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# Parametric Study of the Orbiter Rollout Using an Approximate Solution

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Lyndon B. Johnson Space Center
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SHUTTLE PROGRAM

# PARAMETRIC STUDY OF THE ORBITER ROLLOUT USING AN APPROXIMATE SOLUTION

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## 1.0 SUMMARY

An approximate solution to the motion of the Orbiter during rollout is used to perform a parametric study of the rollout distance required by the Orbiter. The study considers the maximum expected dispersions in the landing speed and the touchdown point. These dispersions are assumed to be correlated so that a fast landing occurs before the nominal touchdown point. The maximum rollout distance is required by the maximum landing speed with a 10-knot tailwind and the center of mass at the forward limit of its longitudinal travel. The maximum weight that can be stopped within 15 000 feet on a hot day at Kennedy Space Center (KSC) is 248 800 pounds. The energy absorbed by the brakes would exceed the limit for reuse of the brakes.

## 2.0 INTRODUCTION

The first part of this section will describe the basic sequence of events during the rollout of the Orbiter. The pitch at touchdown is maintained for several seconds in an attempt to prevent the Orbiter from bouncing. The elevons must be deflected in a positive direction (downward) in order to decrease the pitch. The immediate effect of this deflection is to increase the lift of the Orbiter in addition to causing a nose-down moment. The lift of the Orbiter will decrease as the pitch decreases, but the initial increase in lift may be enough to cause the Orbiter to rise from the runway. This tendency may be decreased by maintaining the initial pitch for a short time.

After the initial delay, the pitch is decreased to some arbitrary value and then held constant until the equivalent airspeed (EAS) decreases to a specified value. The present values of these parameters are 6 degrees and 165 knots, respectively. The delay in completing the pitchdown serves to reduce the maximum load on the main landing gear. The maximum load occurs as the nose gear touches the runway, when the Orbiter is at a negative angle of attack, and the elevons are still deflected upward. A delay in the pitchdown will reduce the dynamic pressure and consequently reduce the load on the main landing gear, but the delay in the pitchdown is limited because it will increase the rollout distance. The deceleration of the Orbiter is greater with all the tires on the runway than at some positive pitch angle, and the start of braking cannot begin before some interval after nose-gear touchdown. The delay in pitchdown is also limited by the ability of the elevons to control the pitch. If the pitchdown is delayed too long, the pitch rate may become uncontrollable and cause excesssively high loads on the nose gear.

The start of braking will be determined by either the maximum energy that the brakes can absorb or by the time that the nose gear touches the runway. There are two pertinent values of the energy that can be absorbed by the brakes. The first of these is the energy that the brakes can absorb and be useable on another flight. The second energy limit is the amount of energy that the brakes can absorb and still provide braking on that landing. The start of the braking cannot begin until the nose gear has been on the runway for approximately 3 seconds and until the speed has become less than the speed corresponding to the higher energy level. It would be desirable not to begin braking until the speed has decreased enough to allow the brakes to be reused.

A complete simulation of the rollout would require the use of a comprehensive six-degree-of-freedom solution. The amount of computer time required to perform a parametric study with such a program is prohibitive. An approximate solution to the motion of the Orbiter during the rollout was documented in reference 1. This approximate solution was used to calculate the total rollout distance for a range of Orbiter weights, longitudinal position of the center of mass, wind condition, and density altitudes. The results of the study are presented in this report.

## 3.0 METHOD

The derivation of the approximate solution to the motion of the Orbiter during rollout is discussed in detail in reference 1. The assumptions that were made during the development of the equation of motion are constant mass, constant windspeed, no crosswind, no thrust, constant grade of the runway, and no brakes on the nose-gear wheels. The absence of nose-gear brakes causes the aerodynamic forces line of action, the aerodynamic pitching moment, and the center-of-mass positions to be introduced into the equation of motion with all the wheels on the runway. The coefficient of rolling friction is constant above some speed, and the braking coefficient is a quadratic function of the groundspeed but is averaged over the integration interval. The effectiveness of the brakes is represented as a constant ratio to the perfect value of unity. The coefficients of lift, drag, and moment are linear functions of the elevon position and the effects of variations in pitch are averaged over the integration interval. The acceleration of the center of mass normal to runway is ignored. The equation of motion has the same form for all phases of the rollout and can be integrated exactly over the chosen interval, which is limited only by the necessity to average the effects of changes in the pitch and the braking coefficient.

It is possible to develop an equation for the amount of energy absorbed by the brakes. This equation is used to determine the maximum speed at which the brakes could be applied without absorbing more than a specified amount of energy. The actual braking speed is either this value or the speed 3 seconds after the nose gear touches the runway.

The approximate solution is used to determine the maximum length of runway that would be required for a range of weights and atmospheric conditions at either KSC or Edwards Air Force Base (EAFB). The nominal landing speed is the minimum landing speed plus the decrease in speed during the 5 seconds prior to touchdown and an additional allowance of 12 knots. The minimum landing speed is limited by the angle of attack at which some portion of the Orbiter would scrape the runway. The decrease in speed during the 5-second interval is based on the deceleration at the minimum landing speed. The nominal touchdown point is 3000 feet from the start of the runway. The maximum expected dispersions in the landing speed and the touchdown point are ±24 knots and ±1650 feet, respectively. The dispersions are assumed to be correlated such that the highest landing speed occurs at the shortest touchdown point. These nominal conditions and dispersions are applicable only for the 240 000-pound Orbiter, but they are applied over the entire weight range as a convenience. This should cause the results of the lower weights to be conservative.

Additional conditions that are used in the calculations are listed in table I. The longitudinal position of the center of mass is limited to lie between 65.0 and 67.5 percent. The final position of the speedbrake is limited by its effect on the rate of rudder movement. The rollout distance is not changed significantly by changes of 5 to 10 percent in the final position of the speedbrake so that the final value is not critical.

## 4.0 RESULTS AND DISCUSSION

The relationship between the ratio of the local atmospheric density to the sea level value of the 1962 Standard Atmosphere (ref. 2) and the density altitude is shown in figure 1. The density altitude is defined as the altitude corresponding to a given density of the standard atmosphere. Therefore, a density ratio of unity corresponds to a density altitude of zero. This figure shows the values for cold, standard, and hot days at both KSC and EAFB. The density altitudes vary between -2068 feet for the cold day at KSC to 6295 feet for the hot day at EAFB.

The minimum and maximum expected landing speeds for the forward limit of the center of mass are shown in figures 2(a) and 2(b) as functions of the Orbiter weight, density altitude, and windspeed. The minimum expected landing speed for a 190 000-pound Orbiter with no wind varies between 165.5 knots and 190.5 knots for density altitudes of -2000 feet and 8000 feet. The minimum expected landing speed of a 240 000-pound Orbiter is between 184.8 knots and 212.5 knots for the same conditions. The maximum expected landing speeds with no wind are between 213.5 knots and 238.5 knots for a 190 000-pound Orbiter and between 232.8 knots and 260.5 knots for a 240 000-pound Orbiter. The landing speed changes directly as the windspeed changes; i.e., a 10-knot tailwind will increase the landing speed by 10 knots.

The minimum and maximum expected landing speeds for the Orbiter with the center of mass at the aft limit are presented in figures 3(a) and 3(b). The minimum expected landing speed for a 190 000-pound Orbiter with no wind varies between 157.5 knots and 180.6 knots for density altitudes of -2000 feet and 8000 feet. The minimum expected landing speed of a 240 000-pound Orbiter is between 175.0 knots and 201.6 knots for the same conditions. The maximum expected landing speeds are between 205.5 knots and 228.6 knots for a 190 000-pound Orbiter and between 223.0 knots and 249.6 knots for a 240 000-pound Orbiter.

The landing speed of the Orbiter will decrease as the center of mass is moved rearward because the elevons must be deflected towards the positive direction (downward) in order to trim the vehicle. This change in the elevon's position will cause an increase in the lift coefficient and a decrease in the speed required to generate the same amount of lift. The maximum expected landing speed of 190 000-pound Orbiter decreases between 8 and 10 knots as the center of mass is moved from the forward limit to the aft limit. The decrease is approximately 10 knots for a 240 000-pound Orbiter.

The minimum control speed is defined as the lowest speed at which a constant pitch or pitch rate can be maintained. The most important influences on the minimum control speed are the atmospheric density, the weight, the location of the center of mass, the pitch, the position of the body flap, and the position of the speedbrake. The position of the body flap and the speedbrake are considered to be constants, and the effect of variations in the atmospheric density can be eliminated by using the EAS. The influence of the weight and position of the center of mass is shown in figure 4 for a pitch of 6 degrees. The trends shown in this figure should be expected because the nose-down moment is increased by either an increase in the weight or by a forward movement of the center of mass. It is possible to maintain a pitch of 6 degrees under the worst conditions until the equivalent airspeed has decreased to 165 knots.

The minimum control speed for a 240 000-pound Orbiter is shown in figure 5 as a function of the pitch for three positions of the center of mass. The minimum control speed decreases as the pitch is increased so that caution is required in the selection of the beginning of the pitchdown. The latter portion of the pitchdown will probably be uncontrollable regardless of when the pitchdown is begun. For example, the pitchdown of a 240 000-pound Orbiter with a forward center of mass cannot be controlled if the pitch is less than 3.25 degrees and the equivalent airspeed is less than 165 knots. Because the latter portion of the pitchdown will almost always be uncontrollable, the initial pitch rate should be low enough so that the pitch rate at the nose-gear touchdown is not excessive. The nominal pitch rate is 2 degrees per second.

The total rollout distance required to stop the Orbiter with the forward center of mass after a landing at the minimum expected landing speed is given in figures 6(a), 6(b), and 6(c). The rollout distance is presented as a function of the weight for constant density altitudes and windspeed. The results in the presence of a 10-knot headwind are shown in figure (6a). The brakes will be applied 3 seconds after the nose gear touches the runway unless this would cause the brakes to absorb more energy than is desirable. In that event, the brakes will not be applied until the speed has decreased sufficiently. The start of braking is determined by the touchdown of the nose gear for the lower weights shown in figures 6(a), 6(b), and 6(c), but it is possible for a heavy Orbiter to absorb enough energy in stopping to require the replacement of the brakes. This will happen for a 231 000-pound Orbiter landing at sea level with a 10-knot tailwind. The braking must be delayed if the Orbiter is heavier than this or the brakes must be replaced before the next mission. There are conditions that could cause the brakes to be destroyed before the Orbiter could be stopped. This would occur if the brakes are applied 3 seconds after the nose gear touches the runway during the landing of a 230 000-pound Orbiter at a density altitude of 6000 feet with a 10-knot tailwind. In general, the weight limit decreases as the density altitude increases or the windspeed increases (a tailwind is positive).

Similar information is presented in figures 7(a), 7(b), and 7(c) for the maximum expected landing speed. The rollout distance required to land a light Orbiter is less than for the minimum expected landing speed. The magnitude of the differences may be questionable because the dispersions are based on a weight of 240 000 pounds. The trend will still be true if a positive dispersion in the landing speed corresponds to a negative dispersion in the touchdown point. As the weight of the Orbiter is increased, the distance required to stop does become larger for the maximum landing speed than for the minimum landing speed. This is what would be expected and increases the confidence in the assumed correlation between the dispersions in the touchdown speed and location. There is no reason to believe that the qualitative form of the correlation is a function of the weight.

The rollout distance is a maximum when a heavy Orbiter with a forward center of mass lands at the maximum expected speed with a 10-knot tailwind. The rollout distance is shown in figures 8(a) and 8(b) as functions of the density altitude for constant values of the weight. The density altitudes that correspond to the cold, standard, and hot days at both KSC and EAFB are indicated. The rollout distances are given in figure 8(a) for reuse of the brakes and in figure 8(b) for single use of the brakes. The distance required to stop a 240 000-pound Orbiter on a hot day at KSC is 17 150 feet if the brakes are to be reusable. This can be reduced to 14 300 feet but, the brakes must be replaced. Whenever two distances are given for the same condition, the first distance corresponds to reuse of the brakes while the second is for a single use of the brakes. The distances required to land a 240 000-pound Orbiter on a hot day at EAFB are 19 500 feet and 16 000 feet. The distances required to land the same weight are 14 900 feet and 13 200 feet for a cold day at KSC. The distances are 16 250 feet and 13 900 feet for a cold day at EAFB.

The rollout distances for an Orbiter with an aft center of mass are shown in figures 9(a) and 9(b). Again, the touchdown occurs at the maximum expected speed with a 10-knot tailwind. The rollout distances for a 240 000-pound Orbiter on a hot day at KSC are 15 800 feet and 12 980 feet. This is a reduction of between 1320 feet and 1350 feet from the distances required when the center of mass is at the forward limit.

The relation between the density altitude and the weight for constant rollout distances is shown in figures 10(a) and 10(b) for an Orbiter with the forward center of mass. These figures show that the weight corresponding to a fixed runway length decreases as the density altitude is increased. This trend should be expected because the landing speed of a constant-weight Orbiter will increase as the density is decreased. In addition, the rate at which energy is absorbed by the aerodynamic forces is less so that the start of braking must be delayed if the same amount of energy is to be absorbed by the brakes. The maximum weight that can be stopped within 15 000 feet on a hot day at KSC without exceeding the brake reuse energy limit is 220 500 pounds. This can be increased to 248 800 pounds, but the brakes would have to be replaced. The corresponding weight for a hot day at EAFB are 203 900 pounds and 231 000 pounds.

The same type of information is presented in figures 11(a) and 11(b) for an Orbiter with its center of mass at the aft limit. The maximum weight that can be landed on a hot day at KSC without exceeding the brake reuse energy limit is 232 800 pounds. This will increase to over 250 000 pounds if this limit is not observed. The corresponding weights for a hot day at EAFB are 217 000 pounds and 248 100 pounds.

The locations of key events during the rollout on a hot day at KSC with a 10-knot tailwind are presented in figure 12(a) for the forward center of mass and in figure 12(b) for the aft center of mass. These data are for landings at the maximum expected speed. The touchdown occurs at 1350 feet. The distances between the touchdown point and the location at the nose-gear touchdown is 5850 feet for a 190 000-pound Orbiter with the forward center of mass. This distance will increase to 8500 feet if the weight is increased to 240 000 pounds. The corresponding distances are 4900 feet and 7300 feet for the aft center of mass. Braking can begin 3 seconds after the nose gear touchdown if the brakes are not to be reusable. This corresponds to distances of 750 feet for an 190 000-pound Orbiter and 900 feet for an 240 000-pound Orbiter. The distance traveled during

3 seconds after nose-gear touchdown is essentially independent of the location of the center of mass. The start of braking must be delayed if the weight is greater than 175 000 pounds and the brakes are to be reusable. The distance traveled during this delay is a function of the weight of the Orbiter but is affected only slightly by the location of the center of mass. The distances traveled before the brakes can be applied are aproximately 1750 feet for a 190 000-pound Orbiter and 4900 feet for a 240 000-pound Orbiter. If the brakes are to be reuseable, the distance traveled after the brakes are applied decreases as the weight is increased because the maximum braking speed decreases. Although the distance required to stop the Orbiter from a given speed increases as the weight increases, the net result is a decrease in the braking distance. The braking distance is not greatly affected by changes in the weight if the brakes are not reuseable because the start of braking is determined by the delay of 3 seconds after nose-gear touchdown. The braking distances required for a 190 000-pound Orbiter with a forward center of mass are 2800 feet and 3250 feet. These distances are 2300 feet and 3650 feet for a 240 000-pound Orbiter.

The location of key events during the rollout following a landing at the minimum expected speed on a hot day at KSC with a 10-knot tailwind is presented in figures 13(a) and 13(b). The touchdown occurs at 4650 feet rather than 1350 feet, but the distance traveled between the touchdown and nose-gear touchdown is less and does not vary as much with weight. Similar results are presented in figures 14(a), 14(b), 15(a), and 15(b) for landings on a hot day at EAFB with a 10-knot tailwind.

## 5.0 CONCLUDING REMARKS

An approximate solution to the motion of the Orbiter is used to study the distance required to stop the Orbiter under different conditions. Both the minimum and maximum expected landing speeds are used in the study. The nominal landing speed is the minimum landing speed plus the decrease in speed during the 5 seconds prior to touchdown at the minimum speed and an additional allowance of 12 knots. The nominal touchdown point is 3000 feet from the threshold of the runway. The maximum expected dispersions in the landing speed and the touchdown point are ±24 knots and ±1650 feet. The dispersions are assumed to be correlated so that the higher landing speed occurs earlier on the runway. Therefore, dispersions in the landing speed and touchdown point tend to compensate for each other. Although the values of these dispersions are for a 240 000-pound Orbiter, they are used over the entire weight range. The rollout distances obtained for the lighter Orbiter should be conservative because the real dispersions should decrease as the weight decreases.

