contact data.

The lifting body vehicles were flown by eight experimental test pilots (A to H in tables 2 to 4). Pilots A and F were experienced X-15 pilots. The rocket-powered X-15 research airplane was similar to the lifting bodies in lift-to-drag ratio and velocity during the landing phase, and the approach pattern was basically the same as that of the lifting body vehicles. All the pilots performed numerous landings using F-104 operational aircraft configured to simulate the lifting body characteristics. In addition, flight profiles were "flown" on a ground-based simulator using lifting body characteristics.

Starting with flight 16 of the HL-10 and for all of the M2-F3 and X-24A flights, the pilots were instructed to touch down as close as possible to a particular runway marker. Runways were marked with tar strips. The most commonly used aim point was the runway marker shown in figure 6, with a rollout directly on the dashed strip. Rudders and main gear braking were the only means of controlling rollout direction; nosewheel steering was not available.

Most of the landings were made on the same runway; however, special flight paths, lakebed conditions, or crosswind limitations sometimes made it necessary to use alternate runways (tables 2 to 4). On these runways the pilot attempted to touch down at other reference marks or tried to estimate a point 0.4 kilometer (0.25 mile) beyond them and land at that point without a visual touchdown reference. There was no visual touchdown reference for M2-F3 flight 20, HL-10 flights 35 and 37, and X-24A flights 21, 23, 24, and 25. Aim points were optional for checkout flights for new pilots or were disregarded in situations that would affect flight safety. Lateral aim points were normally just to the side of a runway tar strip.

The pilot could use landing rockets if necessary, but no go-around capability was available. Landing rockets were used on flight 5 of the M2-F2 (table 2) and flights 1, 2, 3, and 14 of the X-24A (table 4).

RESULTS AND DISCUSSION

Landing parameters for the M2-F2/F3, HL-10, and X-24A airplanes are presented in tables 2, 3, and 4, respectively. Omissions in the tables result from system failures, instrumentation malfunctions, emergency conditions, or other factors as noted. The data were analyzed statistically to allow extrapolation of the results for more landings than were actually made. Therefore, the results are presented in terms of frequency histograms and probability curves. Pearson Type III probability curves were fitted to the data to provide a systematic fairing and a mathematical basis for extrapolation. The calculation technique is described in the appendix. These probability curves are included in the cumulative frequency distribution plots. Values of the statistical mean, maximum, minimum, and standard deviation and the coefficient of skewness for each parameter are summarized in table 5.

True Airspeed at Touchdown

A histogram of the true airspeed at touchdown is presented in figure 7. Airspeeds ranged from 161 to 229 knots, with a mean of 190 knots. The greatest number of landings (16.7 percent) occurred in the interval between 175 knots and 180 knots. The probability distribution (fig. 8) shows a probability of 0.01 of equaling or exceeding 229 knots.

These results are similar to those obtained for the X-15 (ref. 4). The mean true ground speed for the X-15 was 193 knots, with a probability of 0.01 of equaling or exceeding 234 knots. The X-15 landing weight was much greater than that of the lifting bodies, but it had essentially the same lift-to-drag ratios as the lifting bodies.

Normal Acceleration

A frequency distribution for the peak normal acceleration during ground impact is shown in figure 9. Values ranged from 1.15g to 2.37g. The 2.37g hard landing occurred on flight 20 of the M2-F3, and the sink speed was estimated by the pilot to be greater than he had experienced during other landings in the program. The greatest percentage of landings (20.6) occurred in the interval between 1.3g and 1.4g. The mean was 1.53g. The probability distribution (fig. 10) indicates that the probability that the pilot would equal or exceed 2.23g is 0.01.

Roll Angle

A histogram of absolute roll angle is presented in figure 11. A large percentage (69.7) of roll angles just prior to touchdown occurred within 0.5° with an overall mean of 0.82°. The probability curve in figure 12 shows that for a probability of 0.01 the absolute roll angle would equal or exceed 4.6°.

Roll Velocity

Roll velocity histograms are presented in figures 13(a) and 13(b) in terms of rolling either toward or away from the first wheel to contact. Roll velocities were toward the first wheel to contact in 30 landings and away in 30 landings. The trends were similar, with values ranging from 0 to 10 deg/sec in both cases. Symmetrical touchdowns were made in two landings. Values of roll velocity were not used in the analysis for landings in which the first contact point was not determined.

The highest percentage of roll velocities (33.3) occurred in the range of 0 to 1 deg/sec toward the first wheel to contact. The mean roll velocity was 2.37 deg/sec toward the first wheel to contact and 3.30 deg/sec away from the first wheel to contact. Probability distributions in figures 14(a) and 14(b) indicate a 0.01 probability of equaling or exceeding a roll velocity of 9.4 deg/sec toward the first wheel to contact and 11.0 deg/sec away from the first wheel to contact.

Lateral Distance From Intended Touchdown Point

The histogram shown in figure 15 indicates that in 53.2 percent of the landings the pilot could touch down within a ±3.0-meter (10-foot) lateral band from the intended point. Extreme deviations of 30.5 meters and 63.4 meters (100 feet and 208 feet) which occurred on X-24A flights 4 and 2, respectively (table 4), were due to control problems during the final approach. Therefore, aim points were disregarded for safety reasons, and these points were not considered in the analysis. The mean was 5.0 meters (16.3 feet). Figure 16 indicates a probability of 0.01 that the lateral distance from the intended touchdown point would equal or exceed 21.6 meters (71 feet).

Longitudinal Distance From Intended Touchdown Point

For the pilot to touch down accurately at a particular point depended primarily on energy management in the final approach and, to a lesser degree, surface winds. For example, too much energy (either high profile or high airspeed, or both) resulted in overshooting the touchdown point. However, an earlier gear extension and use of aerodynamic drag devices helped the pilot compensate for a high energy final approach.

Landings ranged from 1766.3 meters (5795 feet) short of the intended point to 1275.6 meters (4185 feet) long. The histogram presented in figure 17 shows that the pilots tended to touch down short, with 40.8 percent of the landings within 304.8 meters (1000 feet) short of the intended touchdown point.

For this parameter a normal frequency distribution curve is superimposed on the histogram to indicate the probability of landing either short or long by some distance. The probability of landing within any two distances, short or long, is given by the area under the curve between those two points. The normal curve was computed by using a mean of 34.1 meters (112 feet) short and a standard deviation of 546.7 meters (1793.6 feet). This function indicates a probability of 0.52 that the actual touchdown point would be short of the intended touchdown point. The normal curve also indicates a probability of 0.01 of landing 1307.9 meters (4291 feet) or more short of the intended touchdown point and a probability of 0.01 of landing 1239.6 meters (4067 feet) or more past the intended touchdown point.

The probability distribution with the Pearson Type III curve fit is presented in figure 18 for the combination of short and long touchdowns about the intended point. The figure indicates a probability of 0.01 that the longitudinal distance from the intended touchdown would equal or exceed 1615 meters (5300 feet).

Lateral Distance From Touchdown to Full Stop

Assessments were made to determine how well the pilot could maintain his initial rollout heading even in a crosswind and with only main gear braking and rudders for steering. The frequency distribution is presented in figure 19. Values ranged from 0 to 92.4 meters (303 feet). The extreme deviation can be attributed to crosswinds of 15 knots. However, the largest deviation occurred on flight 24 of the X-24A (table 4). It was the pilot's second flight, and appropriate braking to offset a strong crosswind was not applied. Consequently, the distance was too great to be of practical use and was not measured. Generally, the grouping was good; 80 percent of the landings deviated less than 9.2 meters (30 feet). The mean deviation was 10.6 meters (34.8 feet). The probability distribution in figure 20 indicates a probability of 0.01 that the deviation would equal or exceed 70.1 meters (230 feet). The data are somewhat distorted because two points well out of the normal grouping were considered in the analysis.

Rollout Distance

The rollout distance varied from 1286.3 meters (4220 feet) with hard braking to a maximum of 3885.0 meters (12,746 feet) with no braking. The longer rollouts were generally on the earlier HL-10 landings. More braking was applied later to keep the rollout distance within a conventional runway length. The rollout distance was greatly influenced by the amount of braking applied and to a lesser degree by aerodynamic drag devices; however, all of the flights are presented in this analysis. The landings were all made on a lakebed, thus longer free-rolling runout distances would be expected on concrete runways; the rolling coefficient of friction for Rogers Dry Lake was tested to be an average of 0.05 for an unbraked tire wheel (ref. 15), compared to approximately 0.02 for dry, concrete runways.

The frequency distribution presented in figure 21 shows that the highest percentage of landings (18.4) occurred in the interval between 2286.0 meters (7500 feet) and 2438.4 meters (8000 feet). The mean rollout distance was 2446.3 meters (8026 feet). The probability curve in figure 22 indicates a probability of 0.01 that the rollout distance would equal or exceed 3780 meters (12,400 feet).

SUMMARY OF RESULTS

In a landing contact investigation of 81 landings of the HL-10, M2-F2/F3, and X-24A lifting body vehicles true airspeeds just prior to touchdown ranged from 161 knots to 229 knots, with a mean of 190 knots. The probability distribution indicated a probability of 0.01 that the true airspeed would equal or exceed 229 knots.

The peak normal acceleration during ground impact had a probability of 0.01 of equaling or exceeding 2.23g. The mean of the normal acceleration was 1.53g.

In 69.7 percent of the landings the absolute roll angle just prior to touchdown was less than 0.5°, and there was a probability of 0.01 of equaling or exceeding 4.6°. The mean roll angle was 0.82°.

There was a probability of 0.01 that the roll velocity would equal or exceed 9.4 deg/sec toward the first wheel to contact or 11.0 deg/sec away from the first wheel to contact. The mean roll velocity was 2.37 deg/sec toward and 3.30 deg/sec away from the first wheel to contact.

Lateral distances from the intended touchdown point were within ±3.0 meters (±10 feet) in 53.2 percent of the landings. The mean was 5.0 meters (16.3 feet), with a probability of 0.01 that the lateral distance would equal or exceed 21.6 meters (71 feet).

The longitudinal distances from the intended touchdown point were less than

304.8 meters (1000 feet) short in 40.8 percent of the landings. The mean distance was 34.1 meters (112 feet) short of the intended touchdown point. The normal frequency distribution curve showed a 52-percent probability of landing short of the intended touchdown point. In addition, it indicated a probability of 0.01 of equaling or exceeding a landing 1307.9 meters (4291 feet) short of the intended touchdown point and 1239.6 meters (4067 feet) or more past the intended touchdown point. The Pearson Type III probability curve showed that a longitudinal touchdown dispersion of 1615 meters (5300 feet) or greater would be likely at a probability level of 0.01.

The lateral distances from touchdown to full stop were within ±9.2 meters (±30 feet) in 80 percent of the landings, with a probability of 0.01 of equaling or exceeding 70.1 meters (230 feet). The absolute mean was 10.6 meters (34.8 feet).

The mean rollout distance over a range of braking conditions was 2446.3 meters (8026 feet), with a probability of 0.01 that the rollout would be 3780 meters (12,400 feet) or greater.

Flight Research Center,
National Aeronautics and Space Administration,
Edwards, Calif., November 21, 1971.

APPENDIX

DETERMINATION OF STATISTICAL PARAMETERS AND PEARSON TYPE III PROBABILITY CURVE

The Pearson Type III probability curve used in fitting the data is described in detail in reference 16. The curve is computed as follows:

First the class interval width is selected and the individual measurements are tabulated according to their corresponding class interval. Next the arithmetic mean, $\overline{X}$, of the data is calculated by using the expression

$$\overline{X} = \frac{\sum_{i=1}^{k} fiXi}{N}$$

where

fi is the frequency of occurrence in a particular class interval

Xi is the midpoint of a particular class interval

k is the number of class intervals

N is the total number of samples, $\sum_{i=1}^{k} fi$

The standard deviation, S, coefficient of skewness, α, and standard statistical unit, t, are then obtained by using the following expressions:

$$S = \sqrt{\frac{\sum_{i=1}^{k} fiXi^2}{N} - \left(\frac{\sum_{i=1}^{k} fiXi}{N}\right)^2}$$

$$\alpha = \frac{\sum_{i=1}^{k} fi(Xi - \overline{X})^3}{NS^3}$$

$$t = \frac{Xi - \overline{X}}{S}$$

Probability charts for the Pearson Type III curve are included in references 17 and 18. The probability values are determined by entering the chart with the calculated value of coefficient of skewness and standard statistical units.

