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TECHNICAL NOTE

D-448

SOME LANDING STUDIES PERTINENT TO
GLIDER-REENTRY VEHICLES

By John C. Houbolt and Sidney A. Batterson

Langley Research Center
Langley Field, Va.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
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SUMMARY

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Results are presented of some landing studies that may serve as guidelines in the consideration of landing problems of glider-reentry configurations.

The effect of the initial conditions of sinking velocity, angle of attack, and pitch rate on impact severity and the effect of locating the rear gear in various positions are discussed. Some information is included regarding the influence of landing-gear location on effective masses. Preliminary experimental results on the slideout phase of landing include sliding and rolling friction coefficients that have been determined from tests of various skids and all-metal wheels.

INTRODUCTION

Among the problems to be considered for glider-reentry vehicles is that of providing safe landing on return. Studies pertinent to the landing of these configurations have therefore been made, and the purpose of this paper is to present the results. It is convenient to separate the presentation into two parts.

Part I deals analytically with the effect of the initial conditions of sinking velocity, angle of attack, and pitch rate on impact severity, as well as the effect of rear-landing-gear position, including the influence of landing-gear location on the effective masses.

Part II deals with preliminary results of an experimental investigation of landing gears for glider-reentry vehicles. The configurations studied consist of a skid-type main gear and a nose gear equipped with either a skid or an all-metal wheel. This arrangement is reliable and also saves weight since it does not require cooling during reentry. Reentry vehicles of this type are very restricted in a choice of landing sites. The runway available for recovery may under some conditions be as

short as 5,000 feet and may be composed of either a concrete, asphalt, or lakebed surface. During the landing and subsequent slideout, the landing gear must provide adequate directional stability and, in addition, develop a drag load large enough to stop the vehicle before the end of the runway is reached. The problems arising from these conditions were studied at the Langley landing loads track by making simulated landings using a variety of skid configurations and all-metal wheels.

SYMBOLS

e	distance between center of gravity and main (rear) landing gear
e_{cr}	maximum distance between center of gravity and main landing gear for no second impact
e_{cp}	distance between center of gravity and center of percussion
e_n	distance between center of gravity and nose landing gear
e_R	distance between center of gravity and main landing gear at which tail load balances airplane weight
F	force
g	acceleration of gravity
k	radius of gyration in pitch
L_t	tail load
m	total mass
m_1	effective mass at main (rear) landing gear
m_2	effective mass at nose landing gear
n_1	$n_1 = \frac{\ddot{y}_0 + e\ddot{\alpha}_0}{g}$
V	velocity
W	weight

y	vertical displacement
\dot{y}	vertical velocity
\ddot{y}	vertical acceleration
α	angle of attack
$\dot{\alpha}$	angular velocity in pitch
$\ddot{\alpha}$	angular acceleration in pitch
μ	coefficient of friction

Subscripts:

1	refers to main (rear) landing gear
2	refers to nose landing gear
o	initial condition at center of gravity

I - LANDING IMPACT ANALYSIS

The factors to be considered in part I of the present study are indicated in figure 1. First shown are the approach conditions α_0 , $\dot{\alpha}_0$, and \dot{y}_0 and the distance e between the main landing gear and the center of gravity. Next are indicated the effective masses m_1 and m_2 at the main and the nose landing gear, respectively.

Initial Conditions

The initial conditions which affect the severity of the first impact in landing are shown in figure 2. The vehicle is considered to have a nonrebouncing type of landing gear, which has an essentially rectangular force-deflection curve, as would be obtained, for example, by use of a plastic yielding strut. The important result shown in the figure is the fact that the strut deflection can be expressed completely in terms of the initial velocity and acceleration at the landing-gear location, regardless of whether the velocity is due to a vertical translation or a pitch rate or whether the acceleration is due to a translatory acceleration or a pitch acceleration, as would result in the case of a non l g wing lift or an out-of-trim pitching moment. Note that the distance e of the gear aft of the center of gravity enters into the determination of