The rollout distances required by a light Orbiter is greater for the minimum expected landing speed than for the maximum expected landing speed. The magnitude of the differences is questionable, but the trend should be correct provided that the assumed form of the correlation between dispersions in the landing speed and touchdown point are correct.

The maximum rollout distance at either KSC or EAFB occurs for the hot day with a 10-knot tailwind and the center of mass at the forward limit. The minimum distance required to stop a 240 000-pound Orbiter is 14 300 feet at KSC and 16 100 feet at EAFB. The maximum weight that can be stopped within 15 000 feet on a hot day at KSC is 248 800 pounds. It would be necessary to replace the brakes for all these cases. These results indicate that the runway at KSC is adequate to land an Orbiter weighing 240 000 pounds or less.

All of the data contained in this report could be duplicated in about the same amount of computer time as would be required to generate a single six degree-of-freedom solution. This illustrates the utility of the approximate solution to the motion of the Orbiter during rollout.

## 6.0 REFERENCES

1. Garland, Benjamine J.: An Approximate Solution to the Motion of the Orbiter During Rollout. JSC IN 79-FM-37, September 1979.

2. U. S. Standard Atmosphere. NASA, USAF, USWB, 1962.

TABLE I. - NOMINAL CONDITIONS

| Parameter | Value |
|---|---|
| Body flap position, deg | 0 |
| Initial speedbrake position, percent | 5 |
| Final speedbrake position, percent | 55 |
| Final elevon position, deg | 10 |
| Forward position of center of mass, percent | 65.0 |
| Aft position of center of mass, percent | 67.5 |
| Vertical position of center of mass, in. | 365 |
| Brake efficiency, percent | 75 |
| Brake reuse energy limit, ft-lb | $1.44 \times 10^8$ |
| Brake single use energy limit, ft-lb | $2.34 \times 10^8$ |
| Pitchdown equivalent airspeed, kn | 165 |

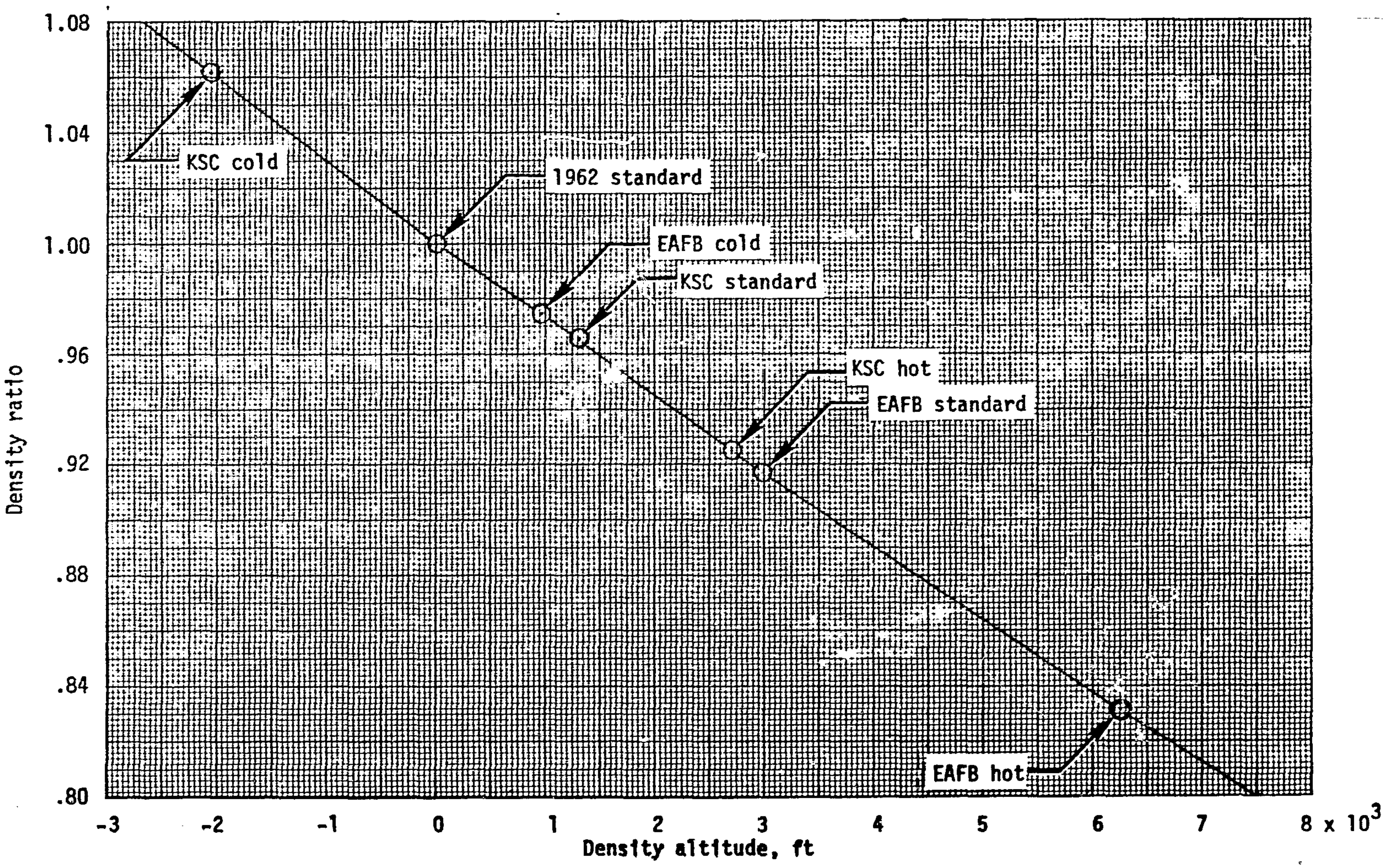


Figure 1.- Relation between density ratio and density altitude for 1962 Standard Atmosphere.

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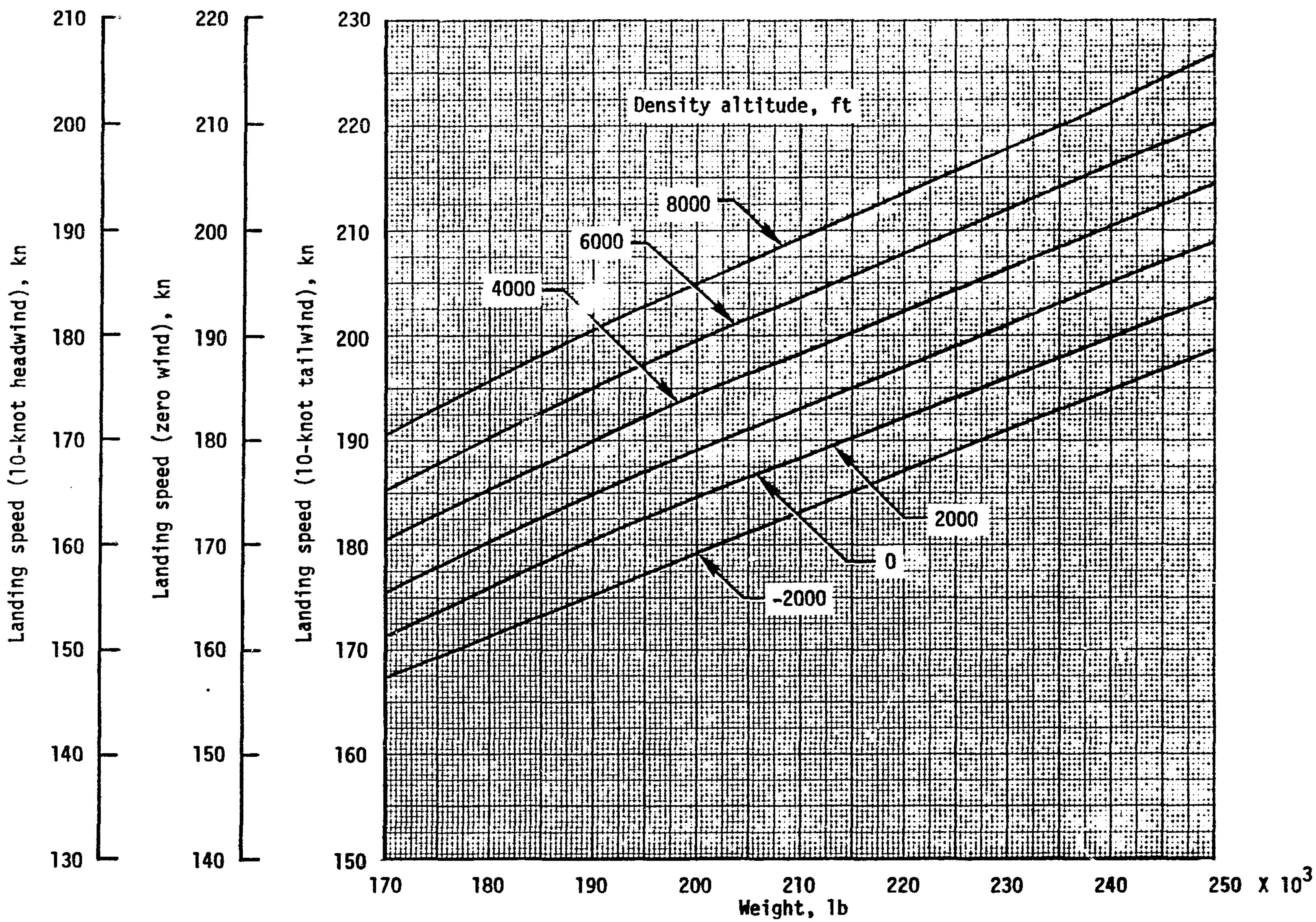
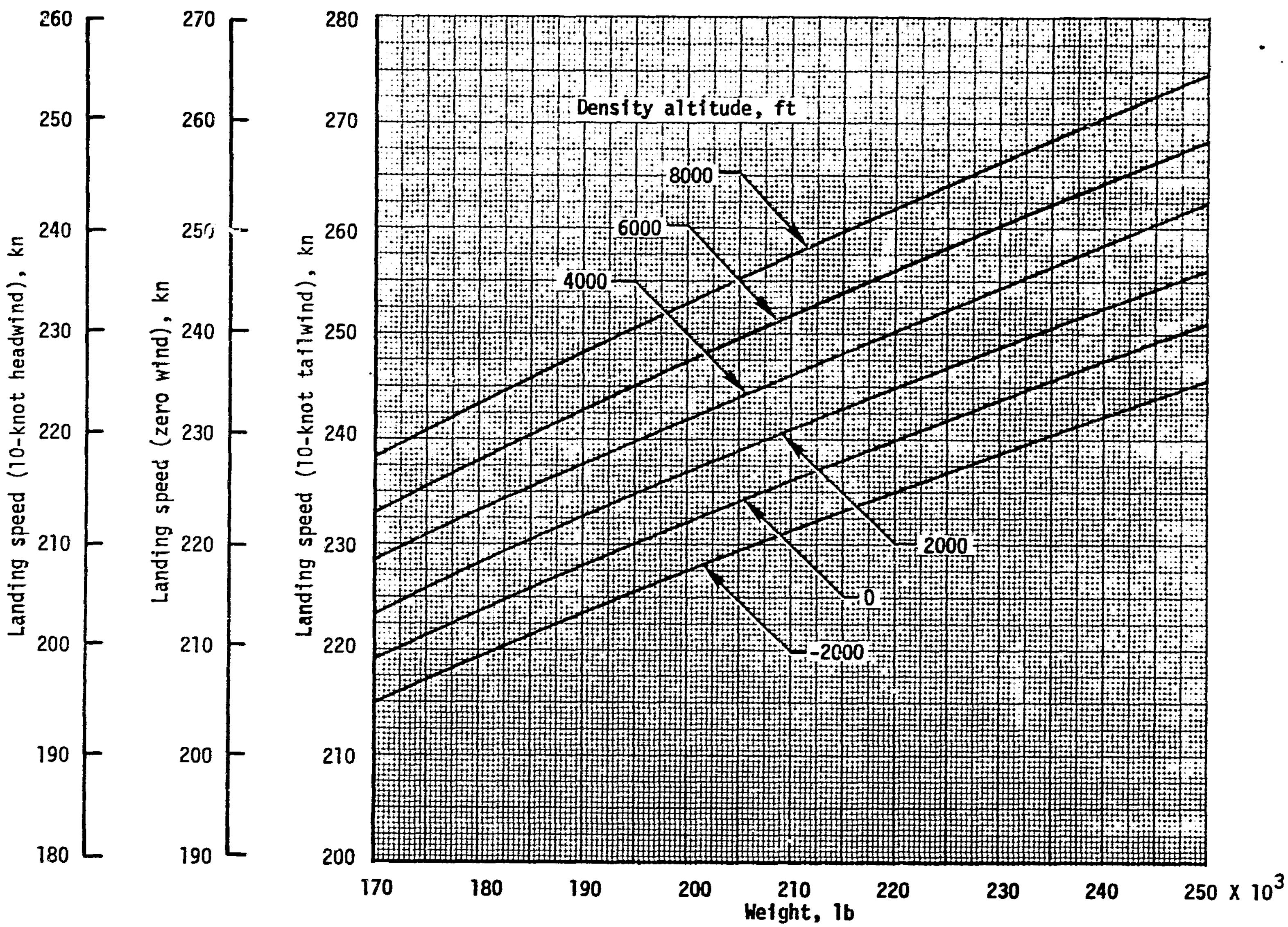


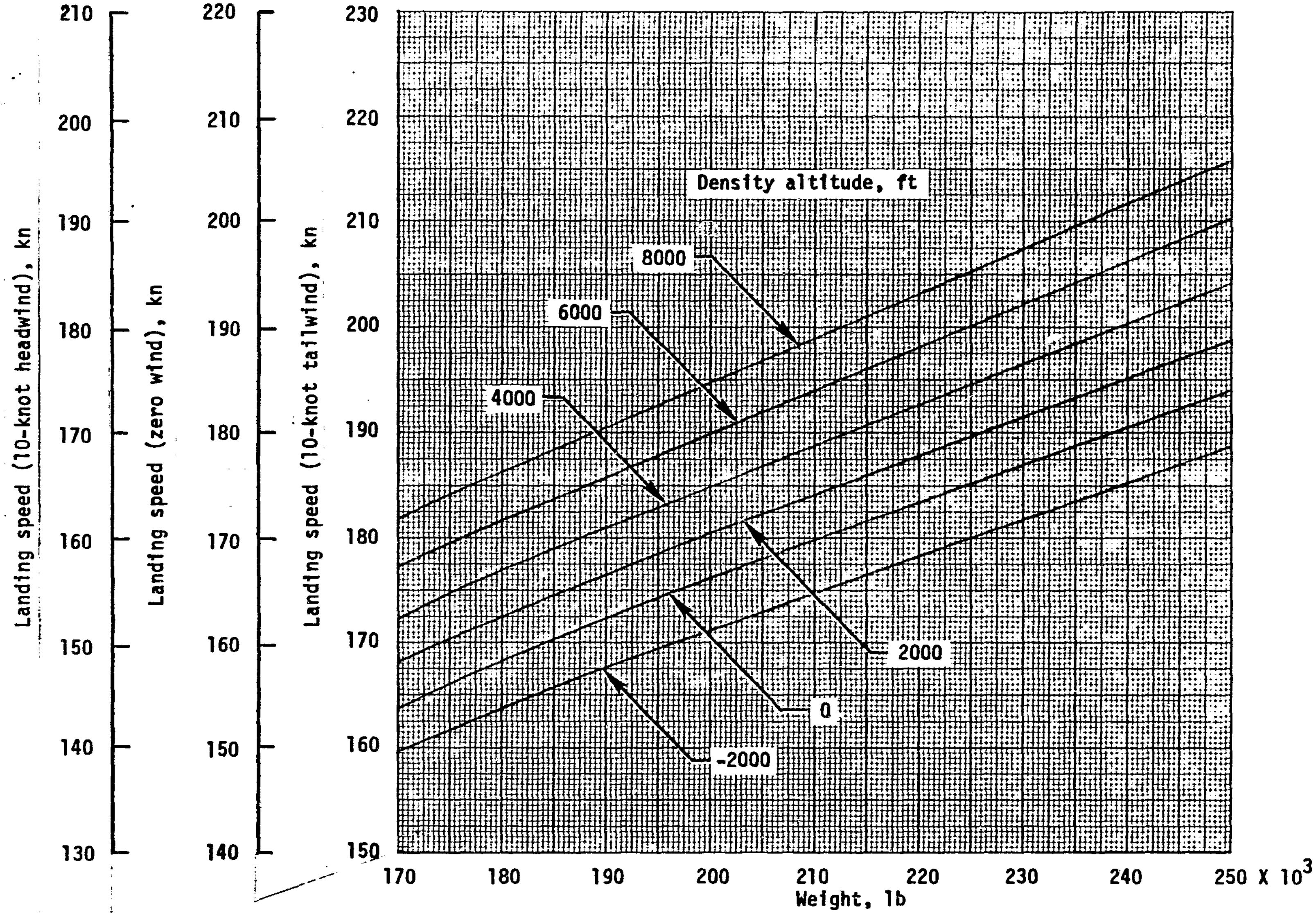

(a) Minimum.