REFERENCES

1. Stickle, Joseph W.: An Investigation of Landing-Contact Conditions for Several Turbojet Transports During Routine Daylight Operations at New York International Airport. NASA TN D-1483, 1962.

2. Hall, Albert W.: A Statistical Study of Normal Load Factor Just Prior to Ground Contact for Five Light Airplanes. NASA TN D-5767, 1970.

3. Wilson, Ronald J.; and Larson, Richard R.: Statistical Analysis of Landing-Contact Conditions for the XB-70 Airplane. NASA TN D-4007, 1967.

4. Wilson, Ronald J.: Statistical Analysis of Landing Contact Conditions of the X-15 Airplane. NASA TN D-3801, 1967.

5. Mechtly, E. A.: The International System of Units - Physical Constants and Conversion Factors. NASA SP-7012, 1969.

6. Pyle, Jon S.; and Montoya, Lawrence C.: Effect of Roughness of Simulated Ablated Material on Low-Speed Performance Characteristics of a Lifting-Body Vehicle. NASA TM X-1810, 1969.

7. Pyle, Jon S.; and Swanson, Robert H.: Lift and Drag Characteristics of the M2-F2 Lifting Body During Subsonic Gliding Flight. NASA TM X-1431, 1967.

8. Pyle, Jon S.: Lift and Drag Characteristics of the HL-10 Lifting Body During Subsonic Gliding Flight. NASA TN D-6263, 1971.

9. Matranga, Gene J.: Analysis of X-15 Landing Approach and Flare Characteristics Determined From the First 30 Flights. NASA TN D-1057, 1961.

10. Dana, William H.; and Gentry, J. R.: Pilot Impressions of Lifting Body Vehicles. Flight Test Results Pertaining to the Space Shuttlecraft, NASA TM X-2101, 1970, pp. 73-88.

11. Kock, Berwin M.; and Fulton, Fitzhugh L., Jr.: Approach and Landing Studies. Flight Test Results Pertaining to the Space Shuttlecraft, NASA TM X-2101, 1970, pp. 99-108.

12. Manke, John A.; Retelle, John P.; and Kempel, Robert W.: Assessment of Lifting Body Vehicle Handling Qualities. Flight Test Results Pertaining to the Space Shuttlecraft, NASA TM X-2101, 1970, pp. 29-41.

13. Gamse, Berl; and Mort, Kenneth W.: Full-Scale Wind-Tunnel Investigation of the HL-10 Manned Lifting Body Flight Vehicle. NASA TM X-1476, 1967.

14. Pyle, Jon S.; and Ash, Lawrence G.: Performance Characteristics of the Lifting Body Vehicles. Flight Test Results Pertaining to the Space Shuttlecraft, NASA TM X-2101, 1970, pp. 43-58.

15. McKay, James M.; and Scott, Betty J.: Landing-Gear Behavior During Touchdown and Runout for 17 Landings of the X-15 Research Airplane. NASA TM X-518, 1961.

16. Elderton, W. Palin: Frequency-Curves and Correlation. 3rd ed., Cambridge University Press, 1938.

17. Peiser, A. M.; and Wilkerson, M.: A Method of Analysis of V-G Records From Transport Operations. NACA Rept. 807, 1945.

18. Locke, F. W. S., Jr.: A Statistical Study of the Maximum Vertical Accelerations Encountered by Flying Boats in Rough Water Landings. Rept. no. DR-1184, BuAer, Dept. of the Navy, June 1950.

TABLE 1.– INSTRUMENTATION ACCURACIES AND RANGES

Parameter	Range	Frequency response, Hz	Accuracy, percent of full range
True airspeed	0 to 437 knots	10	±0.25
Normal acceleration	-1g to 3g	10	±1.00
Roll angle	±200 deg/sec	10	±1.00
Roll velocity	±90°	40	±.10

TABLE 2.– LANDING CONDITIONS FOR THE M2-F2/F3 VEHICLE

Flight (a)	Pilot	Landing weight, kg (lb)	Wind conditions		Runway magnetic heading, deg	True airspeed at touchdown, knots	Peak normal acceleration, g	Roll angle, deg	Roll velocity, deg/sec (d)	Distance from intended touchdown, m (ft)		Lateral distance from touchdown to full stop, m (ft)	Rollout distance, m (ft) (e)
			Velocity, knots	Direction						Lateral	Longitudinal		
[b]1	A	2667 (5880)	Calm[c]	--	180	176	1.81	-----	----- --	--- --------	------ ------	---- -------	2407.9 (7900)
2	A	2699 (5950)	7	SW	180	161	1.92	-0.41	-2.22 (T)	--- --------	------ ------	---- -------	1448.4 (4752)
3	A	2699 (5950)	15	SW	180	164	1.33	2.40	-8.46 (A)	--- --------	------ ------	---- -------	1706.9 (5600)
4	A	2699 (5950)	6	SW	180	187	1.31	-.05	-1.18 (T)	--- --------	------ ------	---- -------	------ -----
[f,g]5	A	2690 (5930)	Calm	--	180	174	1.36	.36	-4.51 (A)	--- --------	------ ------	---- -------	------ -----
[b]6	B	2699 (5950)	Calm	--	180	212	1.57	-1.70	1.11 (A)	--- --------	------ ------	---- -------	------ -----
[b]7	C	2699 (5950)	Calm	SW	180	180	1.26	-.17	.90 --	--- --------	------ ------	---- -------	2895.6 (9500)
8	B	2699 (5950)	Calm	NE	180	175	1.66	-.58	-2.63 --	--- --------	------ ------	---- -------	2094.0 (6870)
9	C	2699 (5950)	6	E	180	178	1.38	.18	-3.26 (A)	--- --------	------ ------	---- -------	2414.0 (7920)
10	C	2699 (5950)	3	NE	180	182	1.52	.24	-3.05 --	--- --------	------ ------	---- -------	2496.3 (8190)
[b]11	D	2699 (5950)	12	SW	180	201	2.20	-.35	.90 --	--- --------	------ ------	---- -------	2414.0 (7920) (l)
12	D	2699 (5950)	Calm	--	180	174	1.59	.12	-.97 --	--- --------	------ ------	---- -------	------ -----
13	D	2699 (5950)	3	SW	180	191	1.33	3.60	-3.88 (A)	--- --------	------ ------	---- -------	2895.6 (9500)
14	D	2699 (5950)	20	SW	180	184	1.42	.30	-.55 (A)	--- --------	------ ------	---- -------	1286.3 (4220) (e)
15	D	2789 (6149)	10	SW	180	178	1.96	1.34	----- --	--- --------	------ ------	---- -------	2459.7 (8070)
[b,h]17	F	2921 (6440)	Calm	--	180	193	1.61	0	.14 (T)	1.5 (5) (right)	-90.5 (-297)	0.9 (3) (left)	2258.6 (7410) (m)
18	F	2994 (6600)	12	SW	180	184	1.54	0	-1.33 (A)	0 (0)	149.4 (490)	7.3 (24) (left)	2165.0 (7103) (m)
19	F	3092 (6817)	Calm	--	180	186	1.49	0	4.83 (A)	.6 (2) (right)	173.7 (570)	.6 (2) (left)	2608.2 (8557) (n)
20	F	3025 (6670)	15	SW	230	175	2.37	0	-3.33 (A)	.3 (1) (right)	-965.6 (-3168)	.3 (1) (left)	2311.3 (7583)
21	D	3070 (6770)	Calm	--	180	180	1.90	-2.44	-1.17 (T)	3.4 (11) (left)	-698.0 (-2290)	5.5 (18) (left)	2579.5 (8463) (l)
22	F	3051 (6726)	10	NE	180	177	1.83	.09	-6.34 (A)	0 (0)	225.9 (741)	28.3 (93) (right)	2456.1 (8058)

[a] Flight 16 omitted because of a gear-up crash landing.
[b] Pilot checkout flight.
[c] "Calm" denotes variable from 0 to 3 knots.
[d] (A) and (T) denote away from and toward first wheel to contact, respectively.
[e] (n), (l), (m), and (e) denote no braking, light, moderate, and emergency braking, respectively.
[f] Landing rockets used.
[g] 360° landing approach.
[h] M2-F2 redesignated M2-F3 following center fin installation.