the velocity and acceleration at the gear. For reentry-type gliders, e generally will be much larger than is used in airplane configurations so as to avoid the tail scrubbing problem that is associated with the necessary high angle-of-attack, low lift-drag-ratio landing approach. Increased e therefore tends to make pitch rate and angular acceleration enter more prominently into the landing problem than heretofore. Conceivably, then, from a design standpoint, it may become necessary to establish realistic values of $\dot{\alpha}_0$ and $\ddot{\alpha}_0$ as well as $\dot{\gamma}_0$ and $\ddot{\gamma}_0$.

Rear-Landing-Gear Location

A more definite consequence of the use of large approach angles of attack and main landing gears placed well to the rear is the fact that increased attention must be focused on impacts which follow the initial impact; the second impact of the rear landing gear may, in fact, be much more severe than the first. An explanation is readily afforded by means of the schematic sketches shown on figure 3. With reference to the top sketch of figure 3, the high angle-of-attack approach and the upward pointing flow vector caused by the sinking speed mean that the stabilizer must have a rather large negative deflection to keep the airplane in trim and may even have to have a download for the situation where the wing center of lift is behind the center of gravity. After initial impact of the rear landing gear and during nose landing-gear impact, the landing condition becomes that shown on the lower sketch of figure 3. The tail has encountered two sizable increases in negative angle of attack, namely, the rotation of the vehicle to horizontal (or even to a slight negative attitude) and a change in the wind-flow direction to nearly horizontal. The download on the tail is now very large. All the loads - the tail load, the weight and download on the wing, and the large upload at the nose - are in directions virtually to drive the tail into the ground. Note that the initial conditions for the second rear impact about to occur in this figure are mainly those of large initial accelerations, the potential-energy type of impact in contrast to the kinetic-energy type of the first impact. Mention may also be made that the use of landing gears with some rebound characteristics would only serve to aggravate the situation. Such gears would feed back a potential energy into the system, which would then have to be taken out again; they should therefore be avoided if possible, especially because of the second rear-impact condition.

The second rear impact occurs only if the gear is located sufficiently aft. For gear location closer to the center of gravity, only one rear impact will occur. The difference in the landing sequences for these two situations is indicated in figure 4. For values of e less than a value which for the present purpose is designated e_{cr} , the vehicle first impacts on the rear gear, then pivots about the rear-gear point,

impacts on the nose gear, and comes to rest. For e greater than e_{cr} the first two phases are the same, but during the nose-gear impact the rear gear deflects further. The nose gear comes to rest, but the rear gear continues to deflect until the final rest position is obtained. Note that for $e > e_{cr}$ three movements of the rear gear occur in contrast to only one for $e < e_{cr}$.

Figure 5 indicates more specifically the effect of rear-gear location on impact severity. A configuration, representative of the X-15 airplane, having a weight of 14,000 pounds, a pitch radius of gyration of 161 inches, and a distance between the center of gravity and the nose gear of 280 inches, was arbitrarily chosen for study, and rear-gear positions covering the range from the center of gravity back to the rear of the fuselage were investigated. Results for energy absorbed and for strut travel are given in terms of the rear-gear location e . The plot at the top of the figure shows the energy absorbed in the first rear impact, the second rear impact, and in the nose gear; and the bottom plot shows rear and nose strut travel. The solid curves apply for an approach angle of attack of 10° , whereas the dashed curves apply to an approach angle of attack of 8° . Two main points are to be made from this figure: first, note the very pronounced increase in rear-strut travel as e is increased from a value of around 135 to 200 inches; at $e = 200$ inches, in fact, the total strut travel is on the order of three times the travel brought about by first impact alone; second, notice the marked decrease in rear-strut travel when the angle of attack is reduced from 10° to 8° . Angle of attack thus appears to be quite important and is discussed in more detail subsequently.