Figure 2.- Expected landing speed of Orbiter with forward center of mass.



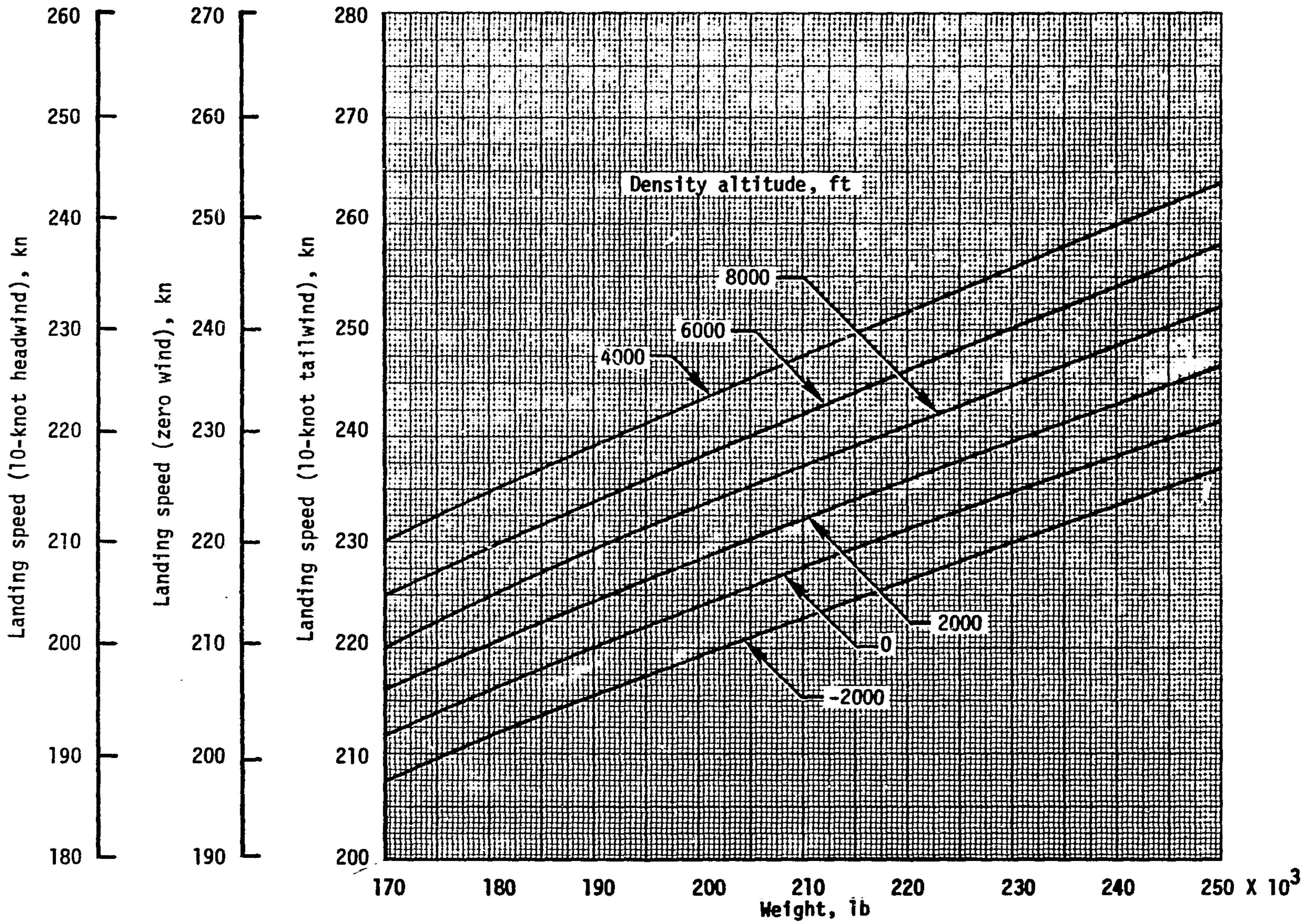

(b) Maximum.

Figure 2.- Concluded.




(a) Minimum.

Figure 3.- Expected landing speed of Orbiter with aft center of mass.


Landing speed (10-knot headwind), kn
260
250
240
230
220
210
200
190
180
Landing speed (zero wind), kn
270
260
250
240
230
220
210
200
190
Landing speed (10-knot tailwind), kn
280
270
260
250
240
230
220
210
200
Density altitude, ft
8000
6000
4000
2000
0
-2000
170
180
190
200
210
220
230
240
250 X 10^3
Weight, lb

(b) Maximum.

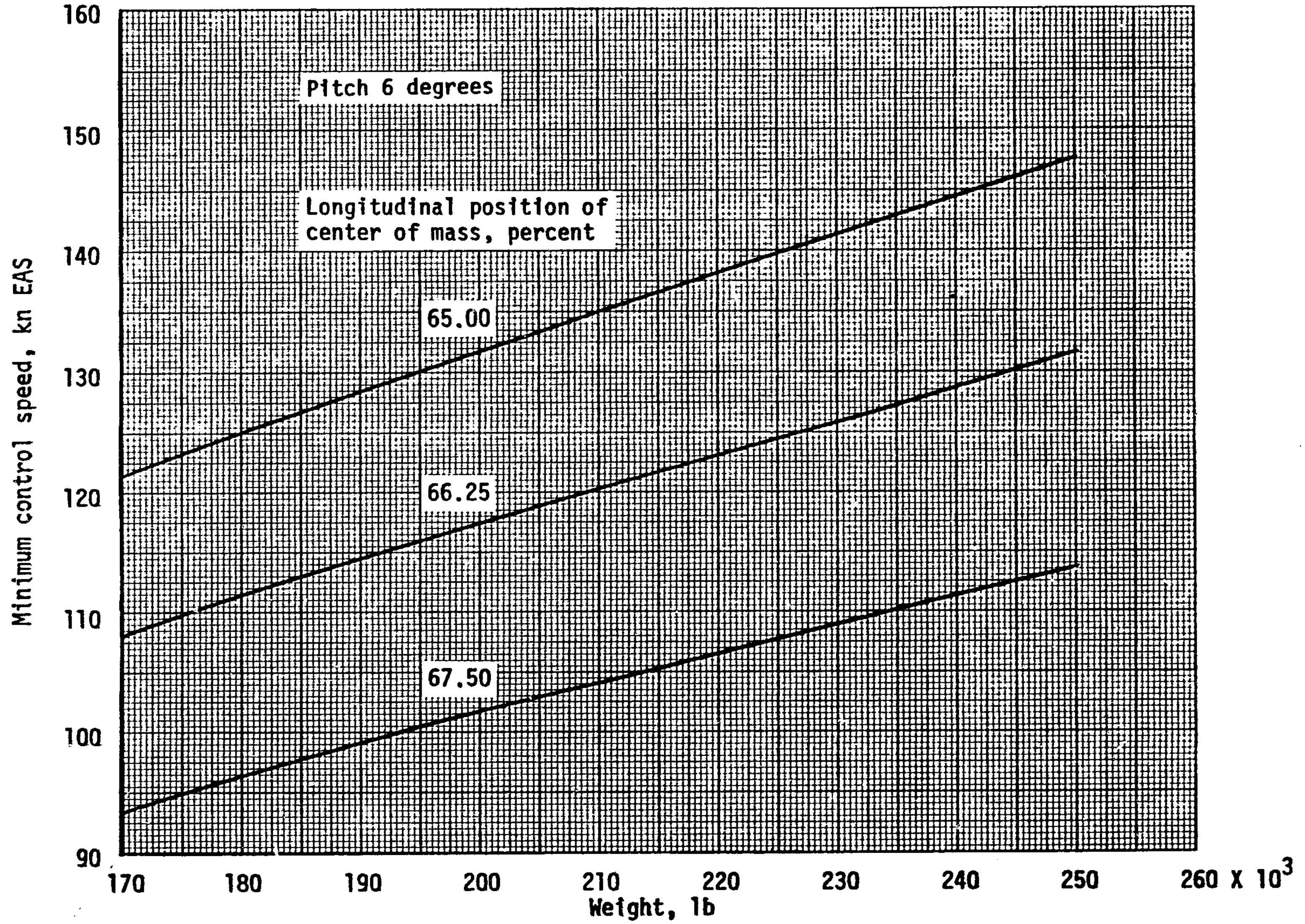



Figure 4.- Minimum control speed of Orbiter as a function of weight and longitudinal position of center of mass.

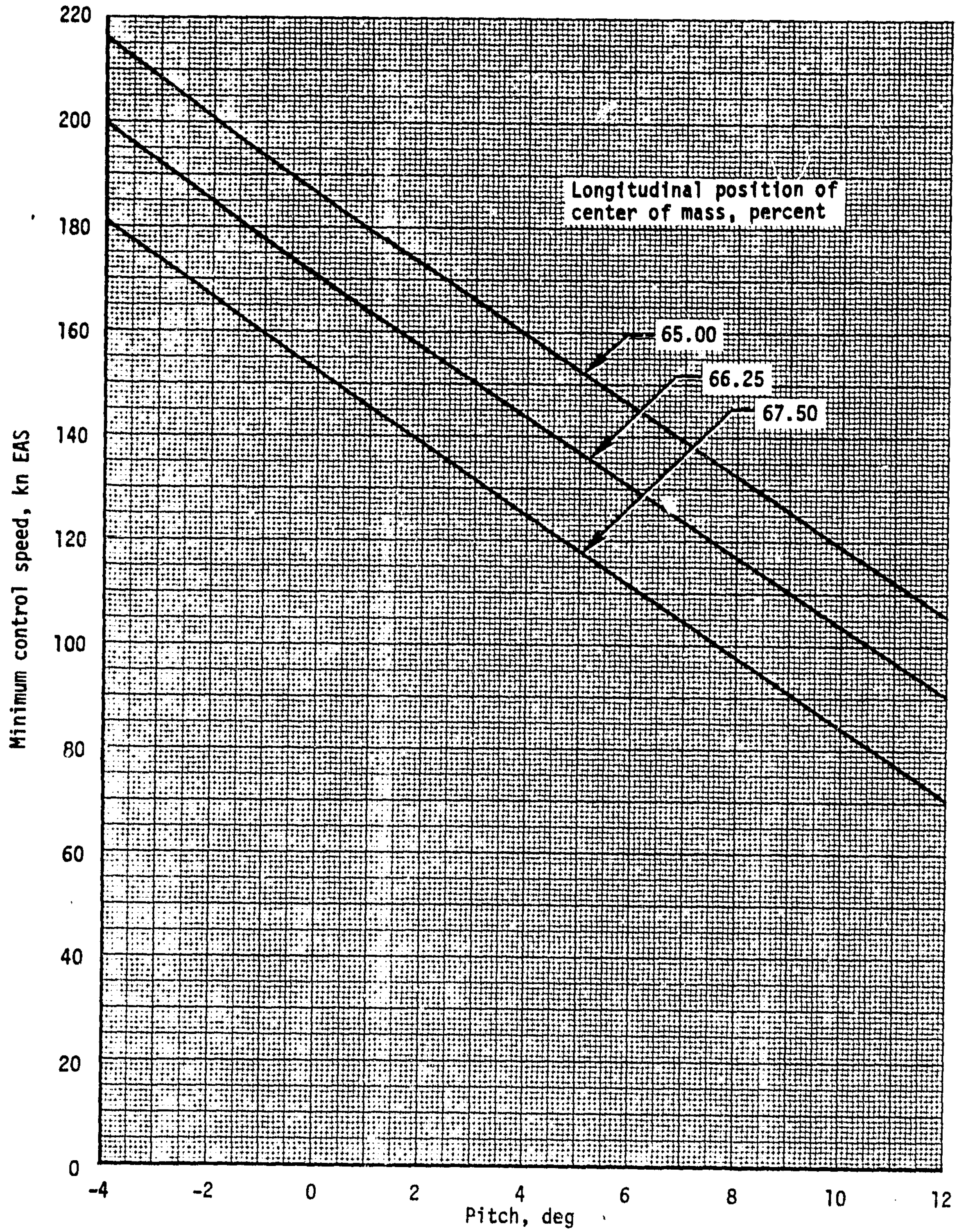
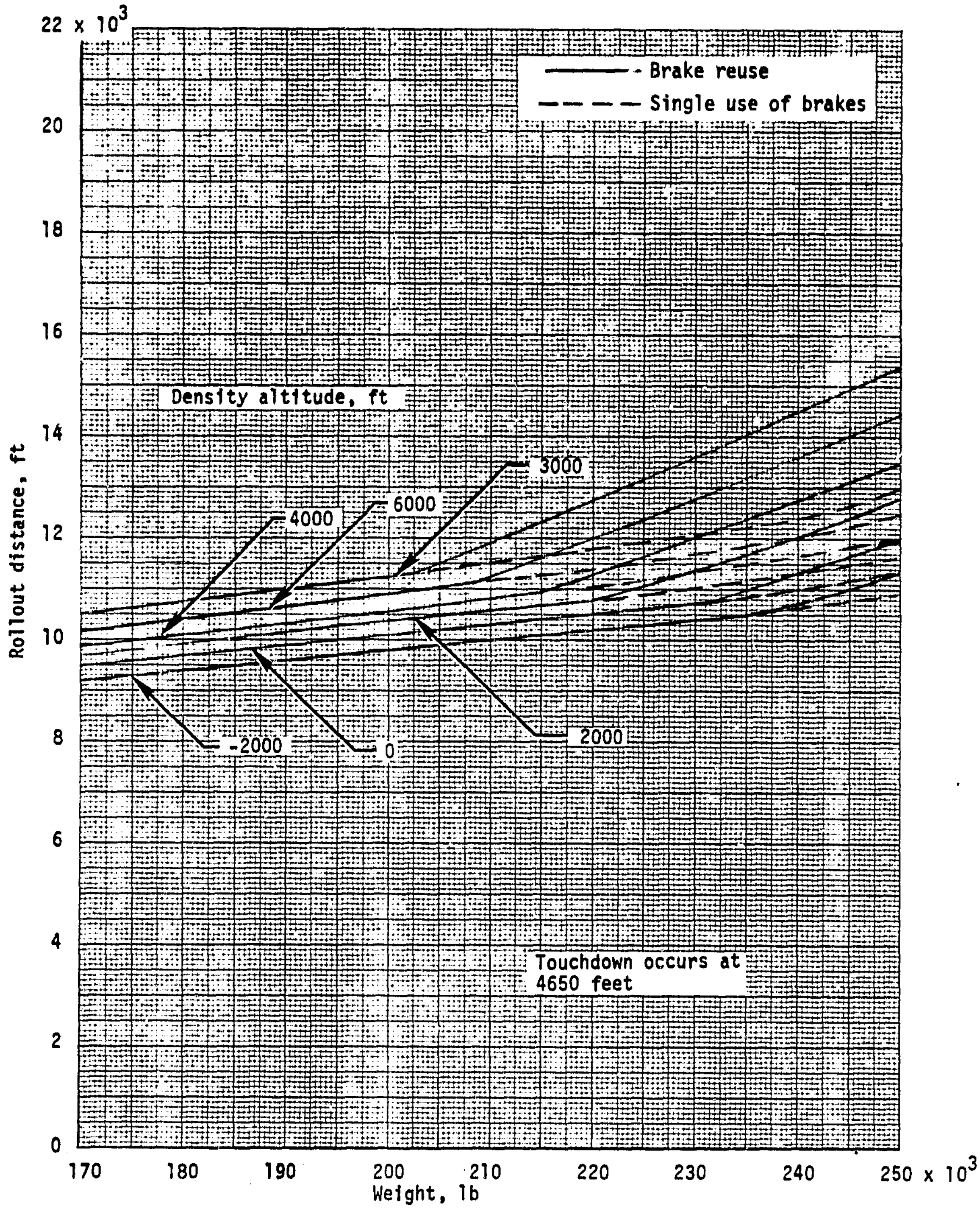
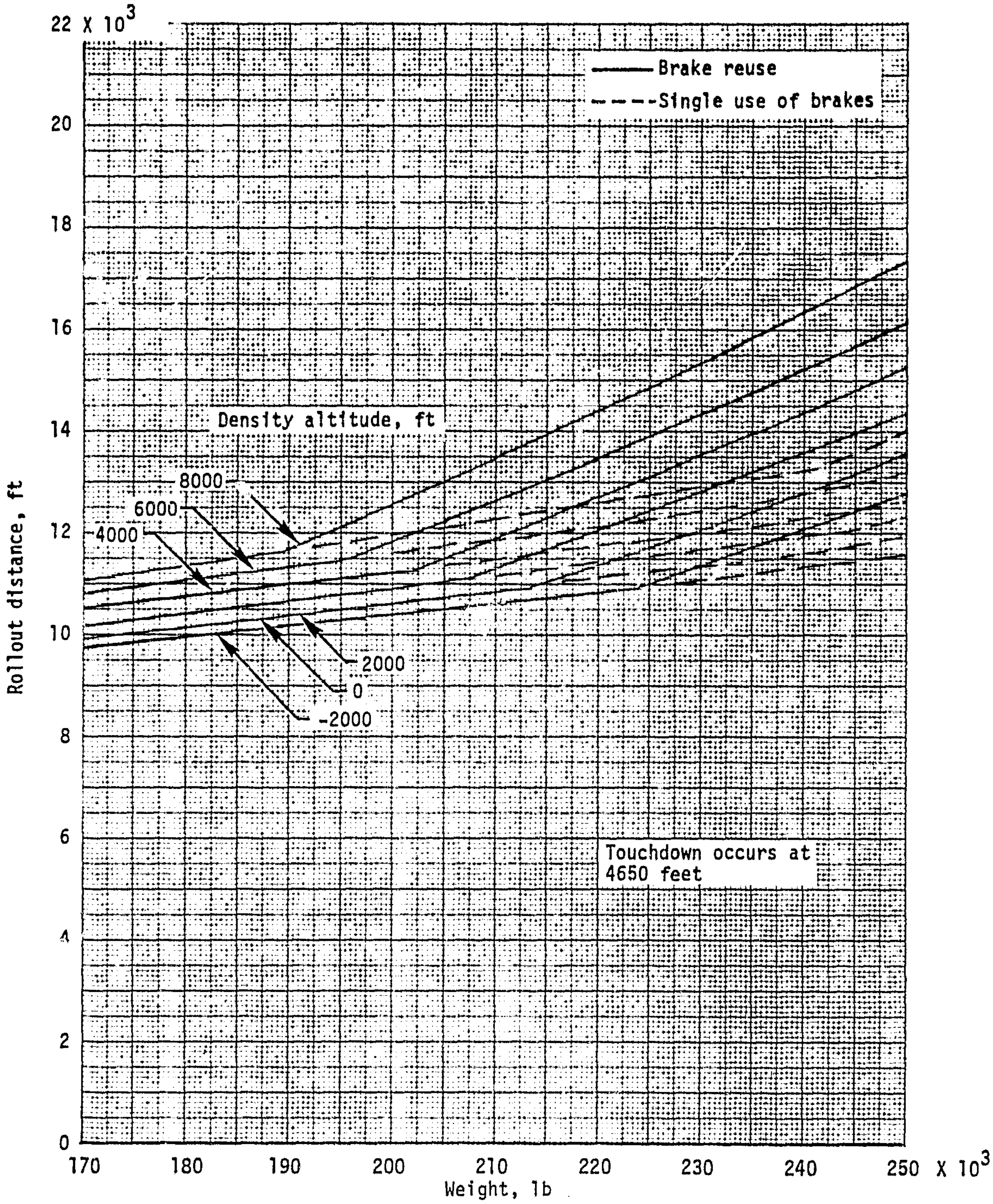