TABLE 3.– LANDING CONDITIONS FOR THE HL-10 VEHICLE

Flight (a)	Pilot	Landing weight, kg (lb)	Wind conditions		Runway magnetic heading, deg	True airspeed at touchdown, knots	Peak normal acceleration, g	Roll angle, deg	Roll velocity, deg/sec (d)	Distance from intended touchdown, m (ft)		Lateral distance from touchdown to full stop, m (ft)	Rollout distance, m (ft) (e)
			Velocity, knots	Direction						Lateral	Longitudinal		
[b]3	B	2744 (6050)	Calm[c]	--	180	---	----	-----	----- --	---- --------	------- ------	---- --------	3627.1 (11,900)
4	D	2889 (6369)	Calm	--	180	---	----	-----	----- --	---- --------	------- ------	---- --------	2849.9 (9,350)
5	D	2879 (6347)	Calm	--	180	---	----	-----	----- --	---- --------	------- ------	---- --------	3383.3 (11,100)
6	D	2877 (6342)	Calm	--	180	---	----	-----	----- --	---- --------	------- ------	---- --------	2318.9 (7,608)
[b]7	E	2886 (6362)	Calm	--	180	---	----	-----	----- --	---- --------	------- ------	---- --------	2895.6 (9,500)
8	E	2886 (6362)	Calm	--	180	210	1.94	0	1.45 (T)	---- --------	------- ------	---- --------	3142.2 (10,309)
9	D	2891 (6374)	Calm	--	180	---	----	-----	----- --	---- --------	------- ------	---- --------	3389.4 (11,120)
10	D	2920 (6437)	Calm	--	180	191	1.53	-----	-1.6 (T)	---- --------	------- ------	---- --------	2507.6 (8,227)
11	E	2924 (6447)	Calm	--	180	---	----	-----	----- --	---- --------	------- ------	---- --------	2981.6 (9,782)
[f]12	D	2937 (6474)	Calm	--	190	---	----	-----	----- --	---- --------	------- ------	---- --------	2862.7 (9,392)
13	E	2976 (6560)	Calm	--	180	214	1.36	0	1.85 (T)	---- --------	------- ------	---- --------	3387.5 (11,114) (n)
14	D	2939 (6480)	Calm	--	180	204	1.62	-1.49	-.27 (T)	---- --------	------- ------	---- --------	3885.0 (12,746) (n)
[g]15	E	2915 (6427)	Calm	--	180	226	1.66	2.43	2.07 (T)	---- --------	------- ------	---- --------	2895.6 (9,500)
[b]16	F	2945 (6492)	4	S	180	216	1.67	.68	-2.62 (A)	0 (0)	-900.1 (-2953)	4.6 (15) (left)	2621.9 (8,602)
[g]17	E	2917 (6430)	Calm	S	180	229	1.94	0	1.29 (A)	5.5 (18) (right)	-337.7 (-1108)	5.5 (18) (left)	3116.6 (10,225) (n)
[g]18	F	2917 (6430)	5	S	180	220	1.97	0	-5.74 (T)	6.4 (21) (right)	-149.7 (-491)	3.0 (10) (left)	2596.3 (8,518) (m)
19	E	2917 (6431)	4	E	180	194	1.62	-.38	.51 (A)	11.3 (37) (right)	-265.5 (-871)	6.4 (21) (left)	2203.4 (7,229) (h)
[b]20	G	2950 (6504)	6	W	180	199	1.20	-----	----- --	7.9 (26) (left)	-116.1 (-381)	12.5 (41) (left)	3026.1 (9,928) (l)
21	E	2911 (6417)	3	S	180	188	1.74	0	-2.10 (T)	22.9 (75) (right)	-133.5 (-438)	25.6 (84) (left)	2796.5 (9,175) (l)
22	F	2945 (6492)	10	SW	180	195	1.40	0	-2.49 (A)	6.1 (20) (right)	-333.8 (-1095)	6.1 (20) (left)	2296.7 (7,535)
23	E	2933 (6466)	4	SE	180	206	1.80	0	1.55 (S)	7.0 (23) (right)	-400.5 (-1314)	2.1 (7) (right)	3135.2 (10,286) (n)
24	F	2909 (6415)	15	SW	180	190	1.32	-----	-2.49 (T)	1.2 (4) (left)	-423.4 (-1389)	1.2 (4) (right)	2197.6 (7,210) (h)
25	E	3126 (6891)	Calm	--	180	199	1.59	0	-.27 (S)	2.4 (8) (left)	260.6 (855)	2.4 (8) (left)	2299.7 (7,545) (h)
26	G	3053 (6730)	15	W	180	206	1.15	-----	.90 (T)	11.0 (36) (left)	-117.3 (-385)	2.1 (7) (left)	2581.7 (8,470) (l)
27	F	2933 (6466)	Calm	--	180	185	1.18	0	-.44 (T)	.9 (3) (left)	-62.2 (-204)	0.9 (3) (right)	2392.1 (7,848) (l)
28	G	2933 (6466)	Calm	--	180	187	1.43	0	.93 (A)	2.7 (9) (left)	-143.3 (-470)	2.7 (9) (right)	2042.2 (6,700) (h)
29	F	2933 (6466)	10	NE	180	192	1.41	0	1.48 (A)	0 (0)	-66.4 (-218)	0 (0)	2616.7 (8,585) (l)
30	G	2933 (6466)	Calm	--	180	198	1.38	-3.03	1.67 (A)	0 (0)	-508.4 (-1668)	.3 (1) (left)	1850.7 (6,072) (h)
31	F	2933 (6466)	Calm	--	180	187	1.57	-1.11	2.80 --	0 (0)	-45.4 (-149)	0 (0)	2175.7 (7,138) (l)
32	G	2933 (6466)	Calm	--	180	193	1.34	1.49	.60 (T)	20.4 (67) (right)	-235.6 (-773)	1.8 (6) (left)	1700.8 (5,580) (h)
33	F	2933 (6466)	12	W	180	200	1.53	0	-.15 --	0 (0)	-125.3 (-411)	0 (0)	2376.8 (7,798) (l)
34	G	2933 (6466)	10	NE	180	199	1.55	.37	5.0 (T)	4.6 (15) (right)	-178.3 (-585)	7.6 (25) (left)	2011.7 (6,600) (m)
35	F	2933 (6466)	25	SW	230	201	1.45	.31	.6 (T)	0 (0)	-1766.3 (-5795)	.9 (3) (left)	1932.4 (6,340) (m)
[h]36	G	3001 (6616)	3	E	170	207	1.29	-----	-3.82 --	---- --------	------- ------	---- --------	------ ----------
[h]37	G	3400 (7496)	Calm	--	350	193	1.46	-----	-1.47 (A)	.9 (3) (left)	737.3 (2419)	0 (0)	2050.4 (6,727)

[a]Flights 1 and 2 omitted because they were B-52/HL-10 compatibility flights; HL-10 was not launched.
[b]Pilot checkout flight.
[c]"Calm" denotes variable from 0 to 3 knots.
[d](A) and (T) denote away from and toward first wheel to contact, respectively; (S) denotes symmetrical.
[e](n), (l), (m), and (h) denote no braking, light, moderate, and heavy braking, respectively.
[f]Emergency landing at Rosamond Dry Lake.
[g]360° landing approach.
[h]Straight-in powered approach.

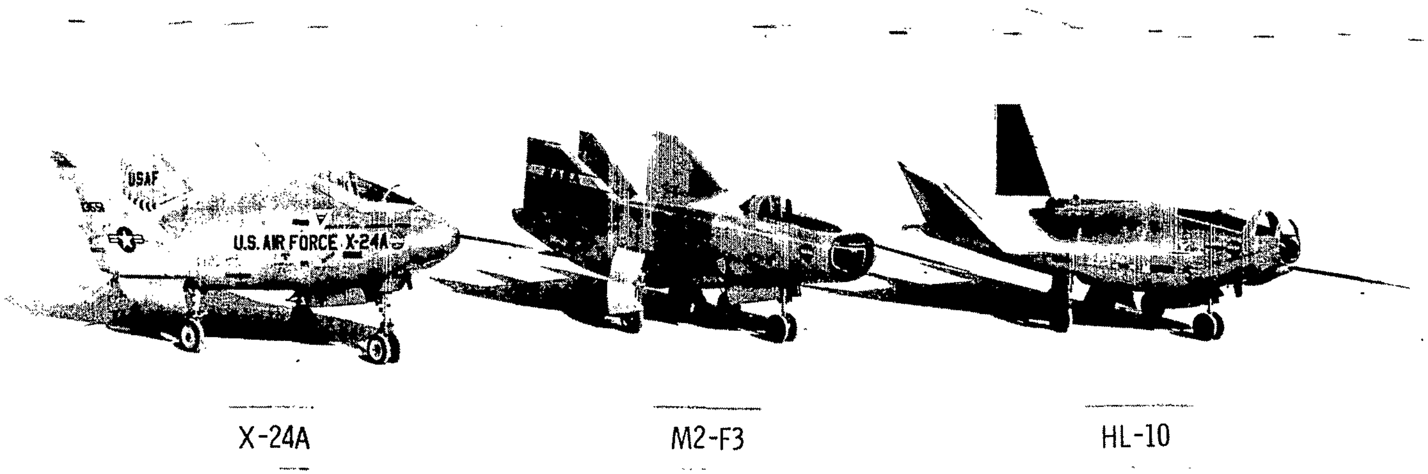
TABLE 4.- LANDING CONDITIONS FOR THE X-24A VEHICLE

Flight	Pilot	Landing weight, kg (lb)	Wind conditions		Runway magnetic heading, deg	True airspeed at touchdown, knots	Peak normal acceleration, g	Roll angle, deg	Roll velocity, deg/sec (c)	Distance from intended touchdown, m (ft)		Lateral distance from touchdown to full stop, m (ft)	Rollout distance, m (ft) (d)
			Velocity, knots	Direction						Lateral	Longitudinal		
[a]1	D	2880 (6350)	Calm[b]	--	180	190	1.65	0.4	-3.08 (A)	---- --------	------ ------	---- --------	2414.0 (7,920)
[a,e]2	D	2880 (6350)	Calm	NE	180	180	1.63	0	-1.93 (T)	63.4 (208) (left)	-96.6 (-317)	21.3 (70) (right)	2201.3 (7,222)
[a]3	D	2885 (6360)	Calm	--	170	176	1.53	0	1.20 (A)	---- --------	------ ------	24.4 (80) (right)	2295.1 (7,530)
[e]4	D	2917 (6430)	Calm	--	180	171	1.32	-1.57	-.29 (T)	30.5 (100) (right)	-627.0 (-2057)	71.9 (236) (right)	3041.9 (9,980) (n)
5	D	2853 (6290)	Calm	--	180	165	1.33	0	.08 (A)	9.1 (30) (left)	-21.3 (-70)	2.4 (8) (left)	1966.0 (6,450) (l)
6	E	2853 (6290)	Calm	--	180	176	1.52	0	1.52 (T)	.3 (1) (left)	-231.0 (-758)	2.7 (9) (right)	2292.1 (7,520) (l)
7	D	2853 (6290)	Calm	--	180	170	1.44	0	-.08 (T)	1.2 (4) (right)	813.2 (2668)	4.0 (13) (left)	1786.1 (5,860) (m)
8	D	2853 (6290)	Calm	--	180	168	1.19	0	-1.04 (A)	11.6 (38) (left)	1275.6 (4185)	39.0 (128) (right)	1998.3 (6,556) (l)
9	D	2926 (6450)	Calm	--	180	178	1.32	0	3.21 (T)	1.8 (6) (left)	60.7 (199)	1.2 (4) (left)	1760.0 (5,774) (m)
10	D	2921 (6440)	15	NE	180	176	1.41	0	6.49 (A)	6.1 (20) (right)	1152.1 (3780)	11.0 (36) (left)	1959.2 (6,428)
11	E	2858 (6300)	Calm	--	180	208	1.47	0	2.38 (A)	11.3 (37) (right)	116.4 (382)	6.7 (22) (left)	2856.3 (9,371) (l)
12	D	2821 (6220)	Calm	--	180	183	1.34	-.77	.17 (A)	11.3 (37) (left)	-60.0 (-197)	.9 (3) (right)	1869.9 (6,135) (m)
13	E	2935 (6470)	Calm	--	180	199	1.29	3.85	-5.48 (A)	2.4 (8) (right)	335.3 (1100)	.6 (2) (right)	2314.3 (7,593) (m)
[a]14	E	2957 (6520)	4	S	180	187	1.20	-1.66	10.00 (A)	.3 (1) (right)	-195.1 (-640)	3.4 (11) (left)	3334.5 (10,940)
15	D	3220 (7100)	6	S	180	177	1.34	-.41	-4.52 (T)	8.5 (28) (left)	-91.7 (-301)	3.7 (12) (left)	1807.5 (5,930) (m)
16	E	2914 (6425)	Calm	--	180	202	1.54	0	4.03 (T)	5.8 (19) (right)	547.4 (1796)	5.8 (19) (left)	2880.7 (9,451) (n)
17	D	2896 (6385)	Calm	--	180	173	1.25	-.38	-4.10 (T)	4.6 (15) (left)	859.2 (2819)	2.4 (8) (left)	2145.2 (7,038)
18	E	2894 (6380)	Calm	--	180	186	1.59	-.41	7.97 (A)	4.3 (14) (right)	879.3 (2885)	6.1 (20) (left)	2240.6 (7,351)
[f]19	E	2894 (6380)	15	NE	180	180	1.56	-1.15	-5.76 (T)	10.7 (35) (right)	321.0 (1053)	92.4 (303) (right)	2366.8 (7,765)
20	D	2846 (6275)	Calm	--	180	175	1.28	0	-.70 (T)	3.7 (12) (left)	1177.4 (3863)	5.5 (18) (right)	1899.2 (6,231)
21	E	2880 (6350)	Calm	--	330	197	1.27	3.33	.25 (T)	0 (0)	117.3 (385)	4.3 (14) (right)	1891.6 (6,206) (m)
[g]22	H	2874 (6336)	Calm	--	150	192	1.67	-.38	-9.96 (T)	---- --------	------ ------	11.3 (37) (right)	1785.5 (5,858)
23	E	2978 (6566)	10	W	330	189	1.69	-2.69	2.37 (A)	0 (0)	-339.8 (-1115)	8.2 (27) (left)	1938.2 (6,359)
24	H	2840 (6261)	10	W	330	202	1.48	0	-2.14 (T)	0 (0)	192.9 (633)	(h)	2655.1 (8,711)
25	E	2985 (6580)	Calm	--	330	200	1.38	5.0	-6.25 (A)	0 (0)	-50.9 (-167)	3.0 (10) (left)	2617.0 (8,586) (l)

[a]Landing rockets used.
[b]"Calm" denotes variable from 0 to 3 knots.
[c](A) and (T) denote away from and toward first wheel to contact, respectively.
[d](n), (l), and (m) denote no braking, light, and moderate braking, respectively.
[e]Control problem during final approach.
[f]Highest crosswind in which pilot would desire to land.
[g]Pilot checkout flight.
[h]Extreme deviation not measured (p. 6).