A further comment pertinent to figure 5 is in connection with the three values of e labeled on the abscissa as e_R , e_{cp} , and e_{cr} . If e is less than e_R , then the download at the tail will cause a tail-down rocking of the airplane, and therefore the region of $e < e_R$ is to be avoided. The value e_{cp} designates the location of the center of percussion; it is important from an effective mass consideration and is discussed further subsequently. The value of e_{cr} was mentioned previously in connection with figure 4; it separates the region where no additional rear-strut movement occurs during nose impact from that where some such movement occurs.

Figure 6 shows shock-strut force for a landing of the X-15 airplane (an e of 195 inches). The second rear impact is three to four times as severe as the first. Although the characteristics of the actual X-15 shock strut are somewhat different from those of the assumed idealization, these results furnish a qualitative substantiation of the predictions in figure 5.

In figure 7, additional results pertaining to the location of the rear landing gear are given; again, a nonrebounding type of gear having an essentially rectangular force-deflection curve was assumed. The solid-line curve is the maximum rear-gear force that can be applied in

first impact without exceeding a chosen design acceleration of 2.5g at any point in the vehicle. Thus, for example, a landing gear located 100 inches behind the center of gravity must not develop more than 20,000 pounds of force. The broken-line curves apply for the nose and second rear impact, and follow from two conditions: first, again that an acceleration of 2.5g is nowhere exceeded and second, that during nose impact the airplane simply pivots around the rear gear. For values of e less than about 135 inches, the force F_2 provided by the nose strut is sufficient to absorb completely the energy remaining in the airplane after initial impact. The force F_1 in the rear strut does not exceed that provided so that no further deflection of the rear strut takes place. However, for e greater than about 135 inches, the force F_1 necessary to satisfy the two conditions previously stated on acceleration and pivoting exceeds that provided. The rear strut therefore has to move farther, and the extent of this additional travel is governed by the distance by which the dashed curves for F_1 fall above the solid curve for F_1 . Results are presented for several combinations of airplane weight and download at the tail and indicate that a much greater strut travel is to be expected for the cases of high W and large L_t . It is interesting to note that the additional rear-strut travel in the region of high e can be avoided if desired; thus, if maximum nose-strut load provided is made to follow the lower dot-dash branch on the right of figure 7 instead of the upper branch, then this lower nose load and the rear-gear load along the solid F_1 line will arrest the airplane without further rear-strut travel, of course at the expense of increased nose-gear deflection.

Approach Angle of Attack

Figure 8 brings out more specifically the influence of approach angle of attack. The left side of the figure shows the total rear-strut deflection that would occur as a function of α_0 for the condition of an initial sinking velocity of 9 fps, and for a rear-strut location e of 195 inches. Note the very abrupt increase in strut deflection in the neighborhood of α_0 of 10° to 12° . From a design standpoint the strut travel must, of course, be limited; if, for example, a value of 1.5 feet is chosen, then the approach angle of attack must not be greater than 9.4° . This angle and the chosen design sinking speed of 9 fps thus fix the upper right-hand corner of the illustrative design-limit envelope shown on the right-hand side of the figure. Choosing lower sinking velocities yields different limiting values of α_0 , which then fix the right edge of the limit envelope. Approach angle of attack is thus an important consideration in the design of reentry gliders for landing.

Further results on angle of attack are given in figure 9, where the vertical velocity of the nose gear is given in terms of approach angle of attack for two different values of e . Initially, the airplane is assumed to be sinking at 9 fps. After initial rear impact the nose velocity has increased to the values shown by the solid lines. In the interval between the end of this first impact and just before nose touch-down, the vertical velocity increases to the dotted-line values. Notice that no strong dependence of nose-gear vertical velocity on angle of attack is indicated; an increase in severity of second rear-gear impact with increased approach angle of attack cannot therefore be attributed to a marked increase in nose-gear-impact severity. The main reason for increased severity of second impacts with large α_0 is associated with the download at the tail. Increasing α_0 means that the tail has to be deflected downward more; this increased deflection leads to a larger tail load, which then not only accelerates the tail into the ground more severely, but also causes an increase in the static load that must be supported by the main gear.