Figure 5.- Minimum control speed of 240 000-pound Orbiter as a function of pitch and longitudinal position of center of mass.



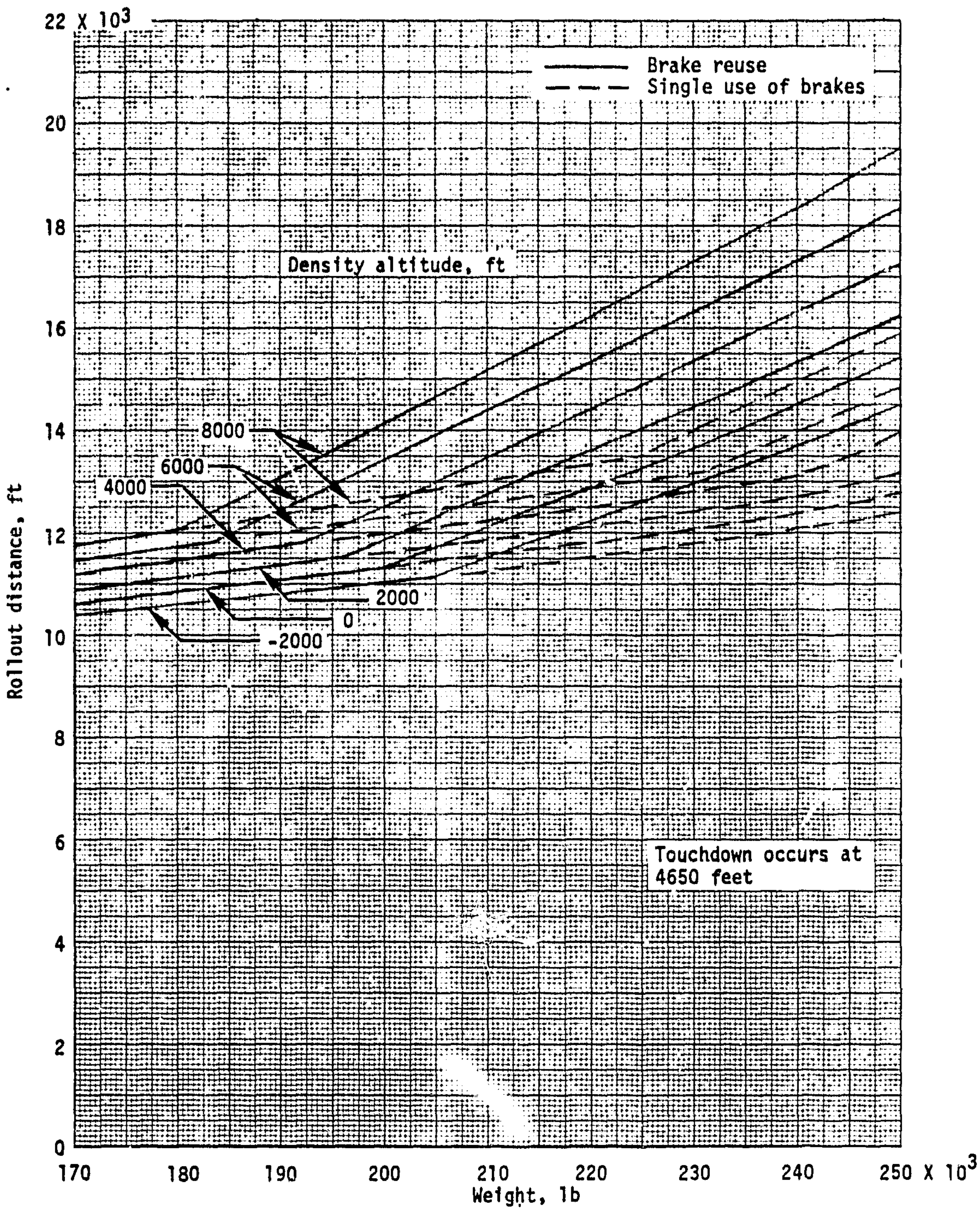

(a) 10-knot headwind.

Figure 6.- Total rollout distance as a function of weight and density altitude for minimum expected landing speed with forward center of mass.




(b) Zero wind.

Figure 6.- Continued.




(c) 10-knot tailwind.

Figure 6.- Concluded.



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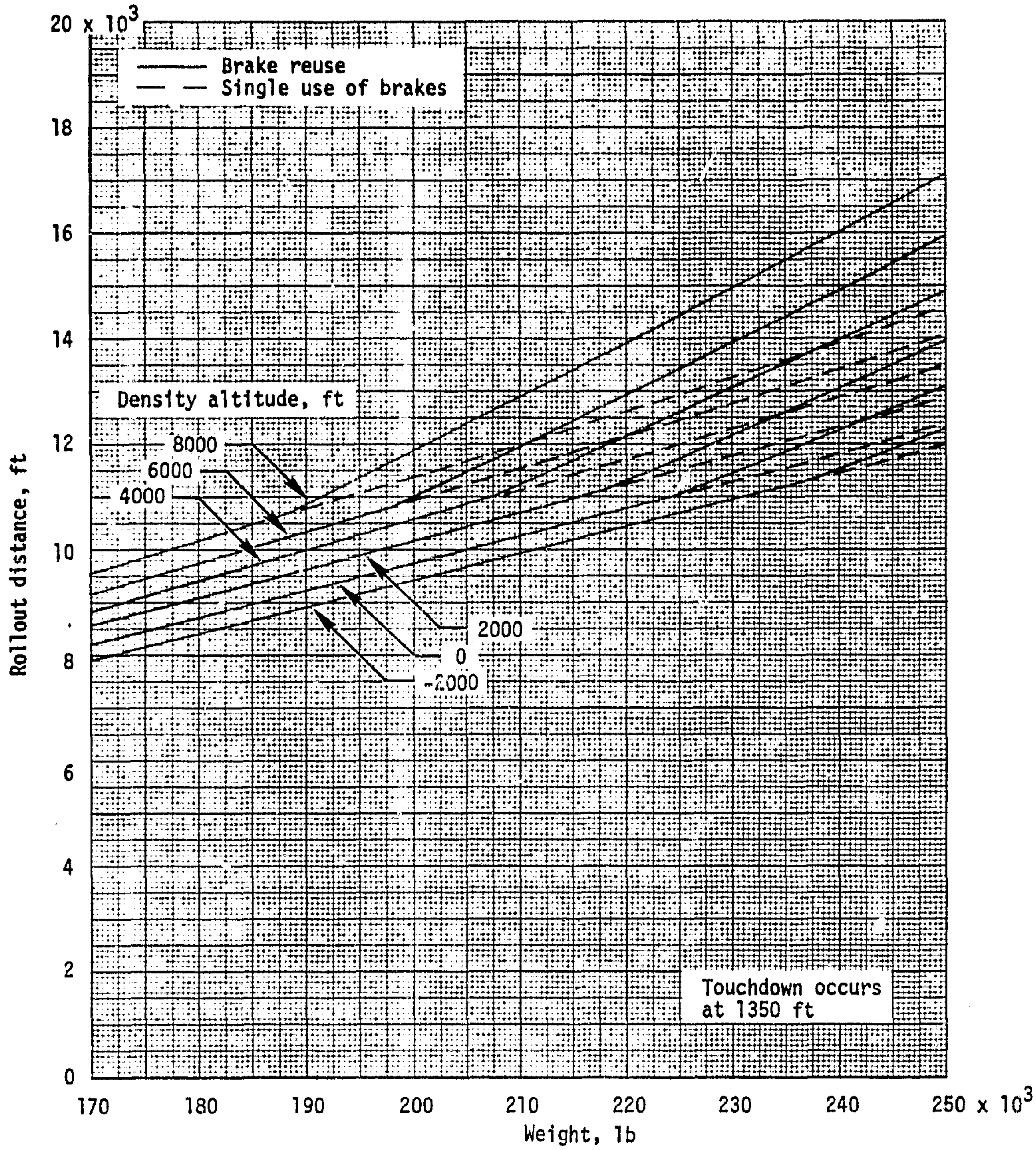
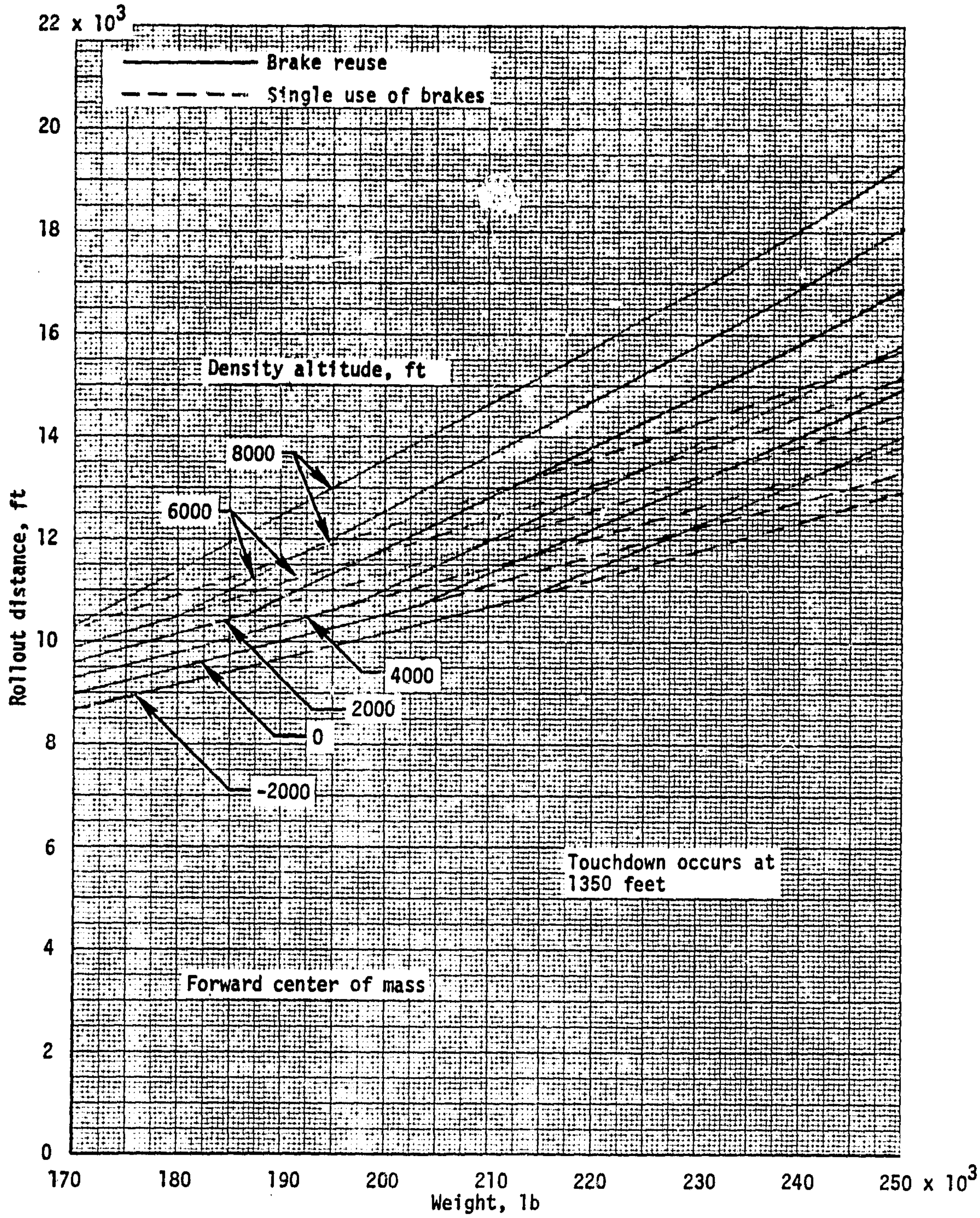