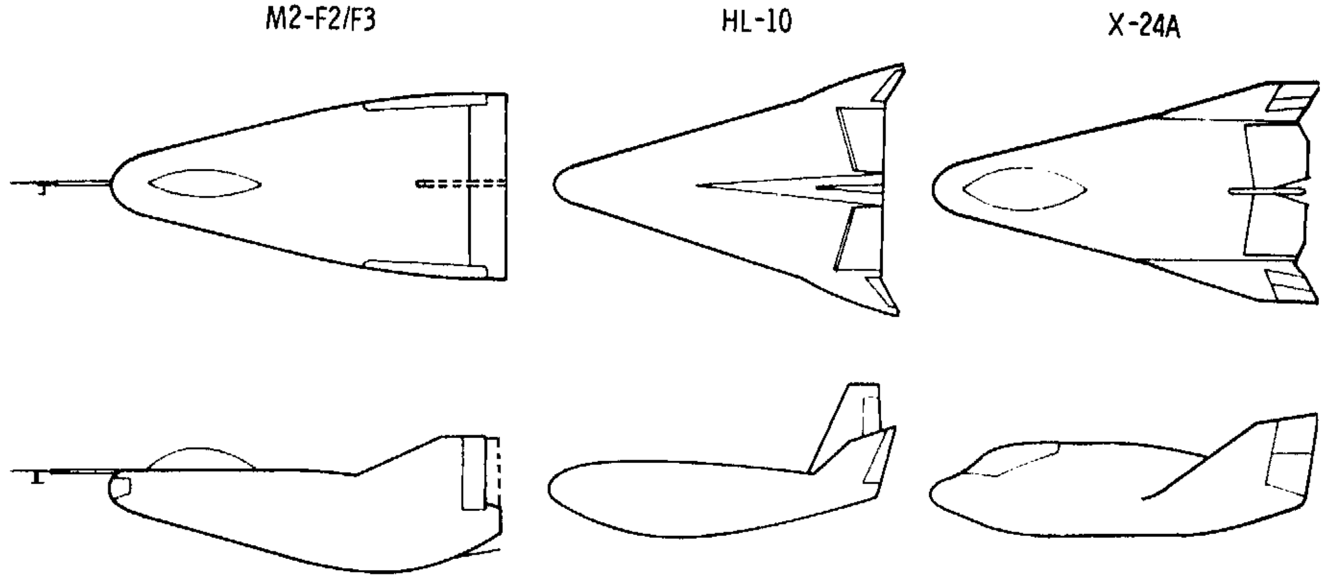
TABLE 5.– VALUES OF STATISTICAL QUANTITIES FOR THE THREE LIFTING BODY VEHICLES

Parameter	Mean	Maximum	Minimum	Standard deviation	Coefficient of skewness
True airspeed	190 knots	229 knots	161 knots	14.57 knots	0.446
Normal acceleration	1.53g	2.37g	1.15g	0.245g	1.034
Absolute roll angle	0.82°	5.00°	0°	1.080°	2.126
Roll velocity toward first wheel to contact	2.37 deg/sec	9.96 deg/sec	0.08 deg/sec	2.125 deg/sec	1.446
Roll velocity away from first wheel to contact	3.30 deg/sec	10.00 deg/sec	0.08 deg/sec	2.600 deg/sec	1.028
Absolute lateral distance from intended touchdown	5.0 m (16.3 ft)	22.9 m (75 ft)	0	4.8 m (15.9 ft)	1.749
Longitudinal distance from intended touchdown	34.1 m (112 ft)	1275.6 m (4185 ft) long	1766.3 m (5795 ft) short	546.7 m (1793.6 ft)	0.088
Absolute lateral distance from touch-down to full stop	10.6 m (34.8 ft)	92.4 m (303 ft)	0	16.7 m (54.9 ft)	3.648
Rollout distance	2446.3 m (8026 ft)	3885.0 m (12,746 ft)	1286.3 m (4220 ft)	514.7 m (1688.6 ft)	0.380



E-21093

Figure 1. Lifting body research vehicles.



Body planform area, m^2 (ft^2)	14.86 (160)	14.86 (160)	17.74 (191)
Body span, m (ft)	2.9 (9.5)	4.42 (14.5)	4.11 (13.5)
Body length, m (ft)	6.70 (22)	6.70 (22)	7.47 (24.5)
Landing weight, kg (lb)	2790 (6150)/3039 (6700)	2903 (6400)	2722 (6000)
Landing wing loading, kg/m^2 (lb/ft^2)	188 (38)/205 (42)	195 (40)	153 (31)

Figure 2. Physical characteristics of the lifting body vehicles.

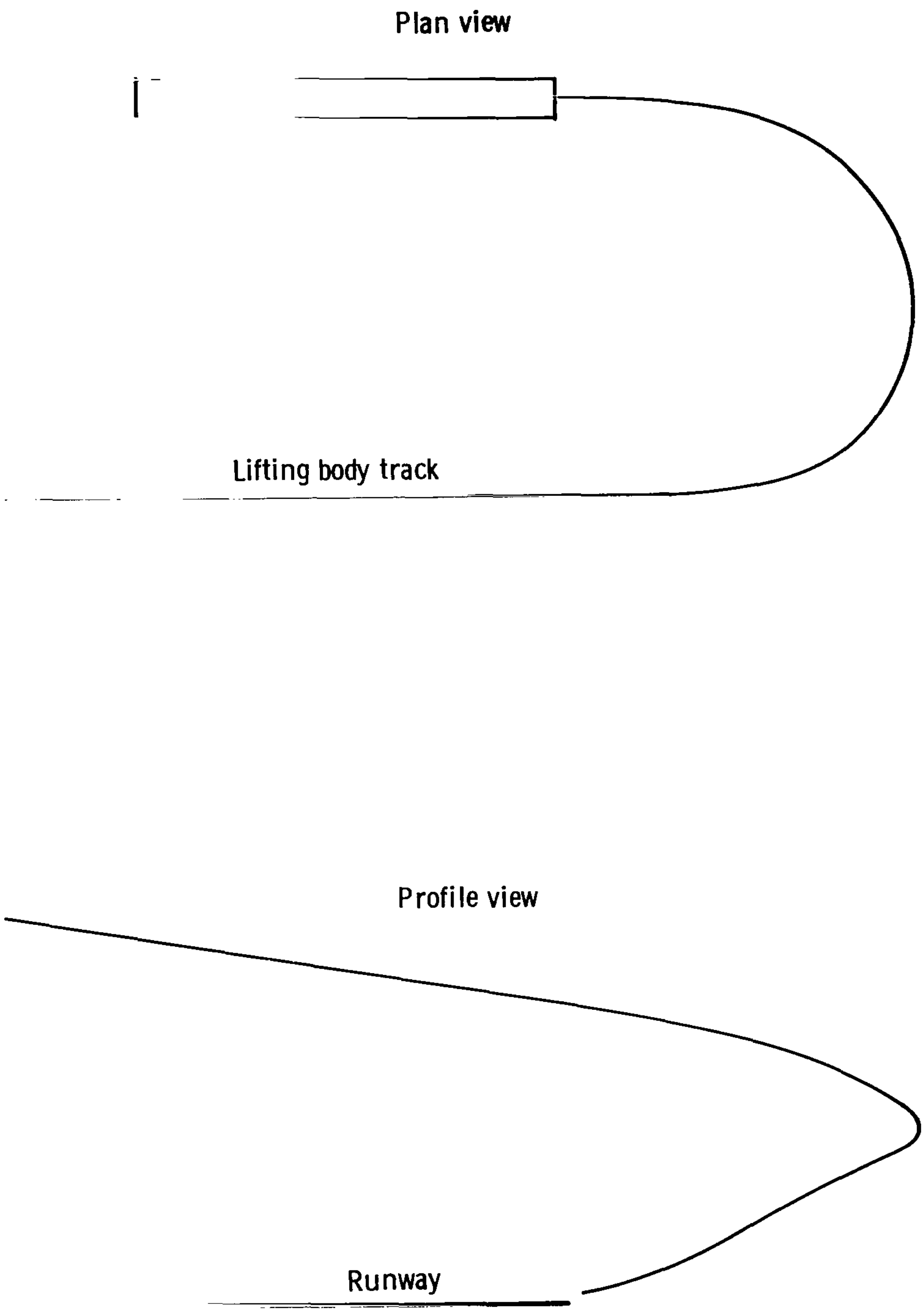


Figure 3. Typical lifting body approach pattern.

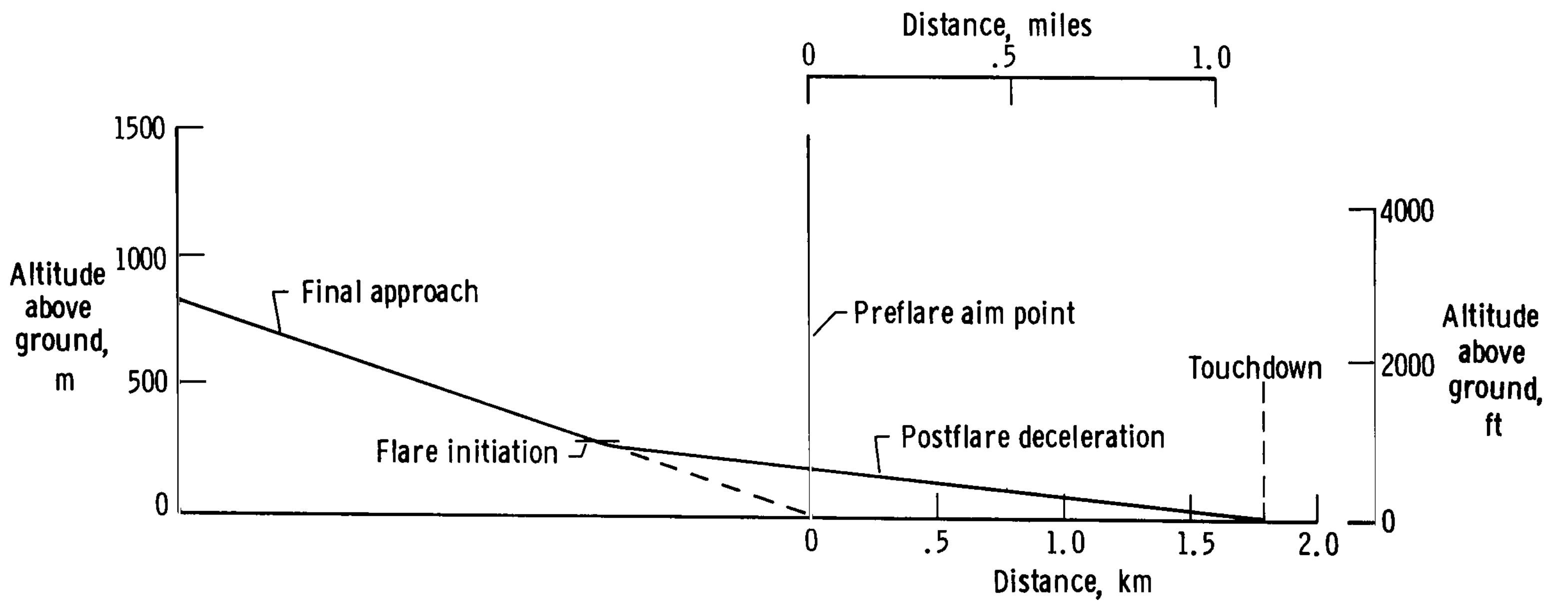


Figure 4. Unpowered landing approach and flare technique.