Effective Masses

Results which pertain to effective masses are next considered briefly. Effective masses are of interest because of the role they play in the drop-test development of the landing struts where, for example, concentrated masses are used. Figure 10 shows the effective mass on the nose strut and the effective mass on the rear strut (expressed as a ratio to the total mass) as a function of the load ratios F_1/F_2 and F_2/F_1 . These results show that care must be used in the selection of the appropriate effective mass because no unique value exists. The notable exception is for the case of $e = 93$ inches, since for this case the effective masses are independent of the applied loads. The dynamical significance of the 93-inch location might be stated as follows: If a pivot point is located 93 inches behind the center of gravity, then the nose strut will be located at the associated center of percussion. Conversely, if the pivot point is considered to be at the nose strut, then a distance of 93 inches represents the center-of-percussion location for the rear strut. Expressed mathematically, the condition for constant effective masses is established when the product of e and the distance between the nose gear and the center of gravity equals the square of the pitch radius of gyration k . The main point to be made about this figure is that the center-of-percussion location is desirable from the standpoint of choosing "universal" effective masses. Other factors are also favorable for this location; that is, the amount of energy to be absorbed is fairly low and the amount of travel necessary for both the rear and nose struts is also quite low. (See fig. 5.)

II - INVESTIGATION OF SKIDS AND METAL WHEELS FOR REENTRY LANDINGS

Apparatus and Test Procedure

Figure 11(a) shows the installation used for the skid tests. A variety of shoe-type skids of different material were attached to the bottom of a special test fixture which in turn was bolted to the axle of a fighter-airplane nose landing gear. Figure 11(b) is a photograph of two steel wire-brush skids which were also adapted for testing with this fixture. For test of the all-metal wheels, the fixture was removed and the wheels were mounted on the strut axle. The two types of wheels tested are shown in figure 12. The wheel shown in figure 12(a) has a steel-wire brush for a tire. The wheel shown in figure 12(b) has a solid-metal tire supported by a series of leaf springs arranged around the periphery of the wheel. The drop linkage and instrumentation used for this investigation were similar to those described in reference 1. The static vertical load was 2,150 pounds and the tests were made at speeds ranging up to 180 feet per second on concrete, asphalt, and a simulated lakebed surface.

The asphalt runway was made with two different types of surfaces. The first 400 feet had a smooth sand finish whereas the remaining length was considerably rougher, having been surfaced with a mix containing a relatively large stone aggregate.

Reliability of Test Results

Because of the equipment used for these tests it was necessary to make each test over the same section of runway. To investigate the effect of making repeated slideouts over the same portion of runway surface, a steel skid was selected as a control. It was the first skid tested and was retested when inspection of the landing surface indicated significant changes. Figure 13 shows the effect on coefficient of friction obtained during these tests of the steel skid on concrete and on both types of asphalt surface. The numbers by each test point indicate the total number of runs that had been made on each surface when that particular data point was obtained. It can be seen that for all surfaces the earlier runs yielded somewhat higher friction coefficients, but the actual difference is small. Other data indicate that this effect is somewhat greater for skids made of metals softer than steel and less for skids of the harder materials.

Results

Skids on concrete.- The variation of the coefficient of friction with forward speed during slideouts on concrete is shown in figure 14. It can be seen that for operation on a concrete surface, the softer materials and wire-brush skids develop the higher coefficients. For the shoe-type skids, the coefficients of the softer metals decrease with increases in forward speed, whereas the coefficients for the hardest materials appear independent of forward speed. These results suggest that the magnitude of the coefficient of friction for the shoe-type skids depends on the force developed as the concrete plows out some of the metal as well as on the force required to shear the junctions formed at the points of actual contact of the friction pairs. (See ref. 2, ch. 5.) The effect of the plowing term, as would be expected, is most apparent for the results obtained with the softer materials and decreases with increase in speed, since the metal becomes hotter and a reduction in the strength properties of the material occurs.