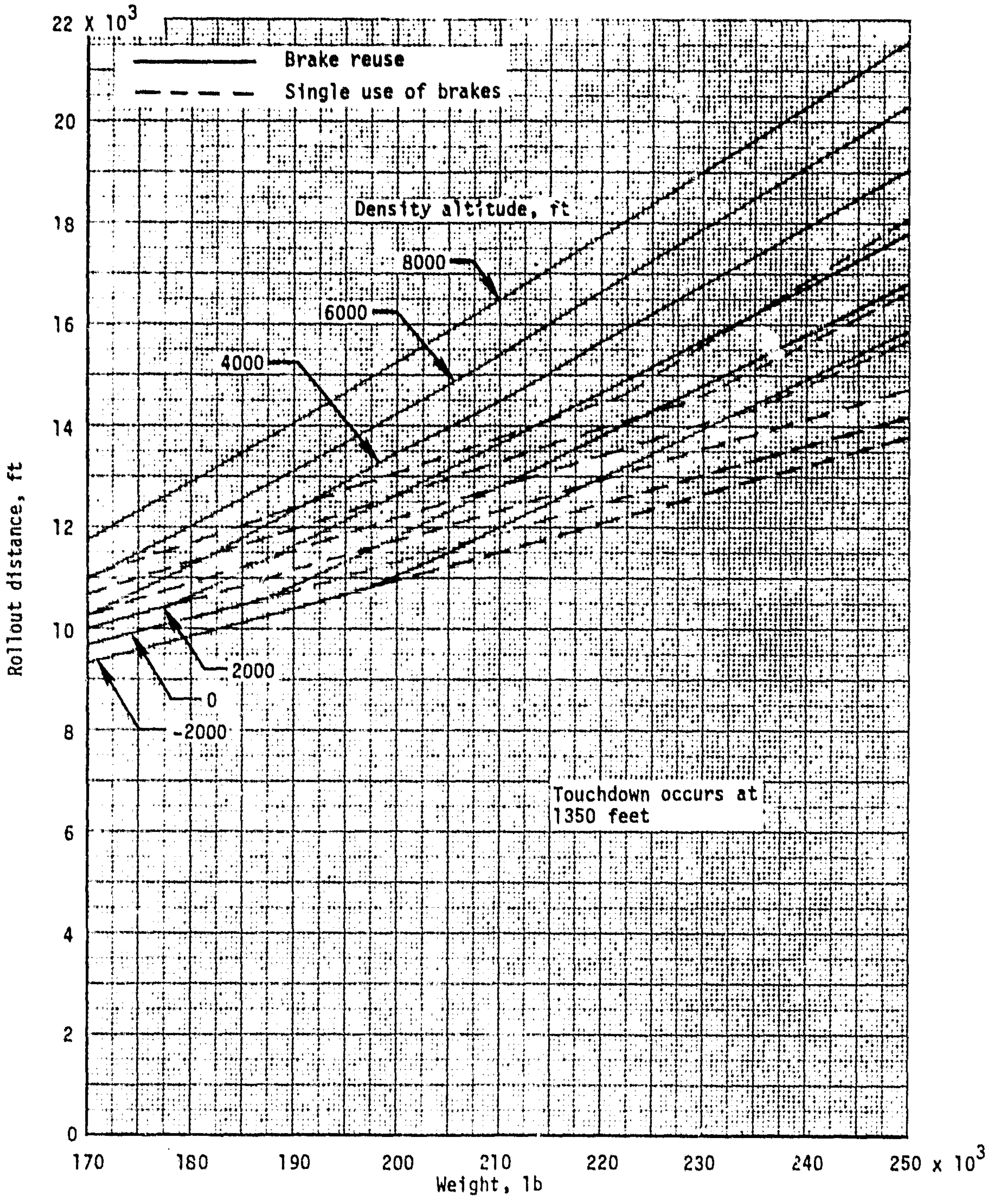

(a) 10-knot headwind.

Figure 7.- Rollout distance as a function of weight and density altitude for maximum expected landing speed with forward center of mass.



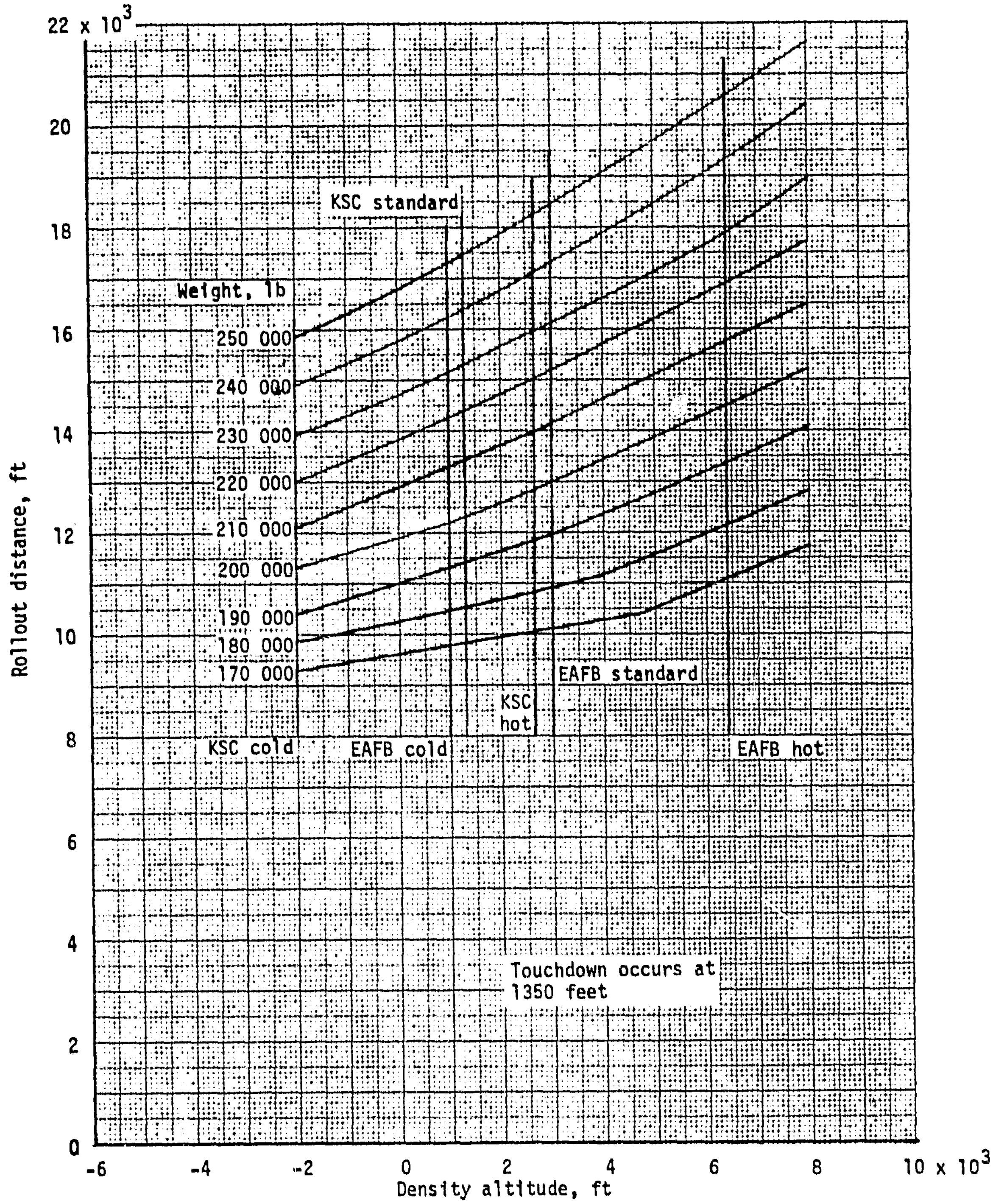

(b) Calm.

Figure 7.- Continued.



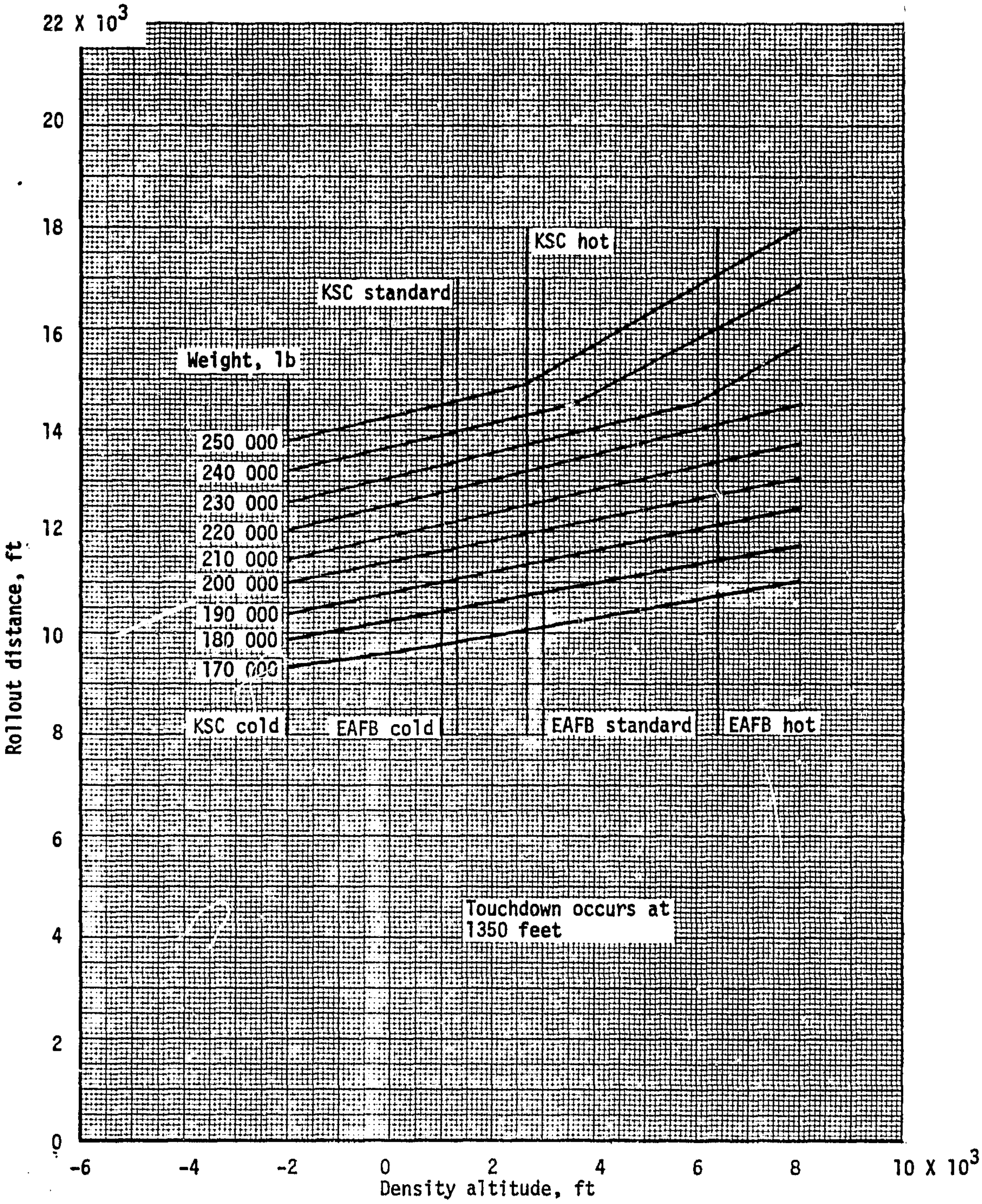

(c) 10-knot tailwind

Figure 7.- Concluded.



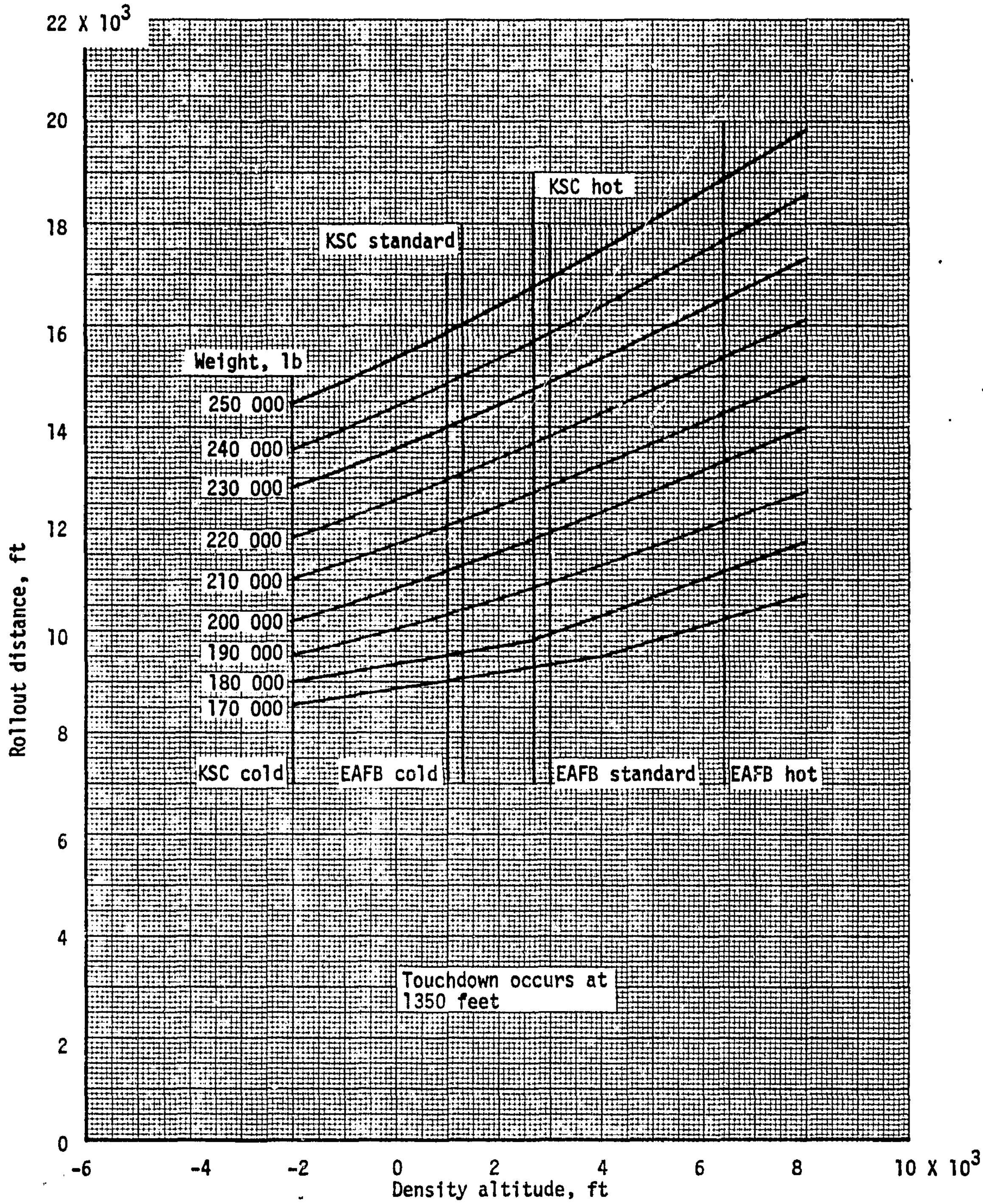

(a) Reuse of brakes.

Figure 8.- Rollout distance for maximum expected landing speed with forward center of mass and 10-knot tailwind as a function of density altitude and weight.