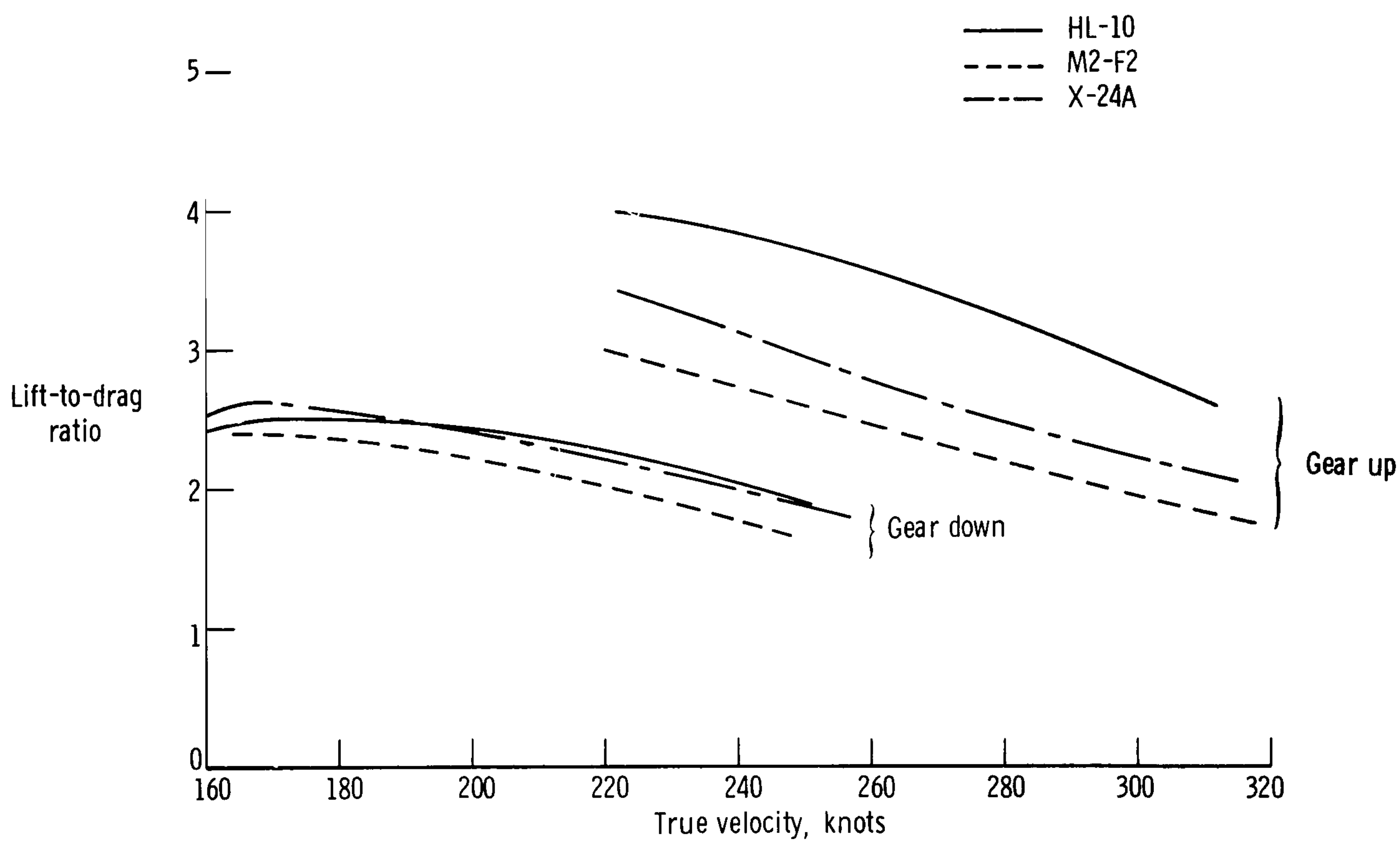
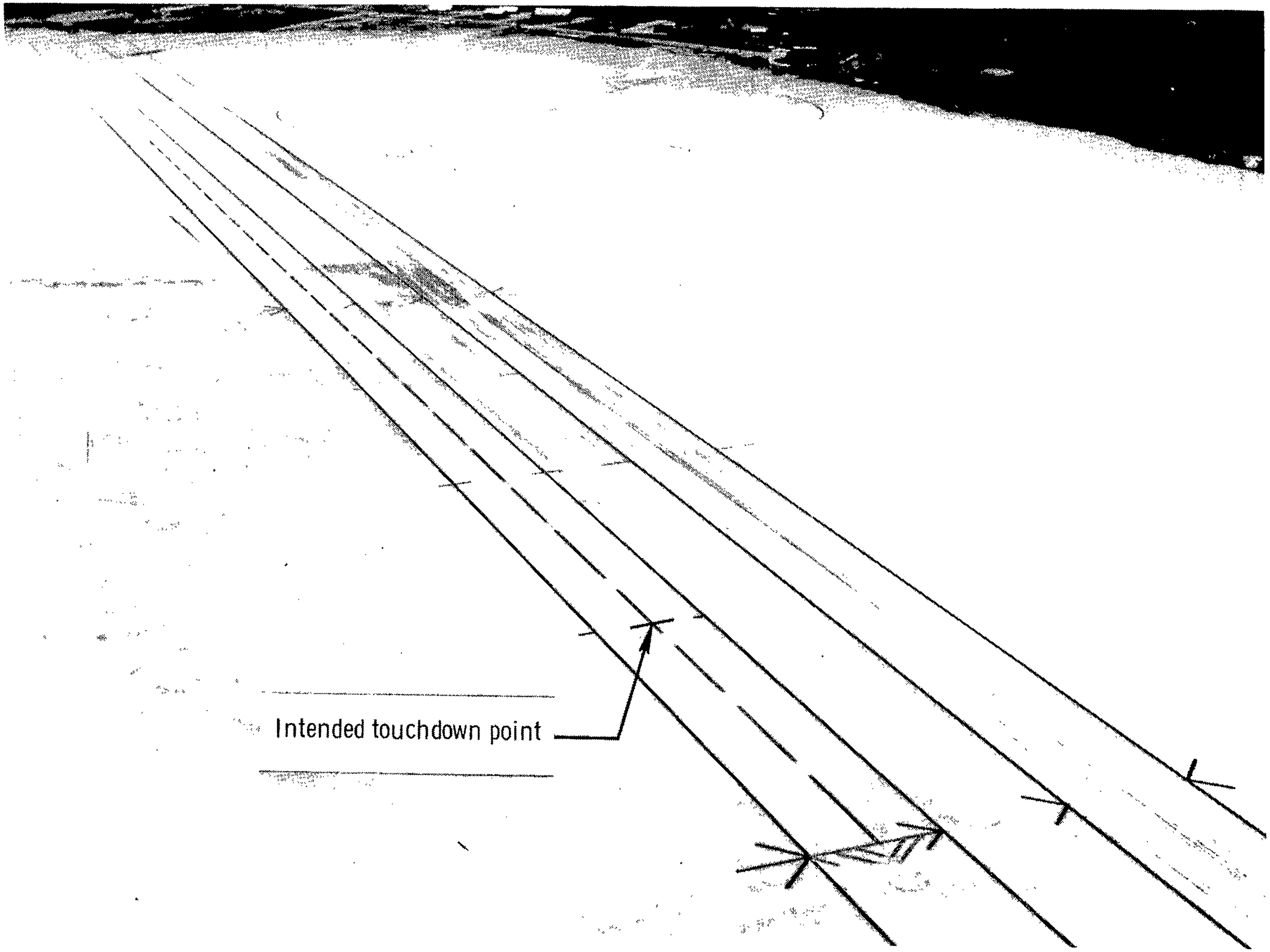


Figure 5. Variation of lift-to-drag ratio for clean and landing configurations of the lifting body vehicles (adapted from refs. 7, 8, 13, and 14).



E-20651

Figure 6. Lifting body runway.

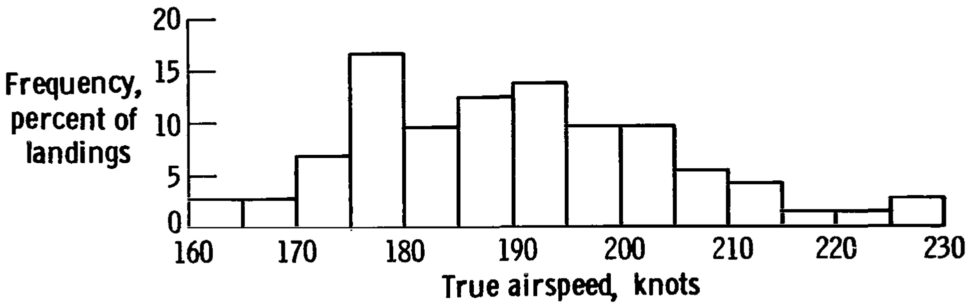


Figure 7. Histogram of true airspeed at touchdown.

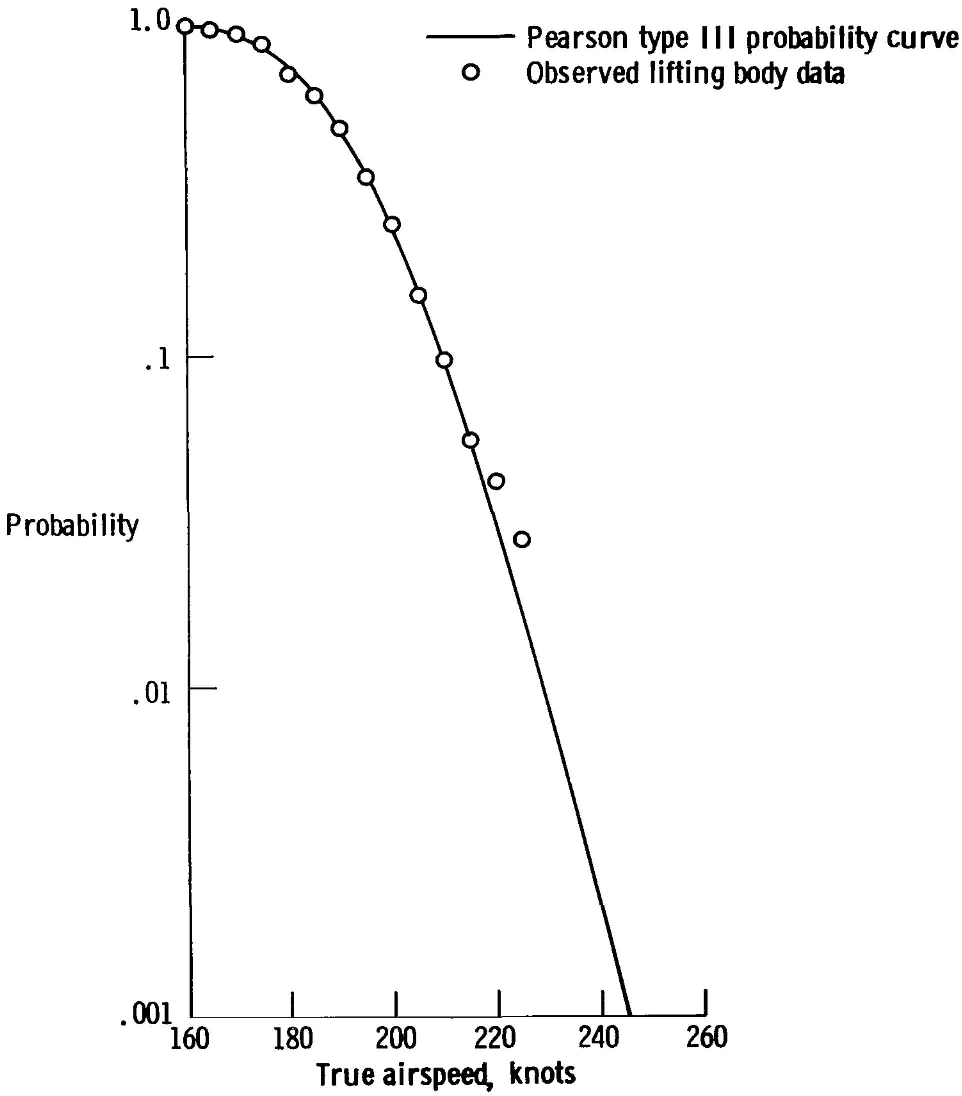


Figure 8. Probability of equaling or exceeding values of true airspeed at touchdown.