Skids on asphalt.- The results obtained on the asphalt surfaces are shown in figure 15. The solid lines are the variations obtained on concrete and are included only for reference. It can be seen that again the wire-brush skid and the shoe-type skids made of the softer metals give the higher coefficients of friction. It can also be seen that the coefficients for the shoe-type skids are somewhat higher on the smooth surface asphalt than on the rough surface. This trend, however, is reversed for the wire-brush skid.

Skids on lakebed.- Difficulties encountered in maintaining a stable lakebed runway limited the number of tests made on this surface. The data obtained for the skids are shown in figure 16. It can be seen that the value for copper, which was much higher than that for steel on concrete (fig. 14), is about the same as that for steel on the lakebed. This result suggests that for a shoe-type skid, the coefficient of friction on lakebed is independent of the skid material. It can also be seen that the 3-inch wire-brush skid developed a coefficient of friction of about 0.6, which was the highest obtained during these tests.

Effect of skid temperature.- In order to simulate the skid temperature expected to exist during landings following atmospheric reentry, some tests were made with the skids heated to approximately 800° F. These tests were made on the concrete and asphalt surfaces, and the results indicated that heating the skids to this temperature had no significant effect on the coefficients of friction.

All-metal wheels.- The rolling coefficients of friction developed by the wheels are shown in figure 17. It can be seen that on both concrete and asphalt surfaces, the wheel equipped with a wire-brush tire had

The principal results indicated by the experimental investigation presented in part II are as follows:

(a) Wire-brush-type main landing skids, together with either a shoe-type skid or all-metal nose-wheel landing gear appeared feasible for use on manned reentry vehicles.

(b) A wire-brush wheel equipped with a brake might also prove practical for the main landing gear.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Field, Va., April 12, 1960.

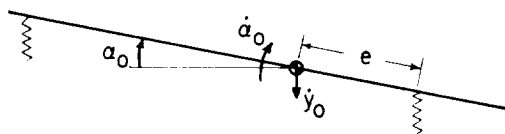
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2. Bowden, F. P., and Tabor, D.: The Friction and Lubrication of Solids. The Clarendon Press (Oxford), 1954.