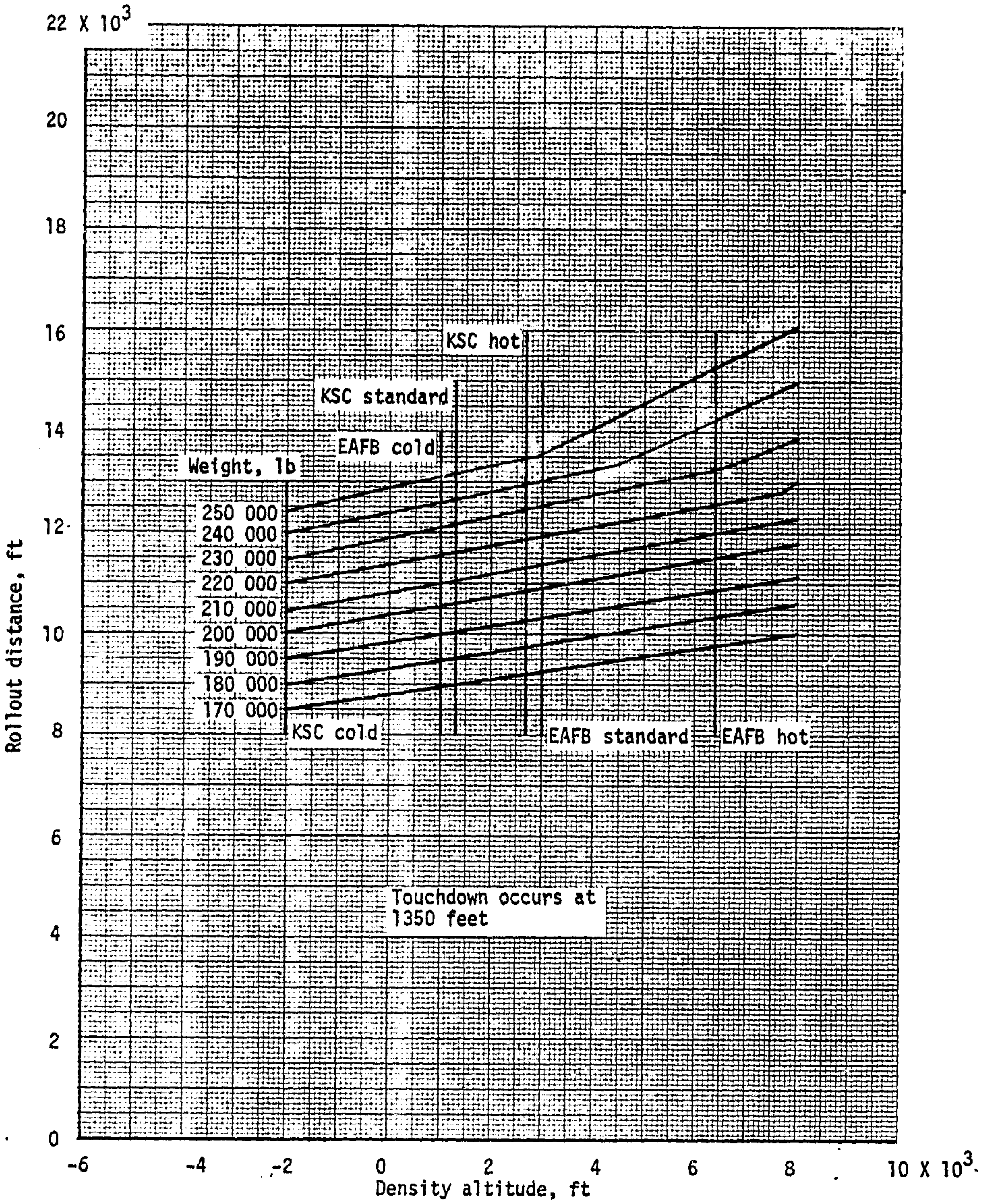

(b) Single use of brakes.

Figure 8.- Concluded.



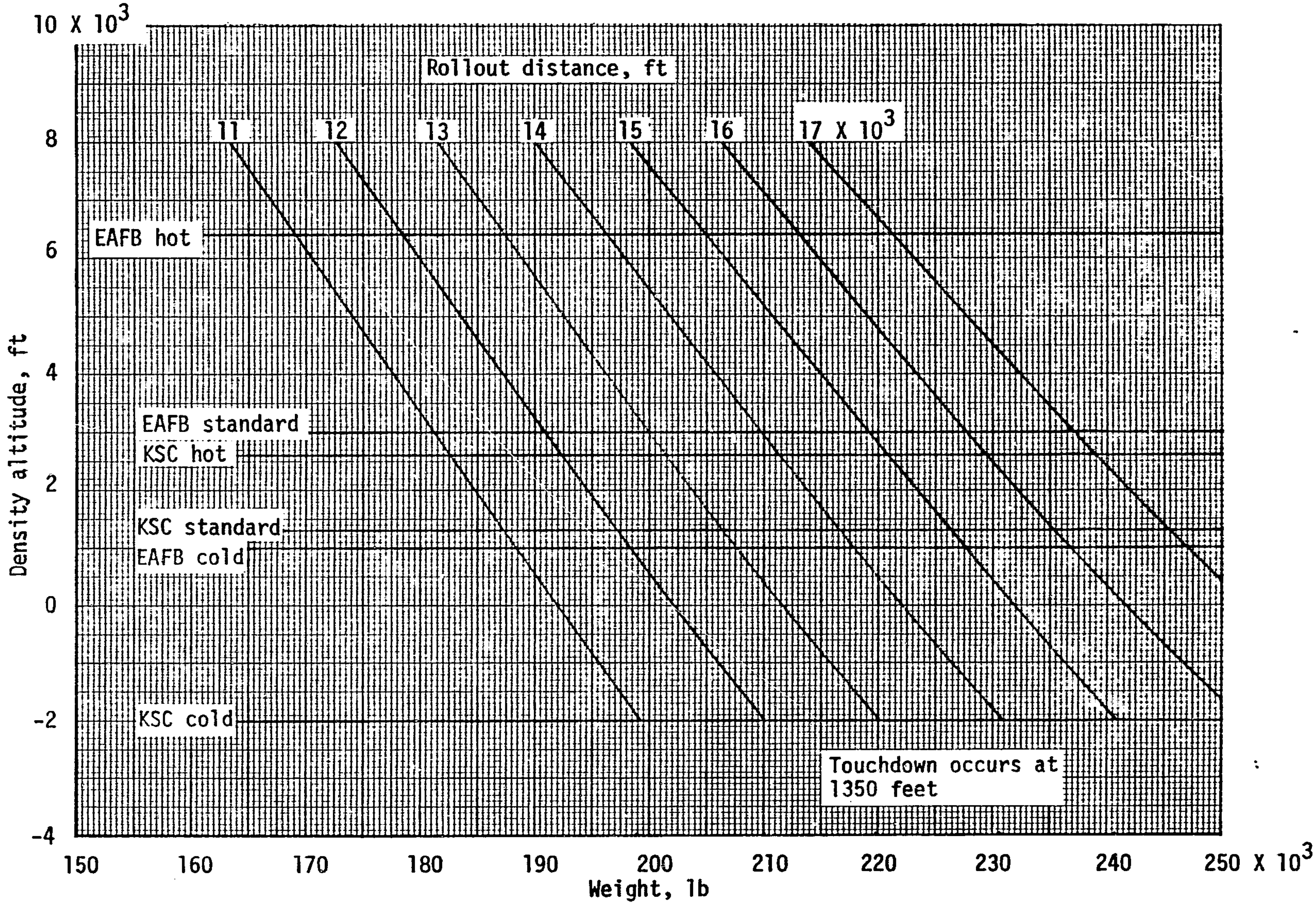

(a) Reuse of brakes.

Figure 9.- Rollout distance for maximum expected landing speed with aft center of mass and 10-knot tailwind as a function of density altitude and weight.



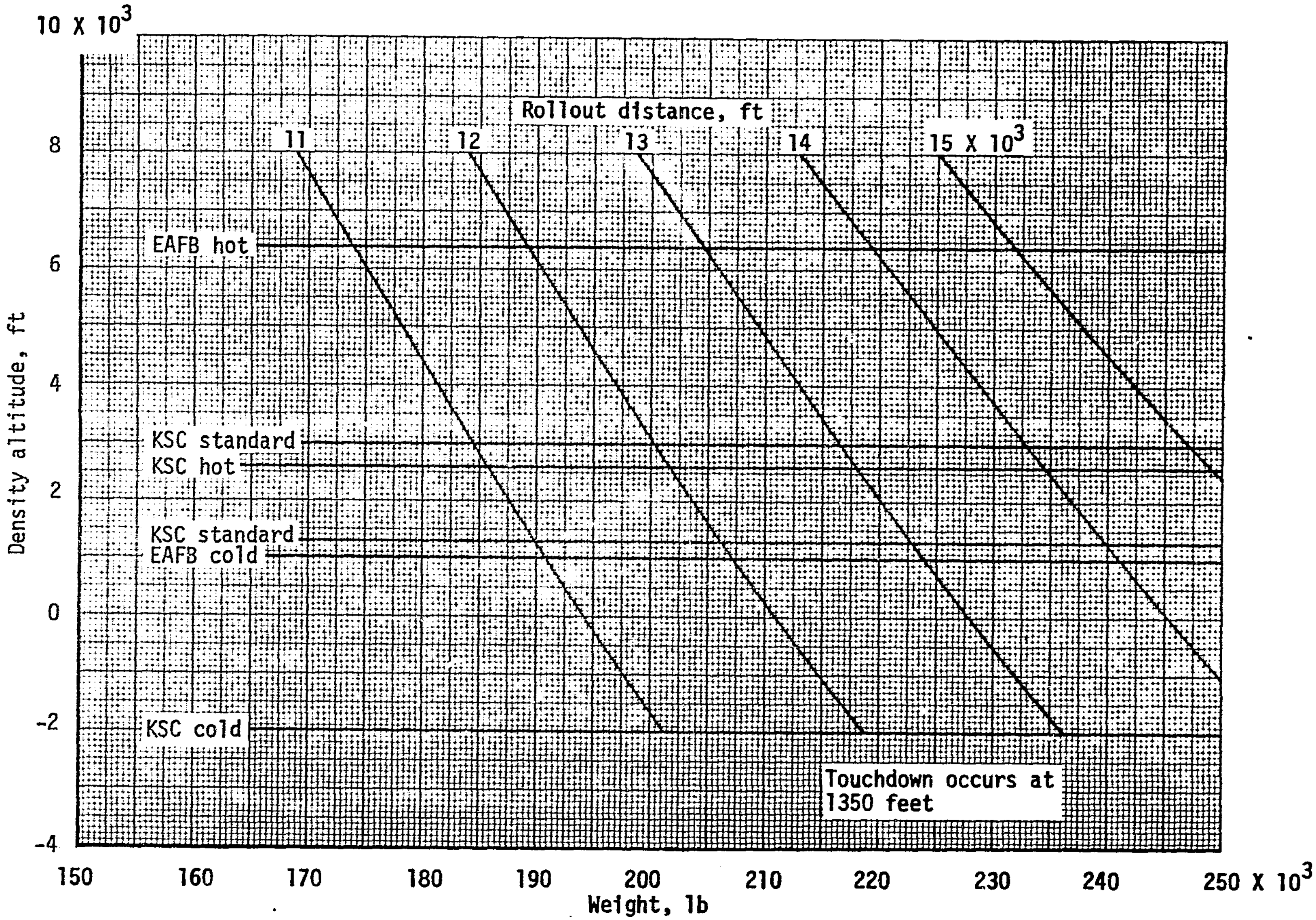

(b) Single use of brakes.

Figure 9.- Concluded.



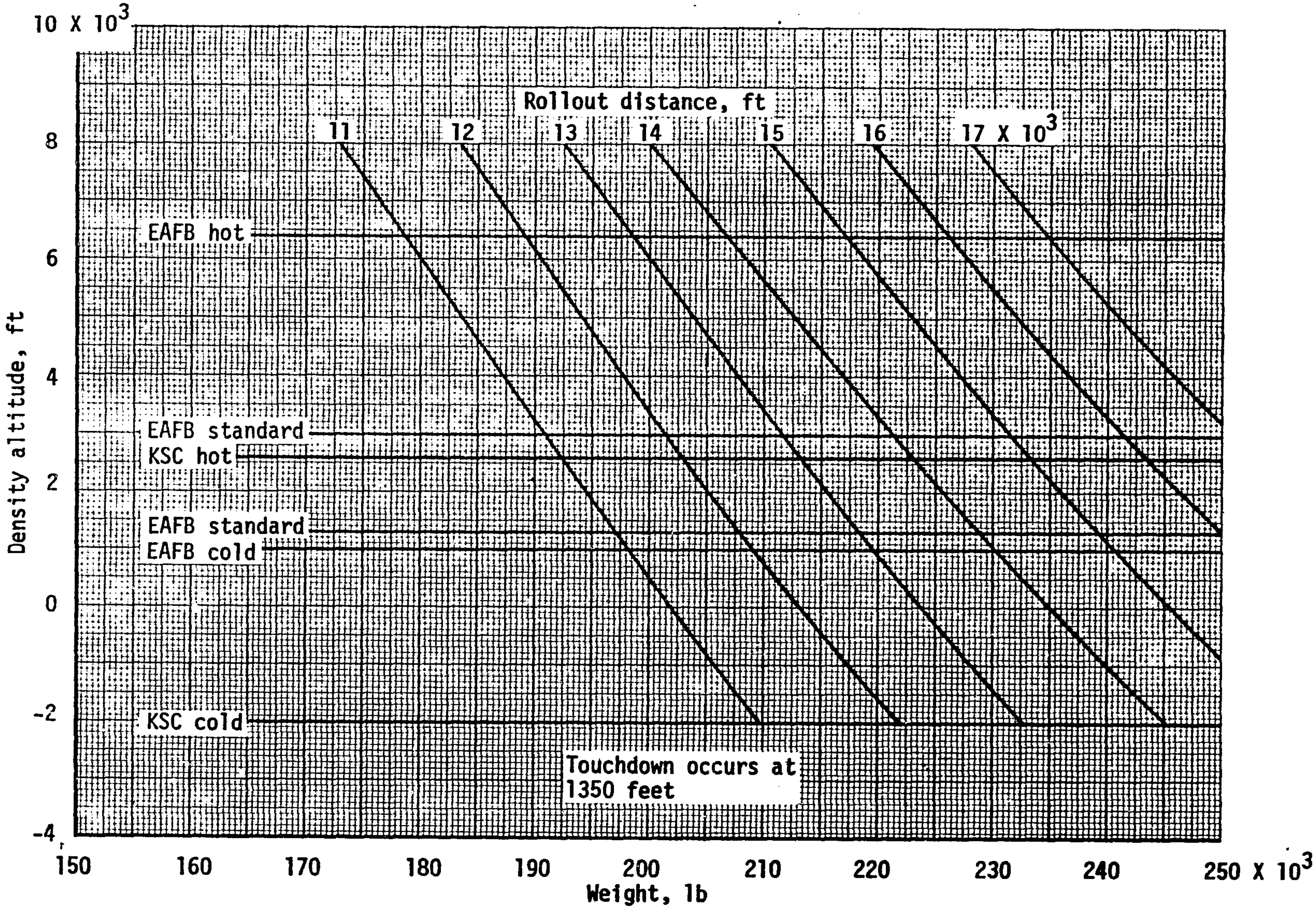

(a) Reuse of brakes.

Figure 10.- Relationship of density altitude to Orbiter weight for constant rollout distance with 10-knot tailwind and forward center of mass.



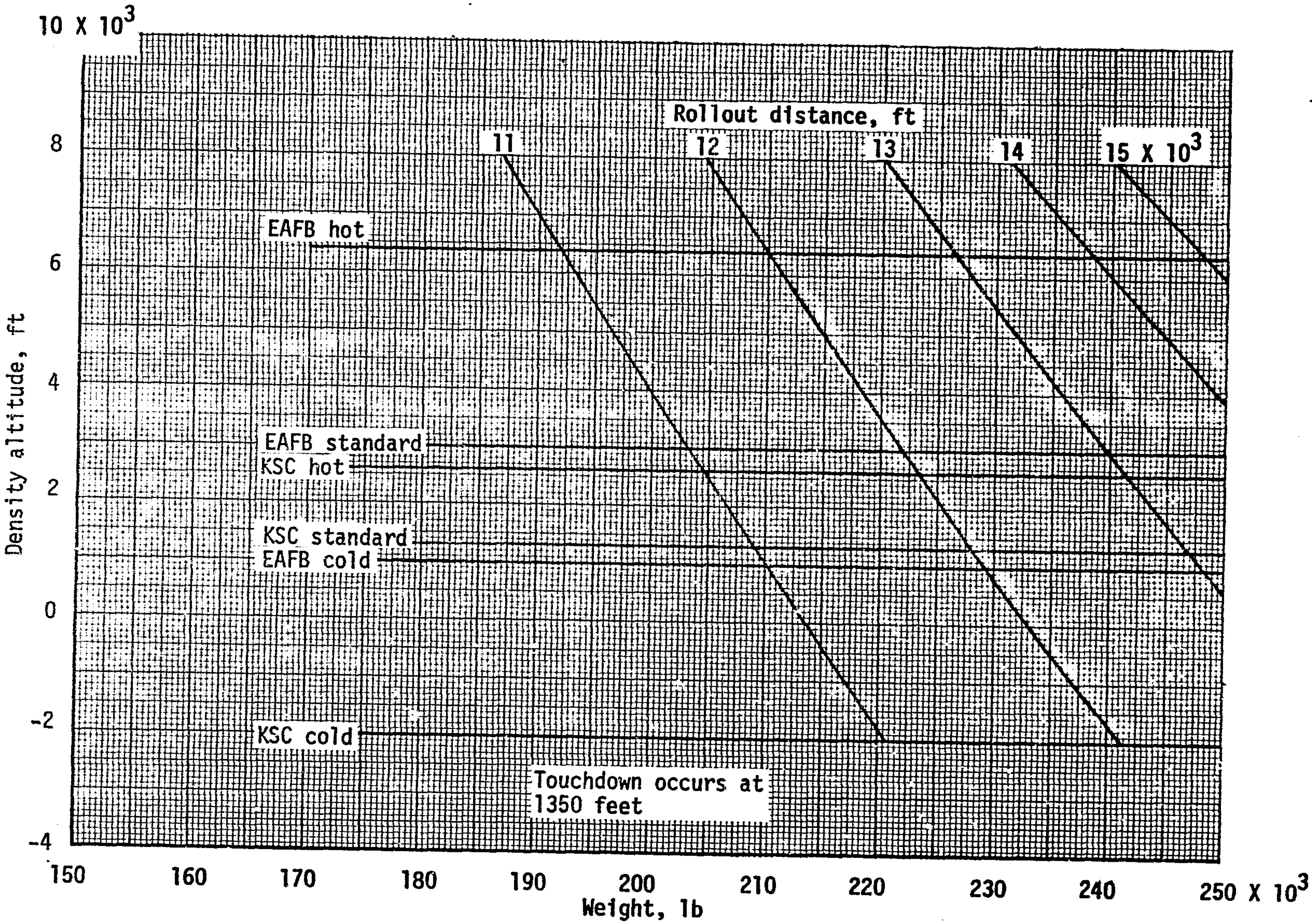

(b) Single use of brakes.