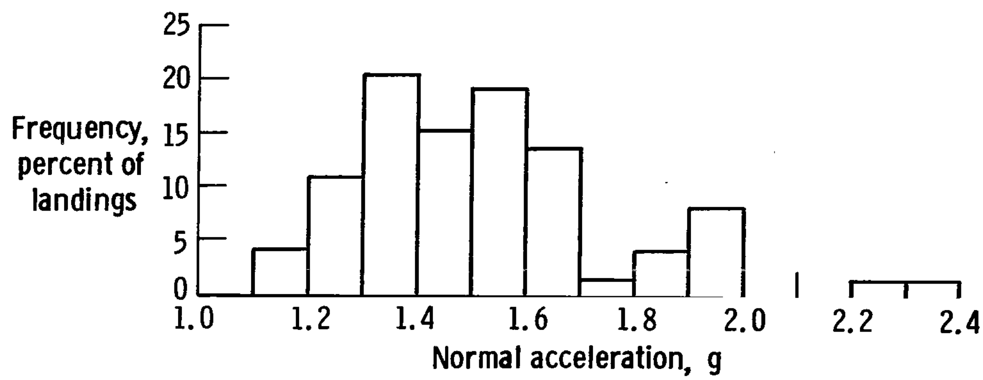


Figure 9. Histogram of peak normal acceleration during ground impact.

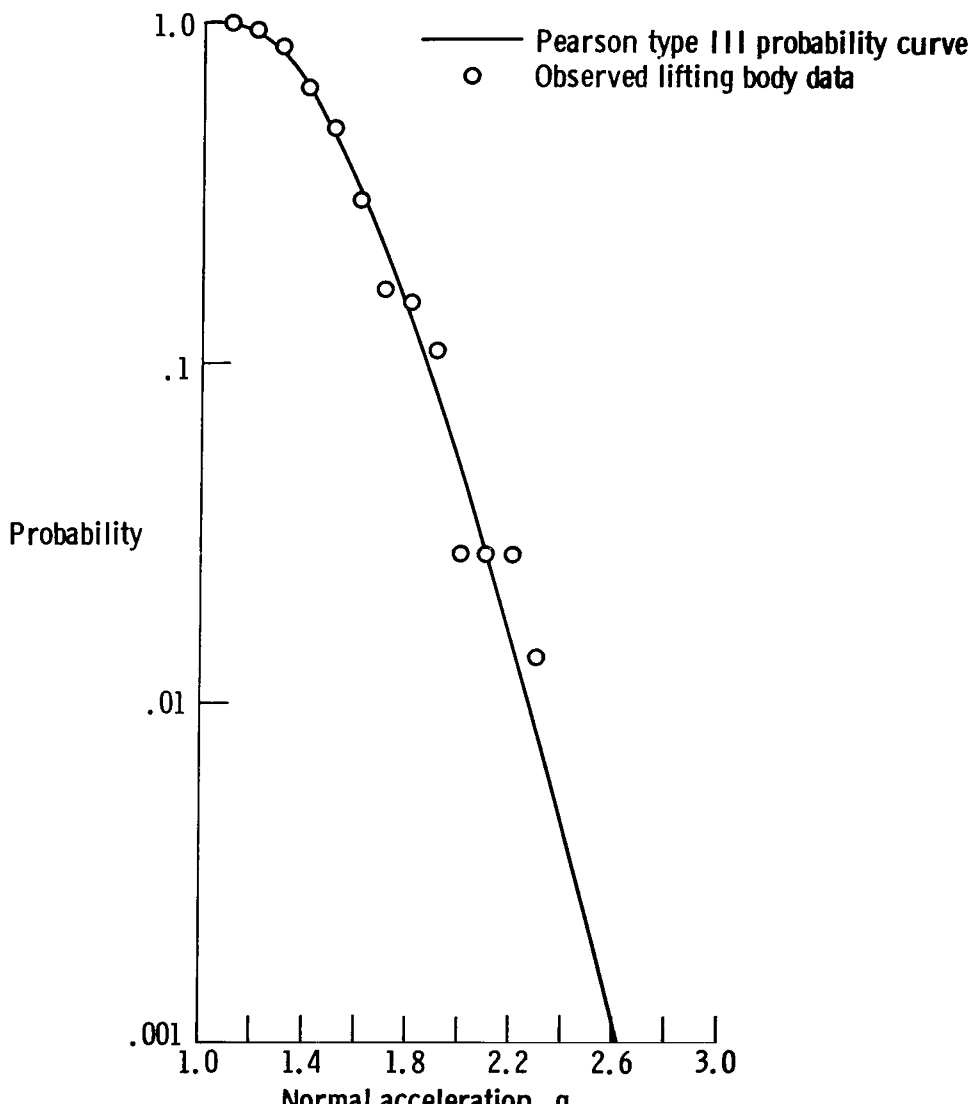


Figure 10. Probability of equaling or exceeding values of peak normal acceleration during ground impact.

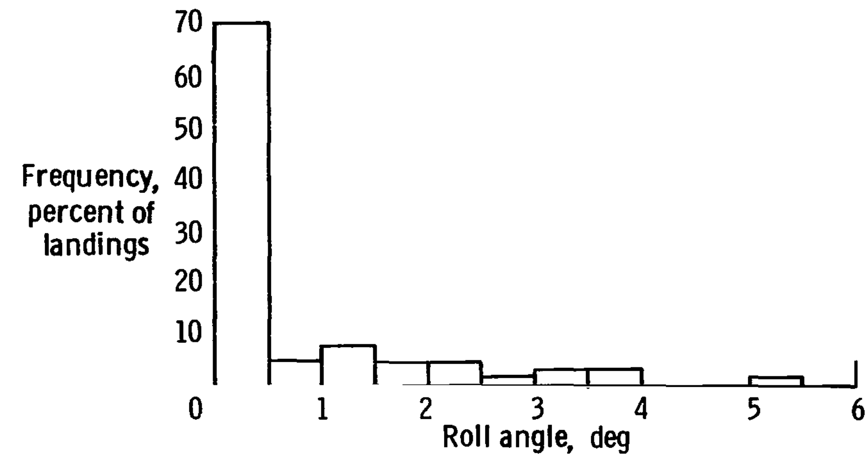


Figure 11. Histogram of absolute roll angle at touchdown.

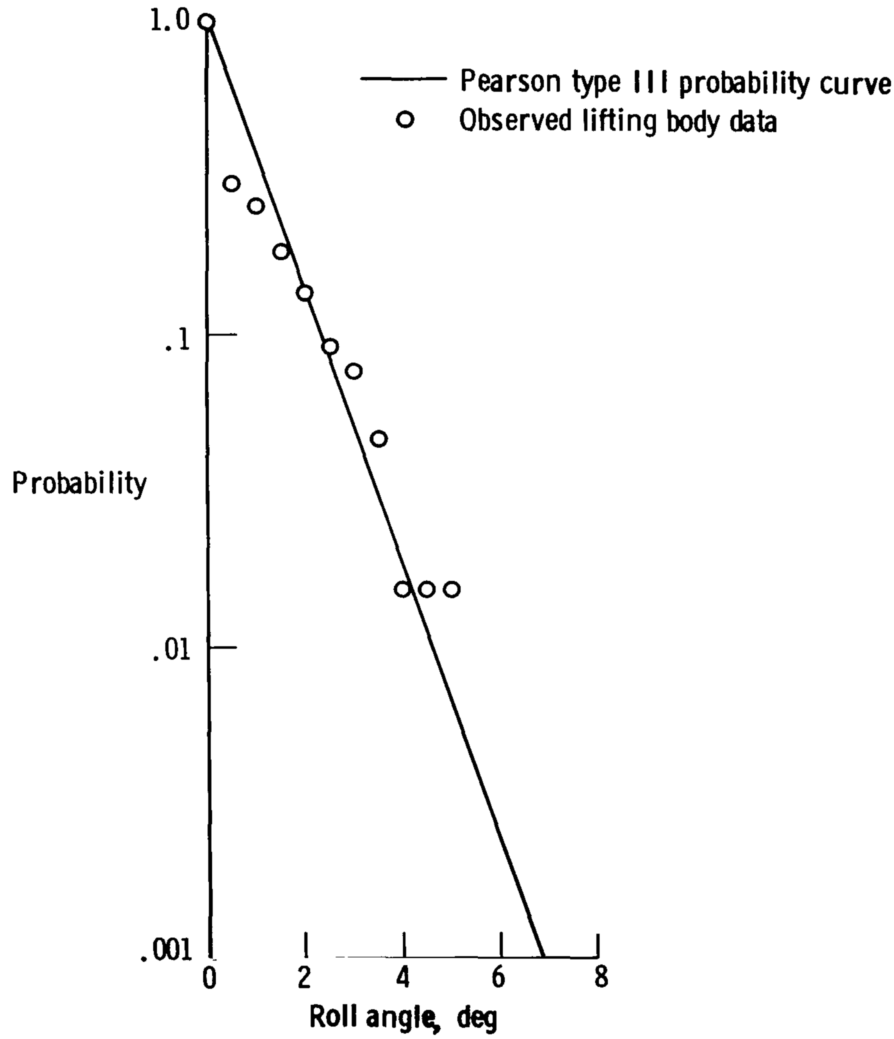
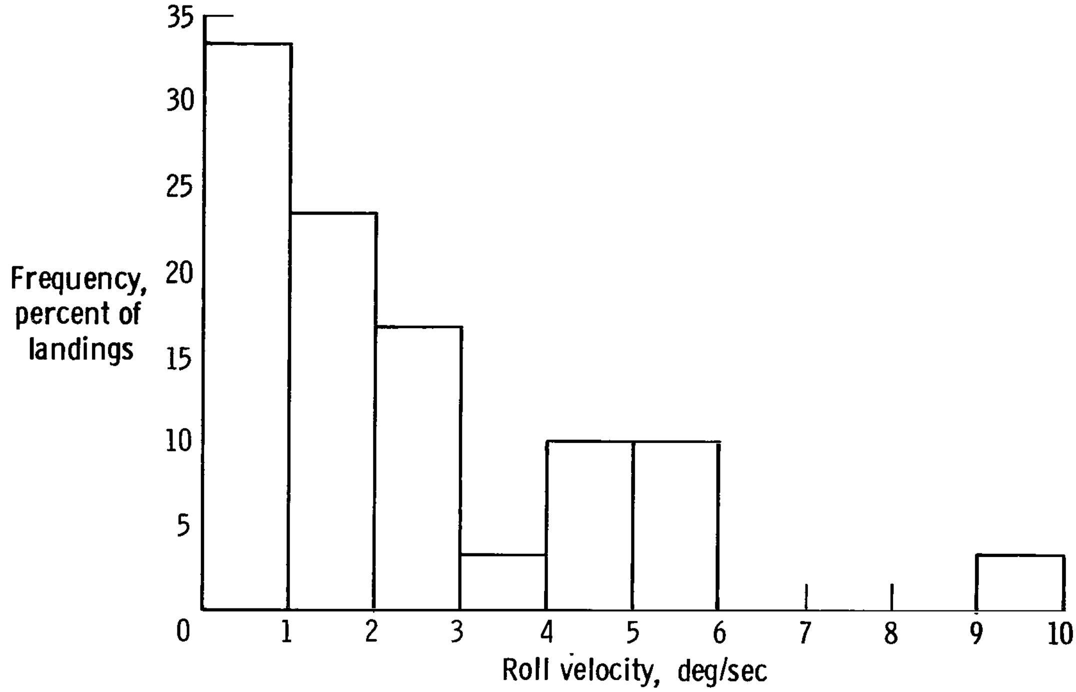