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FACTORS STUDIED
 APPROACH CONDITIONS AND REAR GEAR LOCATION



EFFECTIVE MASSES



Figure 1

INFLUENCE OF INITIAL CONDITIONS ON LANDING SEVERITY

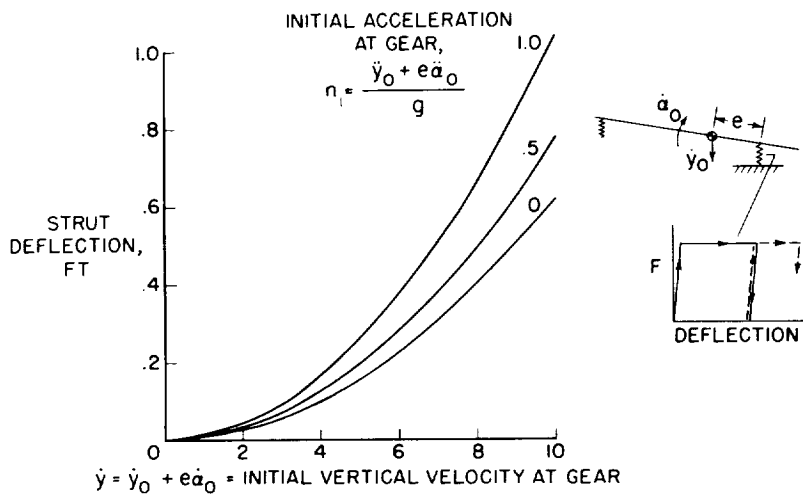


Figure 2

LANDING SEQUENCE SHOWING CONDITIONS
LEADING TO SEVERE SECOND IMPACT

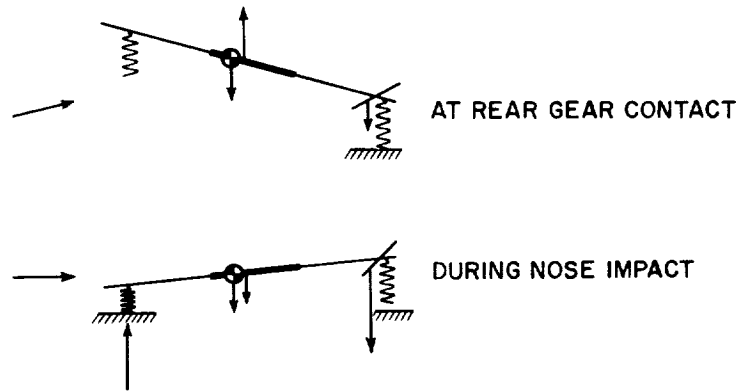


Figure 3

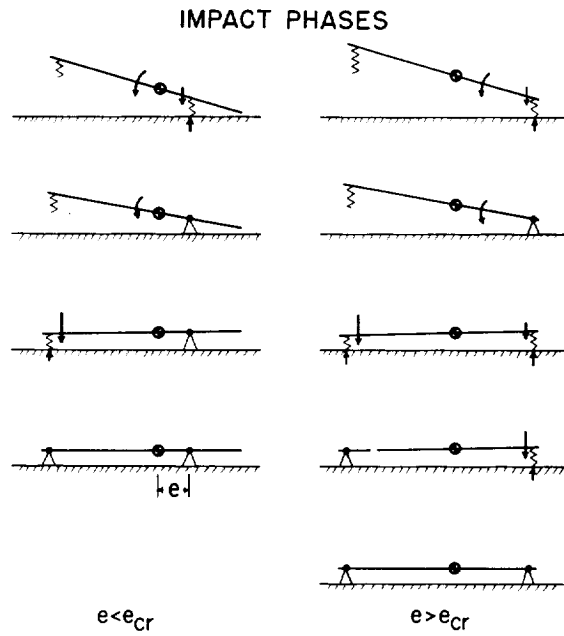


Figure 4

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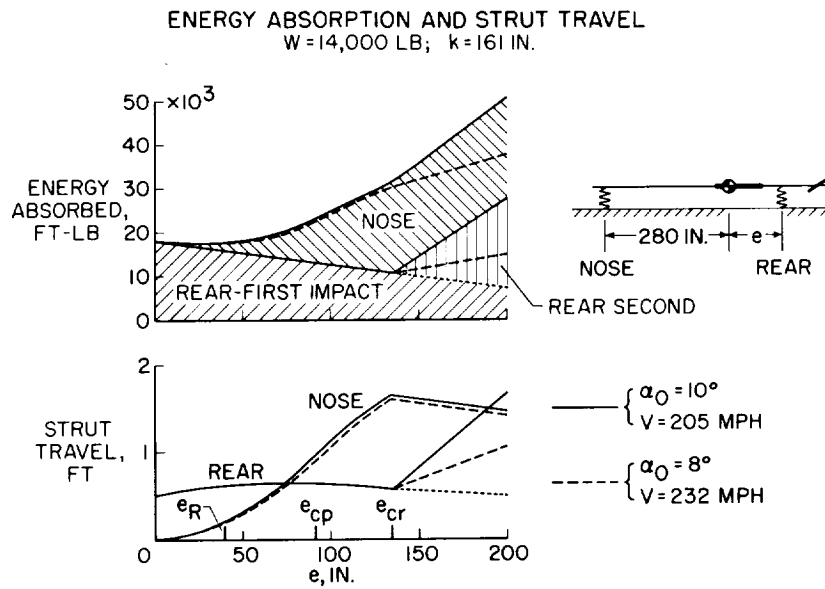