Figure 10.- Concluded.



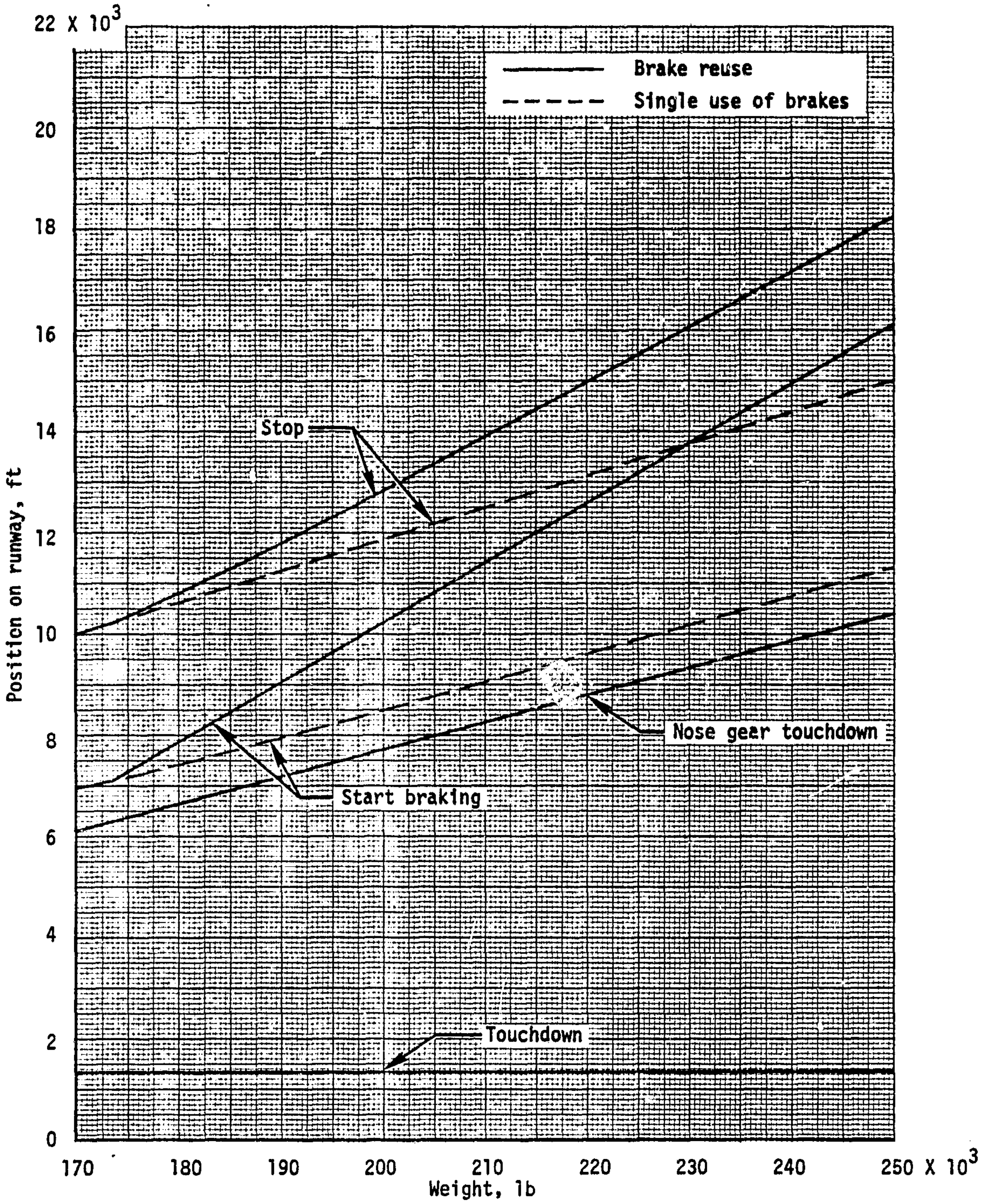

(a) Reuse of brakes.

Figure 11.- Relationship of density altitude to Orbiter weight for constant rollout distance with 10-knot tailwind and forward center of mass.



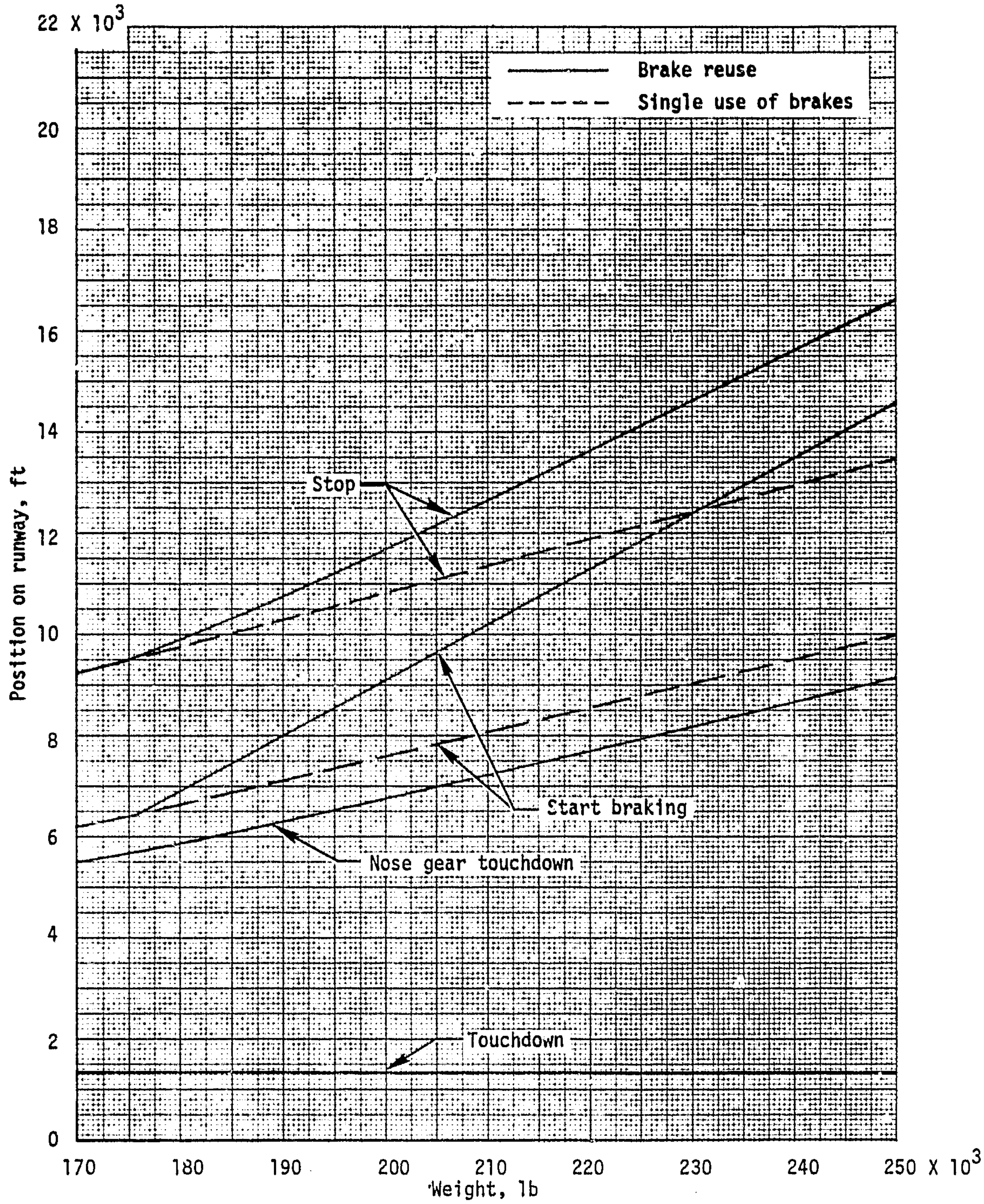

(b) Single use of brakes.

Figure 11.- Concluded.



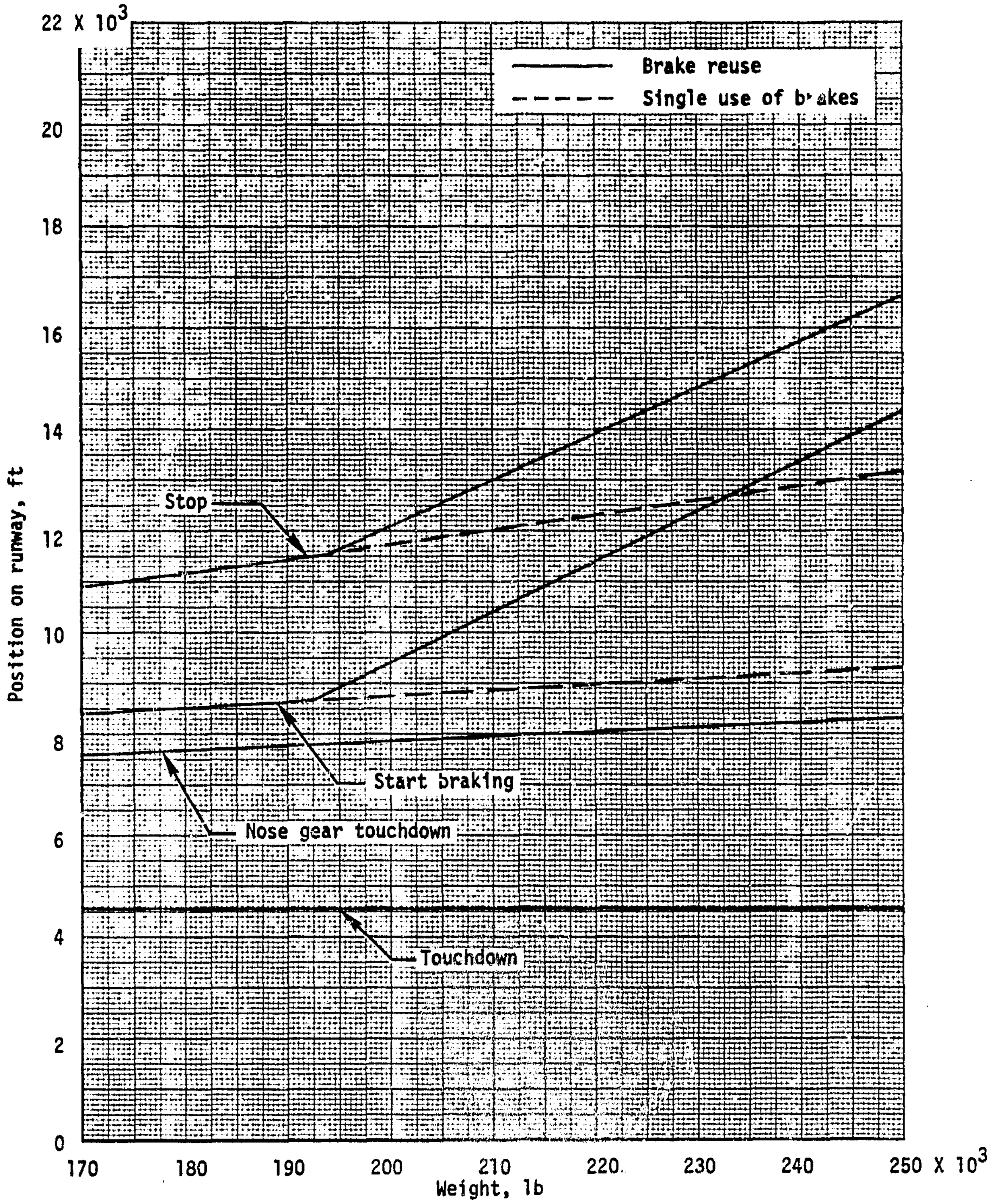

(a) Forward center of mass.

Figure 12.- Locations of key events during rollout on hot day at KSC with 10-knot tailwind (maximum expected landing speed).



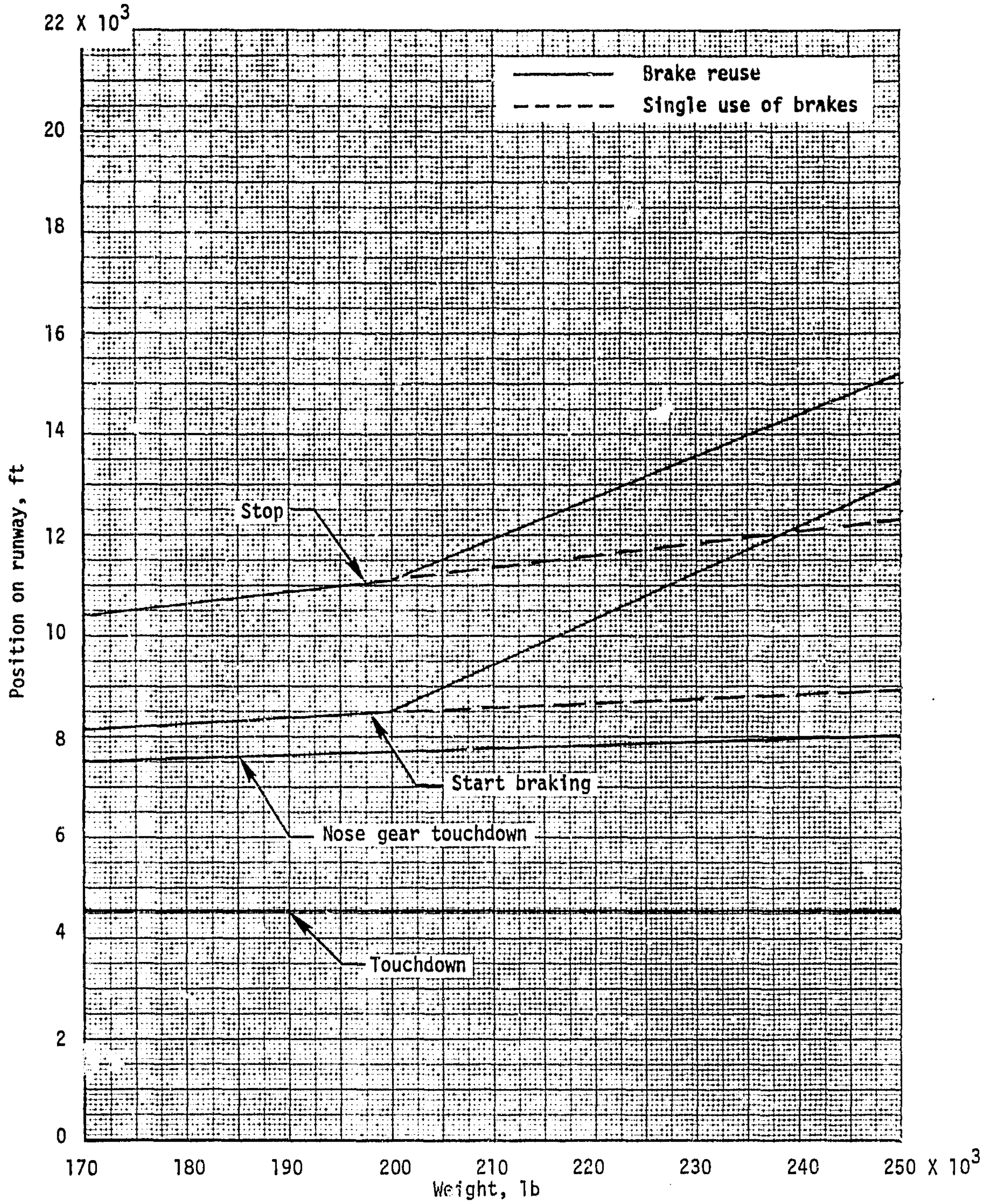

(b) Aft center of mass.