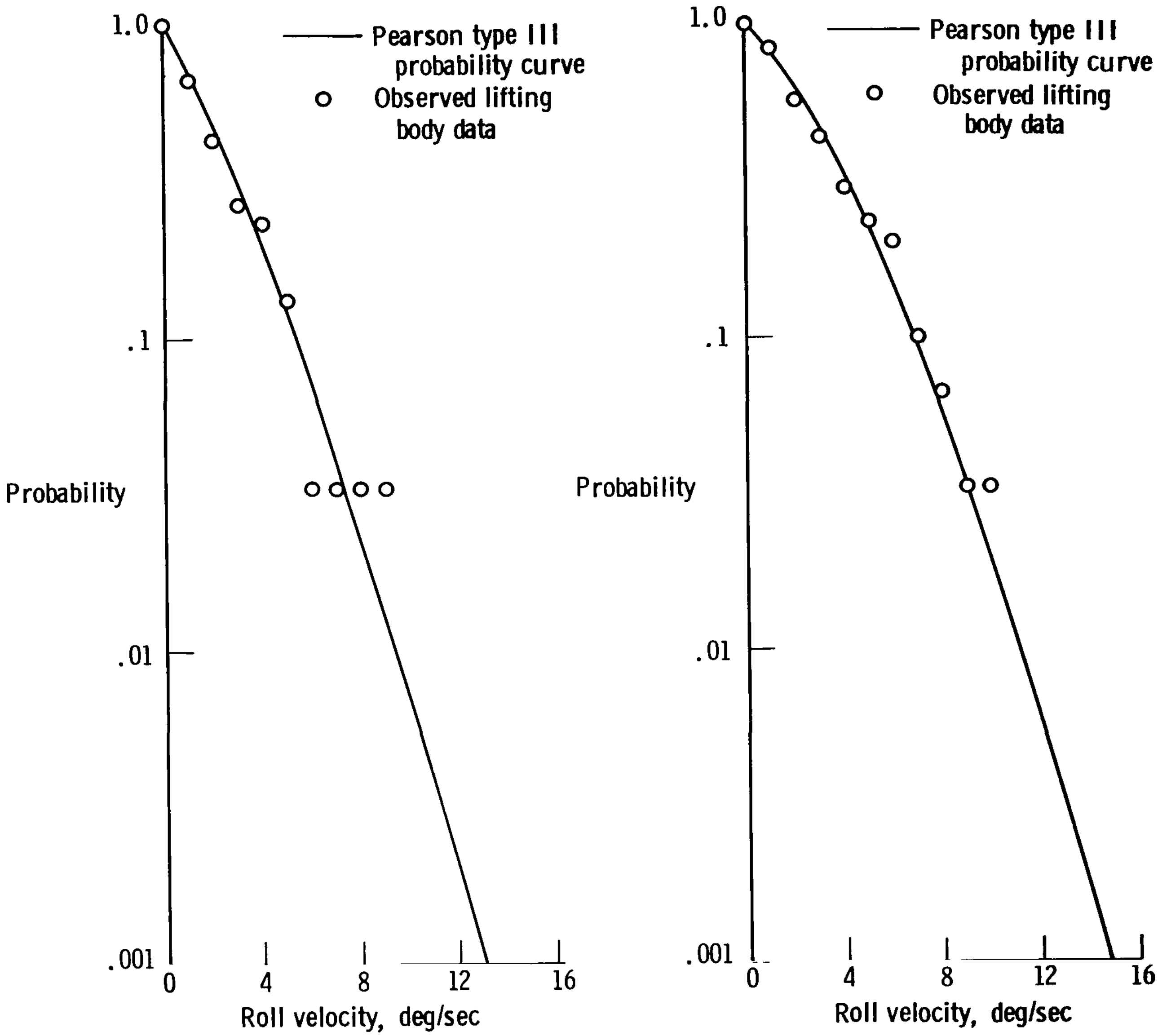
Figure 12. Probability of equaling or exceeding values of roll angle at touchdown.



(a) Toward first wheel to contact.

(b) Away from first wheel to contact.

Figure 13. Histograms of roll velocity at landing contact.



(a) Toward first wheel to contact.

(b) Away from first wheel to contact.

Figure 14. Probability of equaling or exceeding values of roll velocity at landing contact.

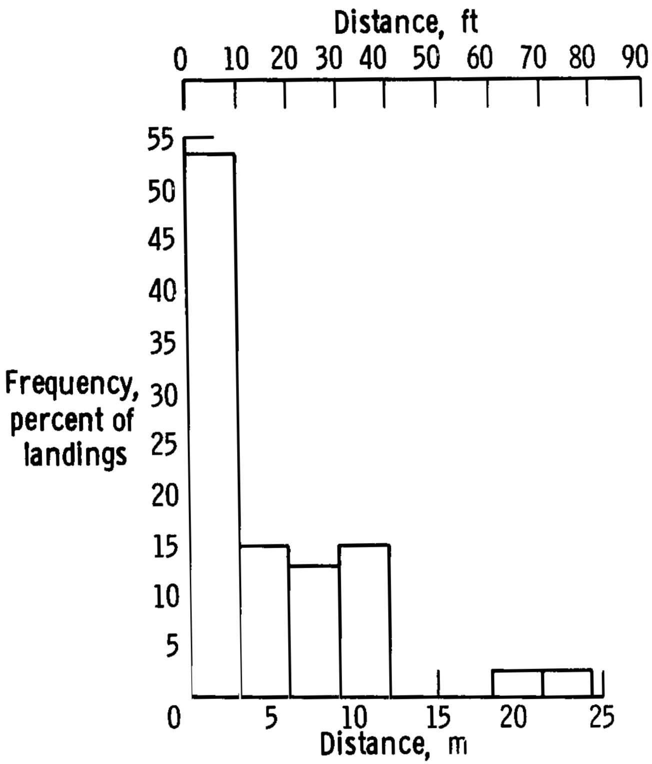


Figure 15. Histogram of absolute lateral distance from intended touchdown point.

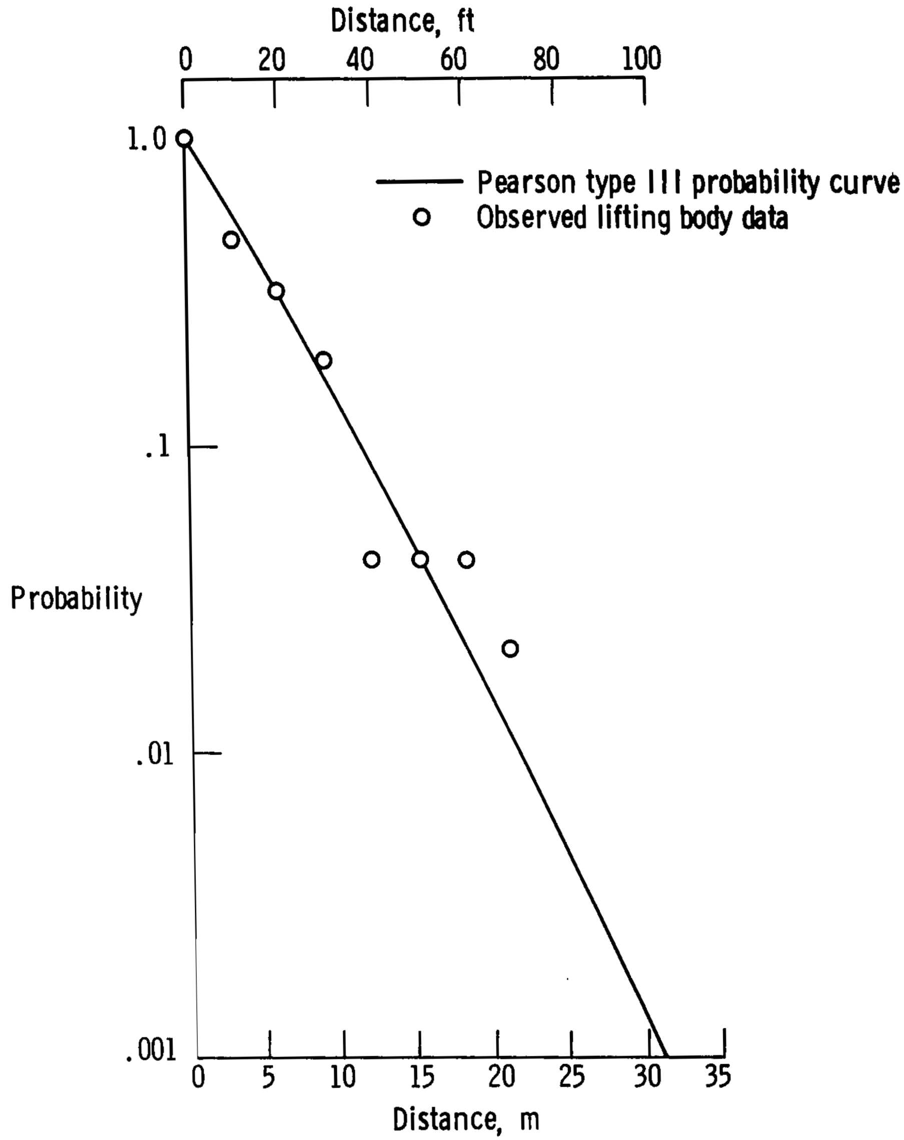


Figure 16. Probability of equaling or exceeding values of absolute lateral distance from intended touchdown point.

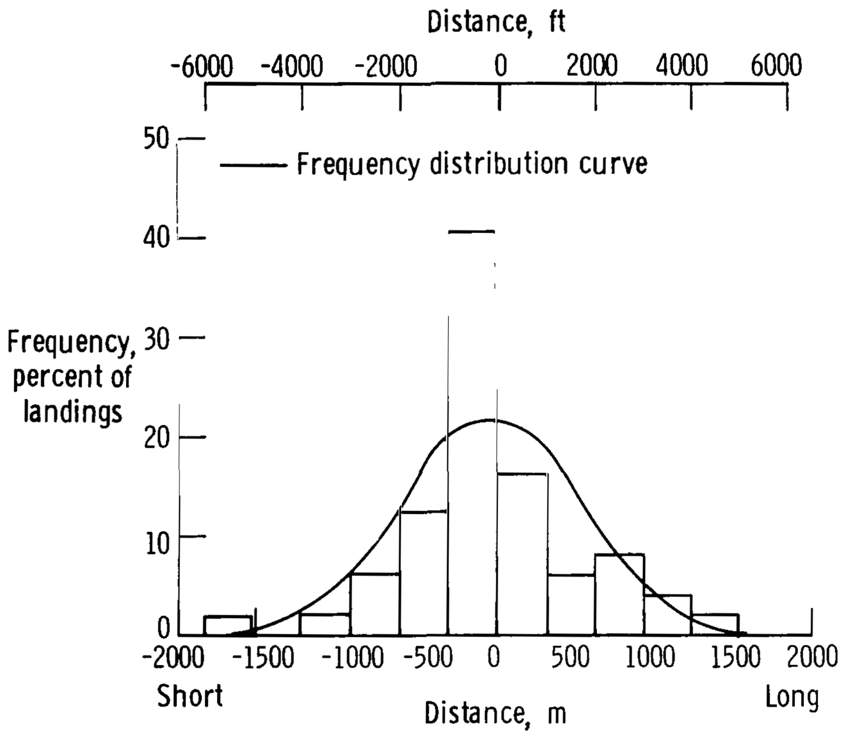


Figure 17. Histogram of longitudinal distance from intended touchdown point.