Figure 5

FORCE IN REAR STRUT OF X-15 DURING LANDING

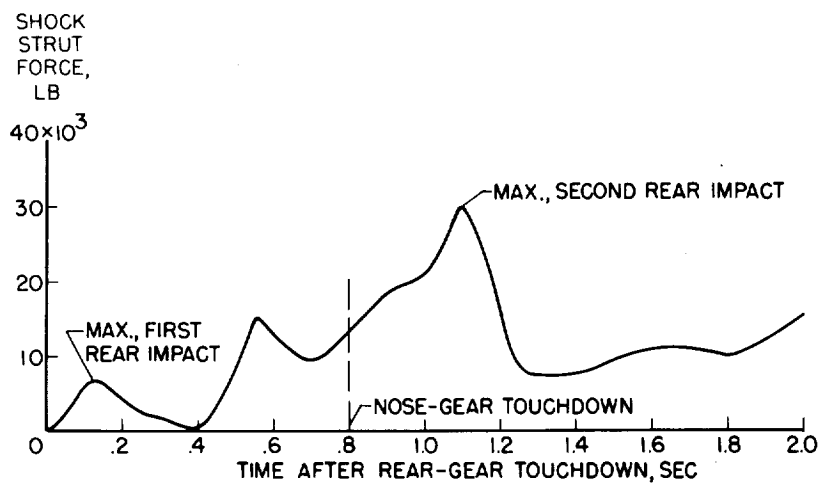


Figure 6

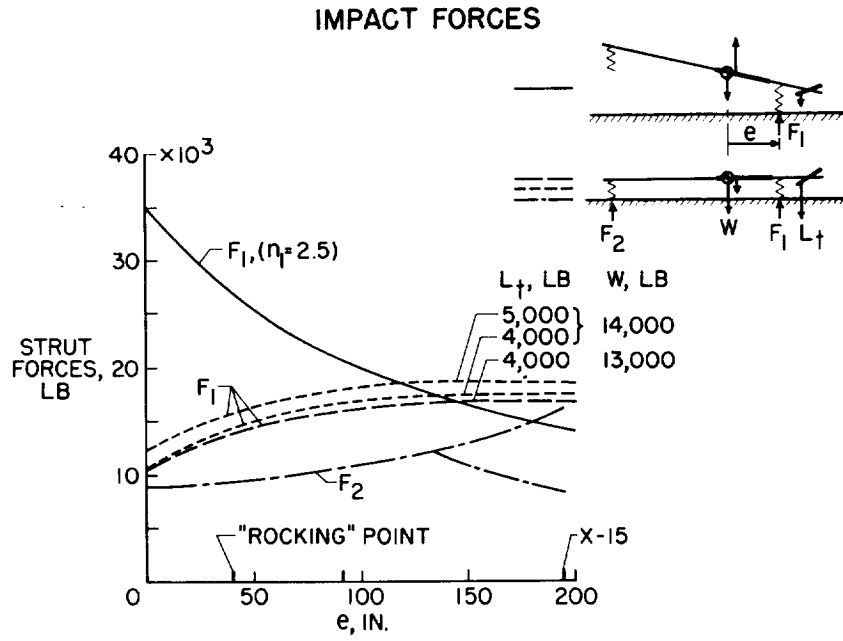


Figure 7

INFLUENCE OF APPROACH ANGLE OF ATTACK