Figure 12.- Concluded.



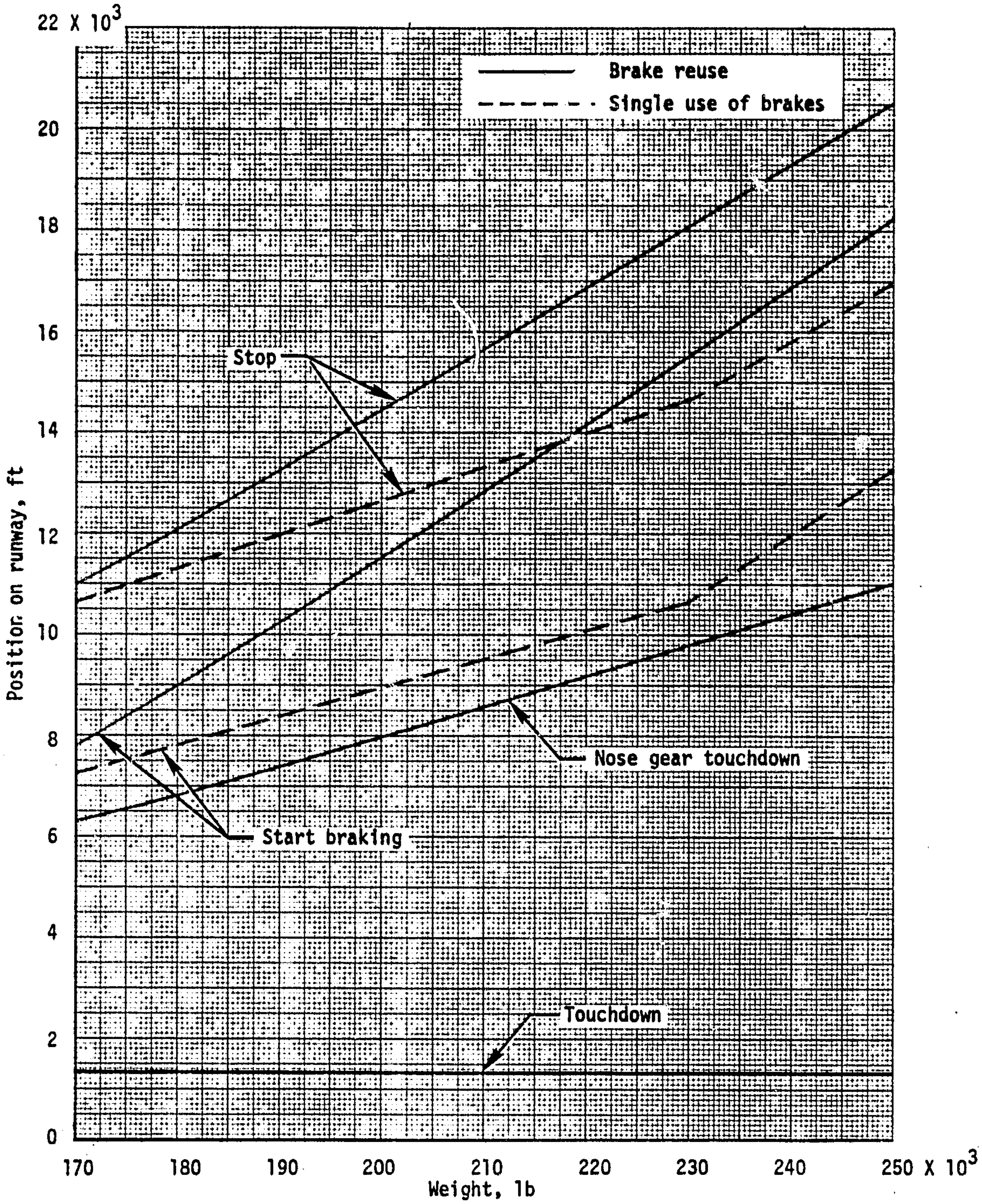

(a) Forward center of mass.

Figure 13.- Locations of key events during rollout on hot day at KSC with 10-knot tailwind (minimum expected landing speed).



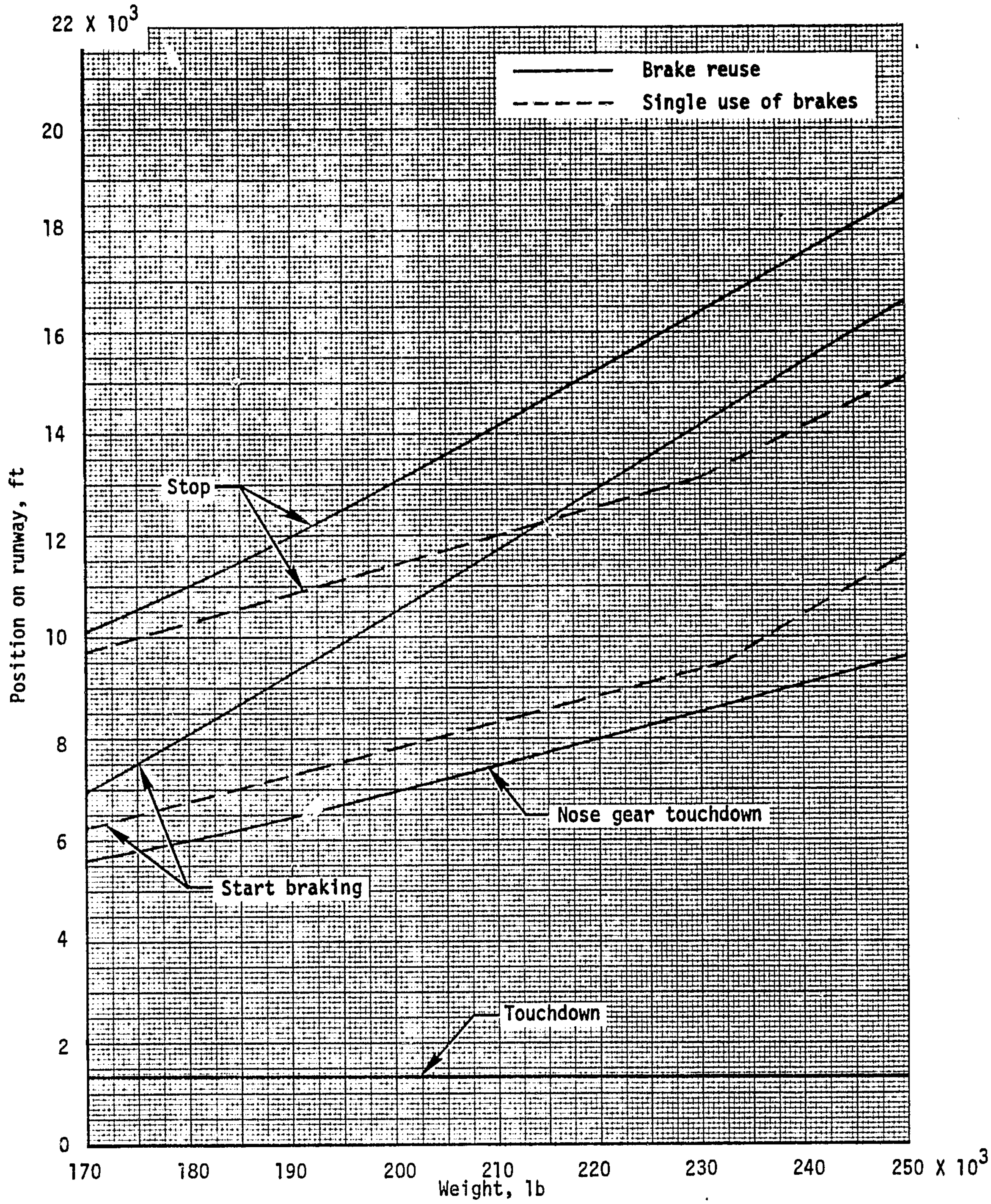

(b) Aft center of mass.

Figure 13.- Concluded.



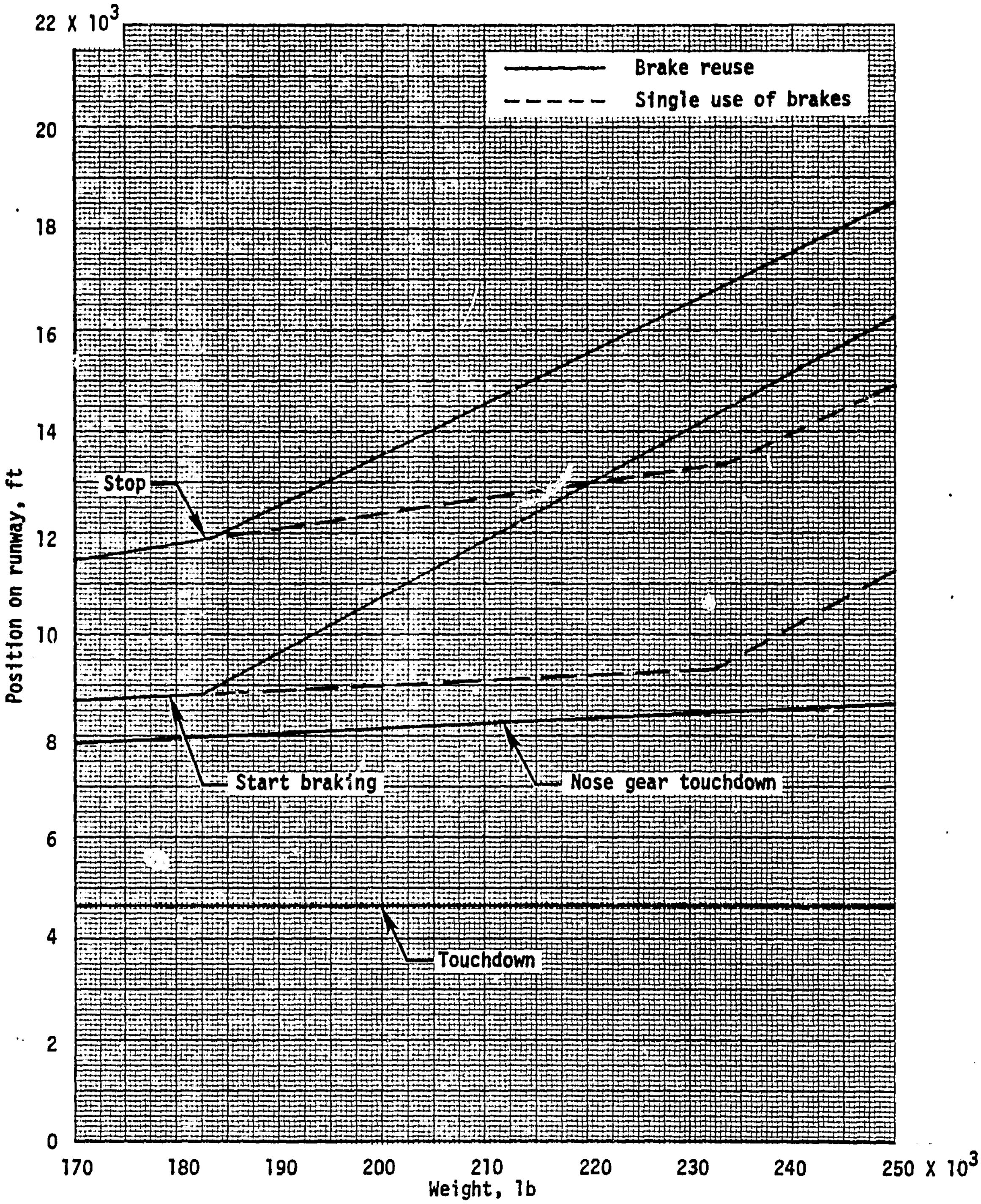

(a) Forward center of mass.

Figure 14.- Location of key events during rollout on hot day at EAFB with 10-knot tailwind (maximum expected landing speed).



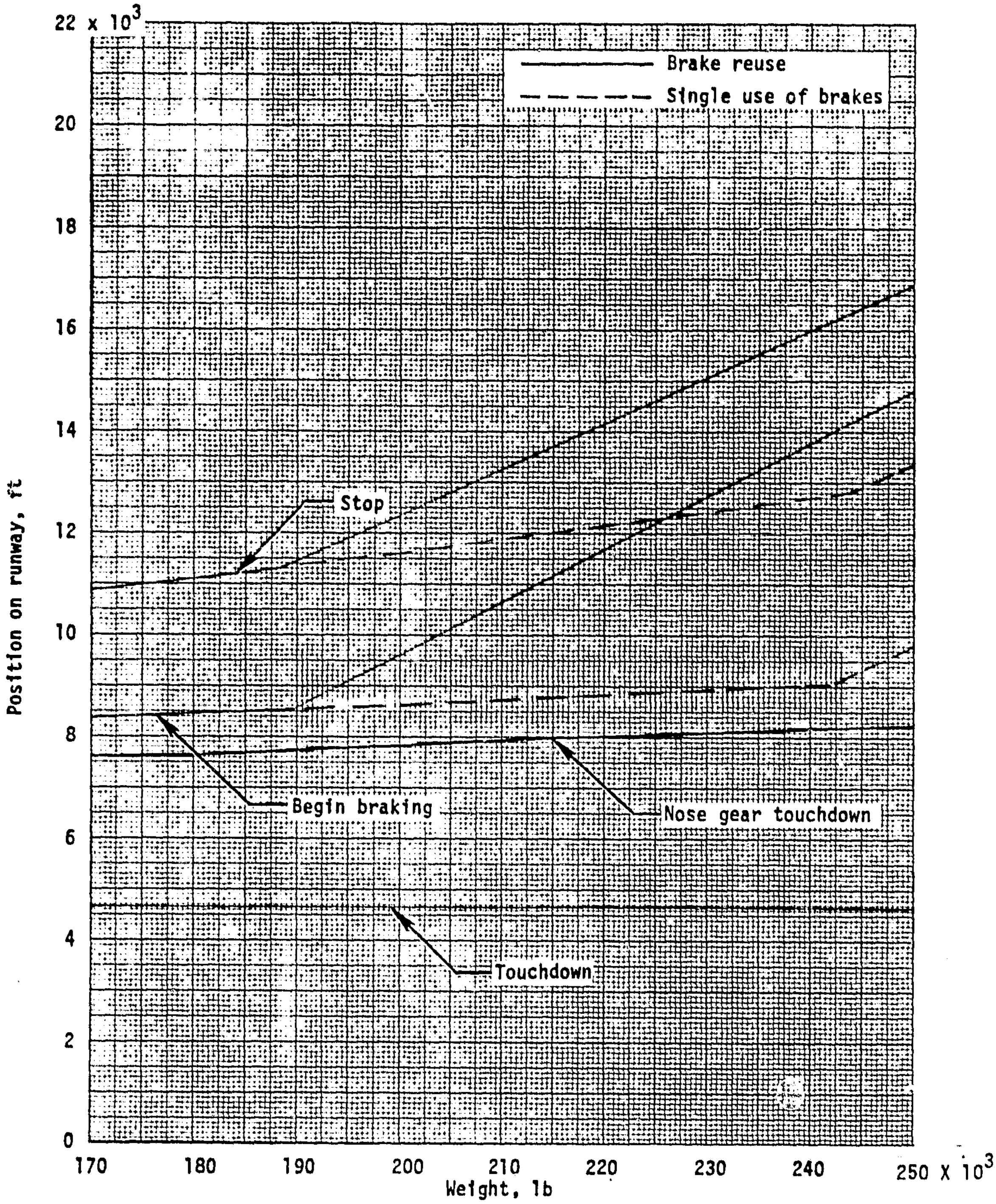

(b) Aft center of mass.

Figure 14.- Concluded.




(a) Forward center of mass.

Figure 15.- Location of key events during rollout on hot day at EAFB with 10-knot tailwind (minimum expected landing speed).




(b) Aft center of mass.

Figure 15.- Concluded.

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