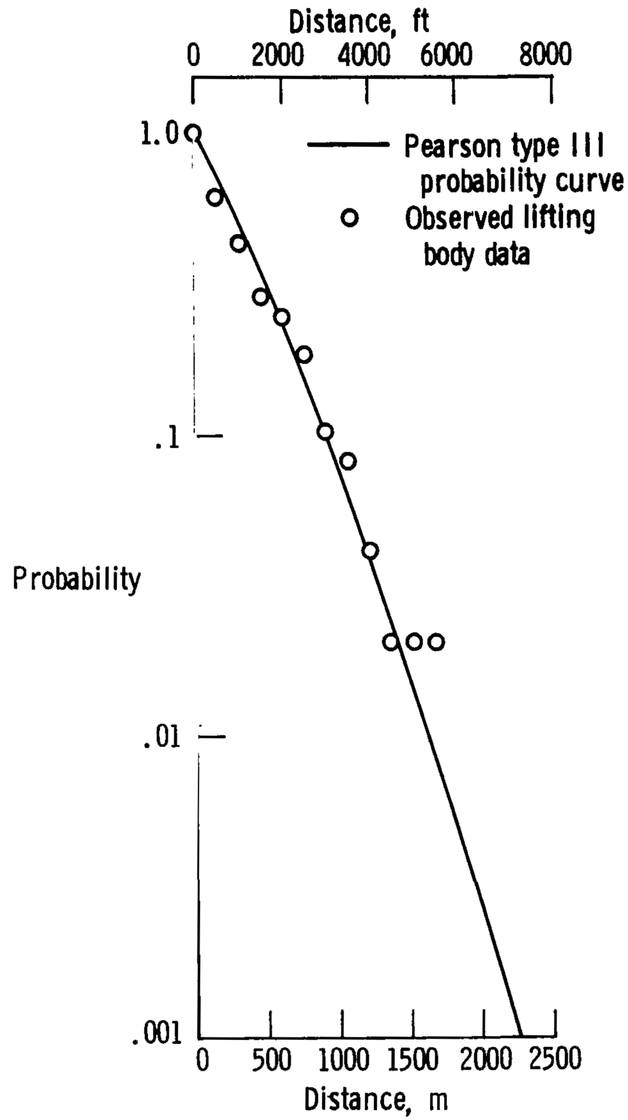


Figure 18. Probability of equaling or exceeding values of longitudinal distance from intended touchdown point.

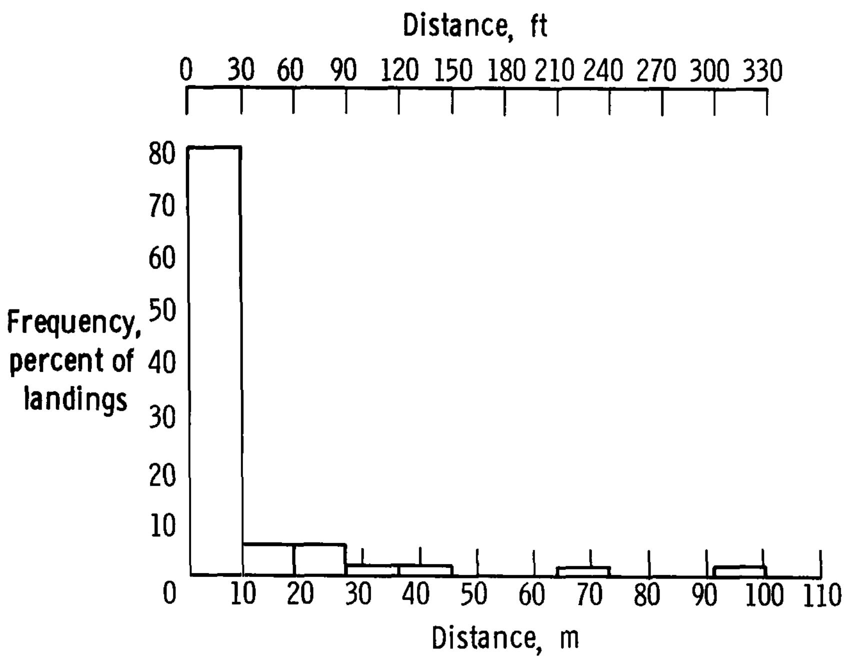


Figure 19. Histogram of lateral distance from touchdown to full stop.

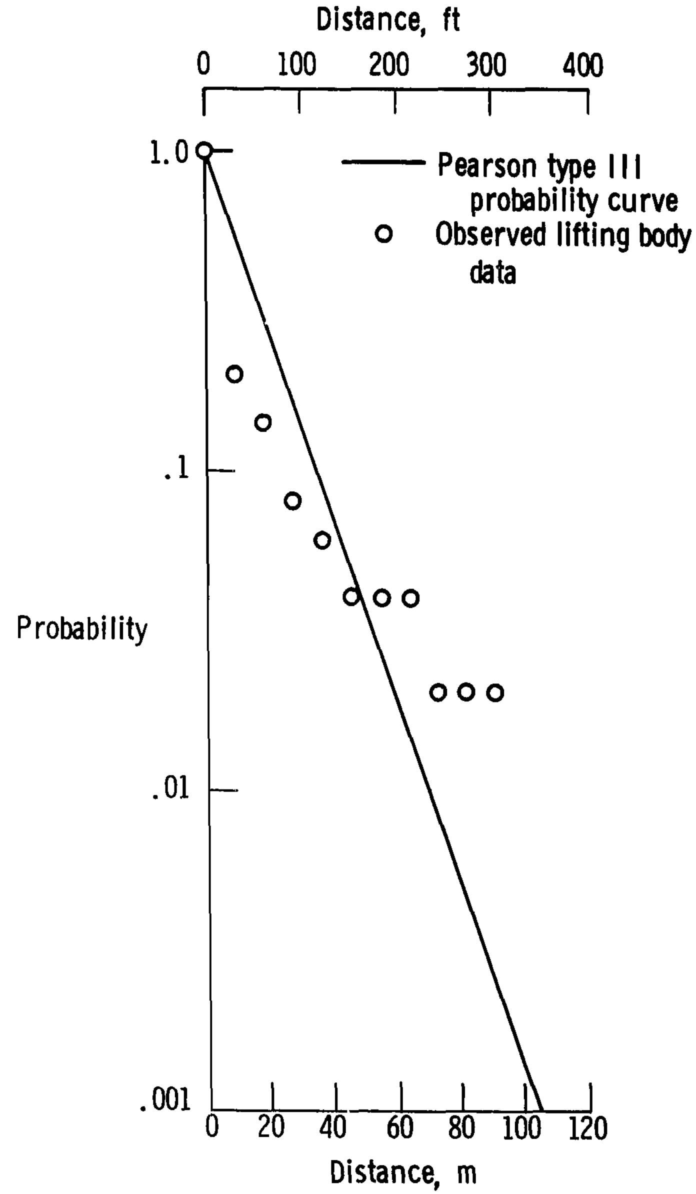


Figure 20. Probability of equaling or exceeding values of lateral distance from touchdown to full stop.

NASA-Langley, 1972 — 31 H-684

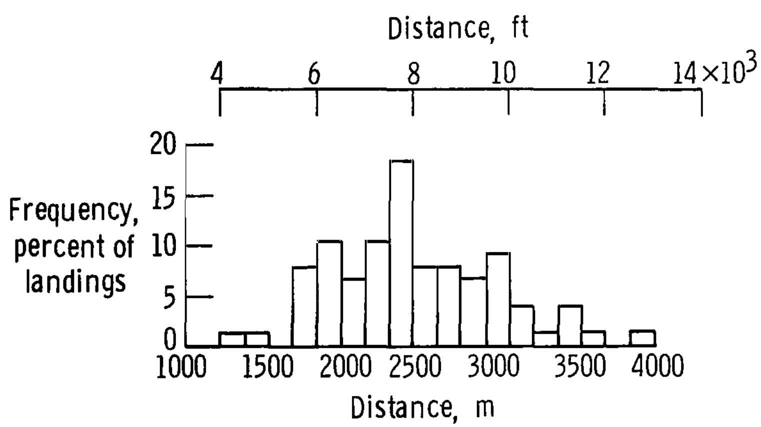


Figure 21. Histogram of rollout distance.

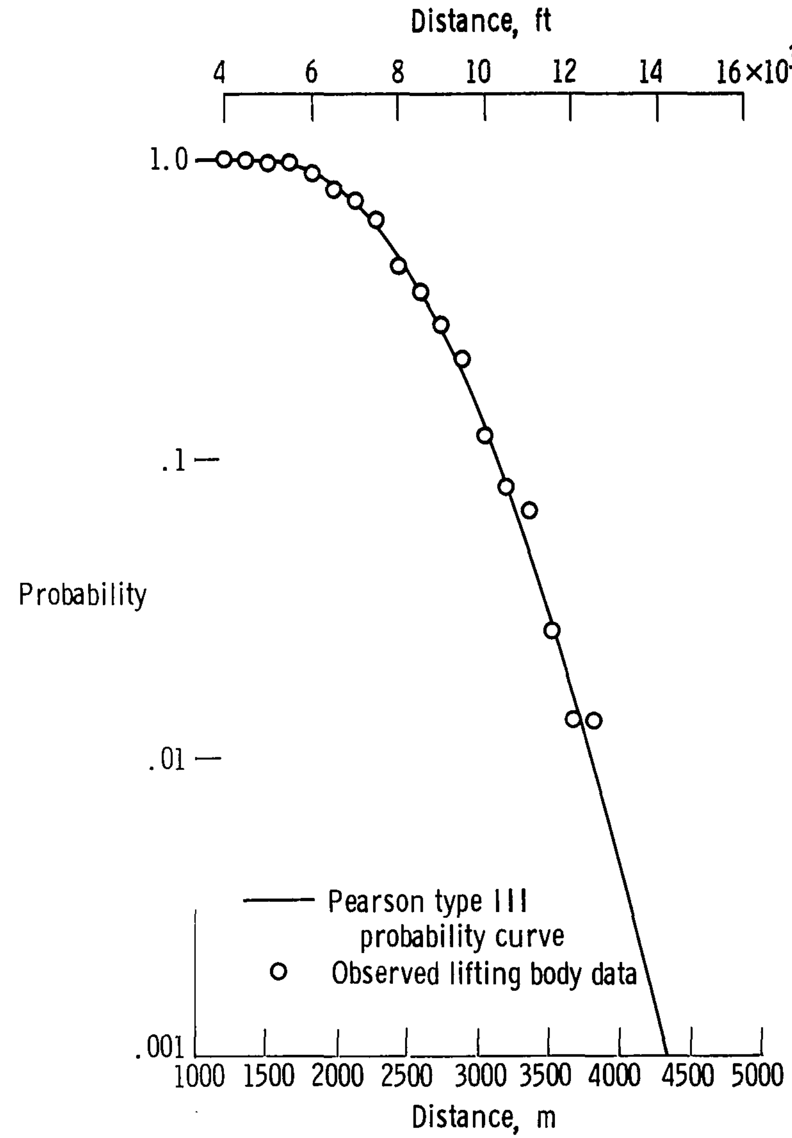


Figure 22. Probability of equaling or exceeding values of rollout distance.

"The aeronautical and space activities of the United States shall be conducted so as to contribute . . . to the expansion of human knowledge of phenomena in the atmosphere and space. The Administration shall provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof."

— NATIONAL AERONAUTICS AND SPACE ACT OF 1958

NASA SCIENTIFIC AND TECHNICAL PUBLICATIONS

TECHNICAL REPORTS: Scientific and technical information considered important, complete, and a lasting contribution to existing knowledge.

TECHNICAL NOTES: Information less broad in scope but nevertheless of importance as a contribution to existing knowledge.

TECHNICAL MEMORANDUMS: Information receiving limited distribution because of preliminary data, security classification, or other reasons.

CONTRACTOR REPORTS: Scientific and technical information generated under a NASA contract or grant and considered an important contribution to existing knowledge.

TECHNICAL TRANSLATIONS: Information published in a foreign language considered to merit NASA distribution in English.

SPECIAL PUBLICATIONS: Information derived from or of value to NASA activities. Publications include conference proceedings, monographs, data compilations, handbooks, sourcebooks, and special bibliographies.

TECHNOLOGY UTILIZATION PUBLICATIONS: Information on technology used by NASA that may be of particular interest in commercial and other non-aerospace applications. Publications include Tech Briefs, Technology Utilization Reports and Technology Surveys.

Details on the availability of these publications may be obtained from:

SCIENTIFIC AND TECHNICAL INFORMATION OFFICE

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Washington, D.C. 20546