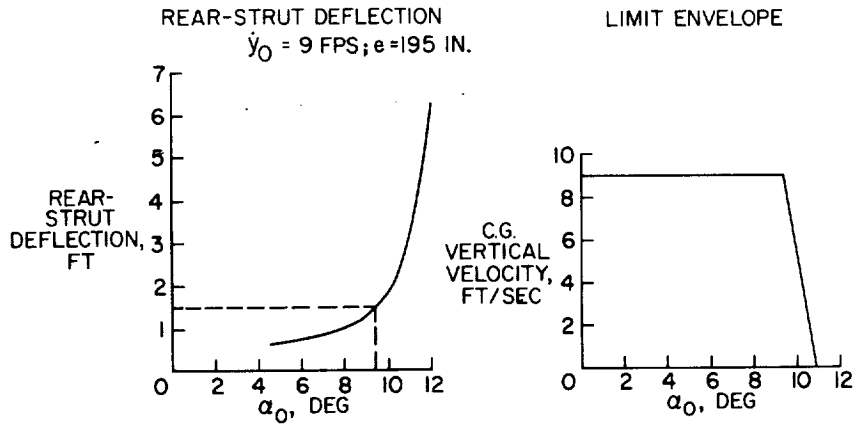


Figure 8

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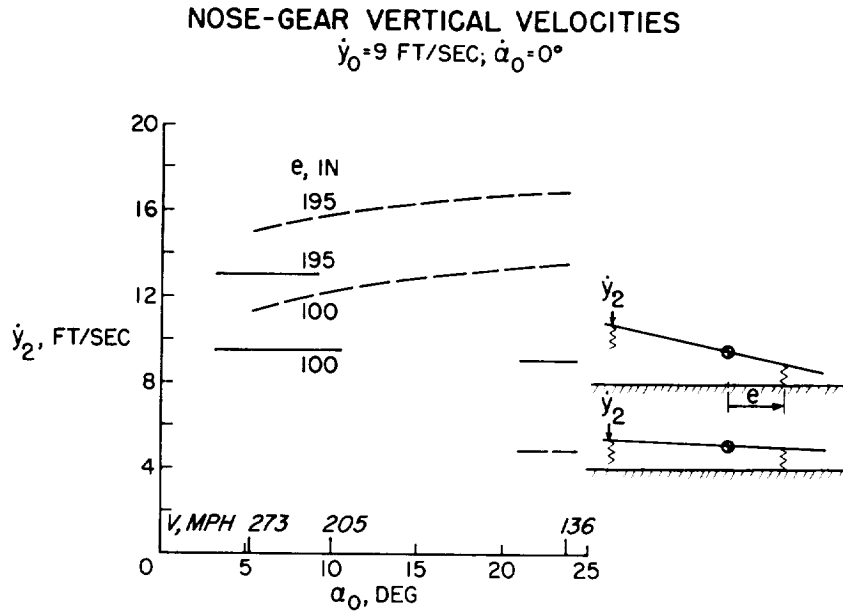


Figure 9

INFLUENCE OF LOADS ON EFFECTIVE MASSES

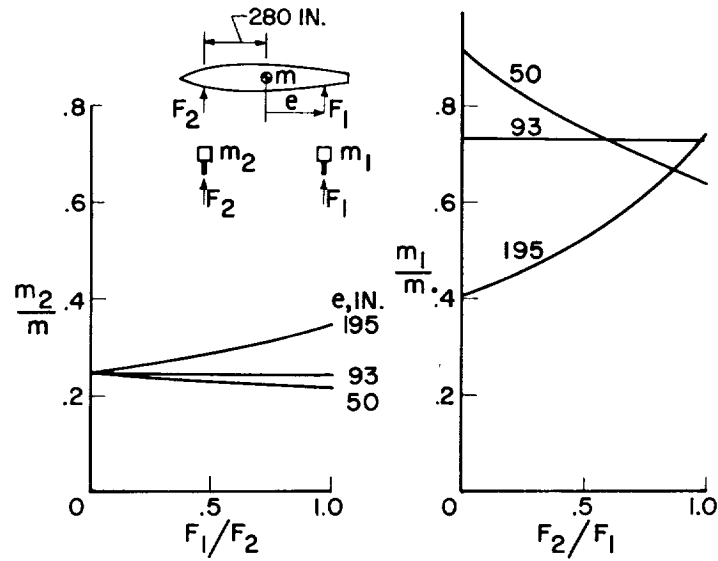
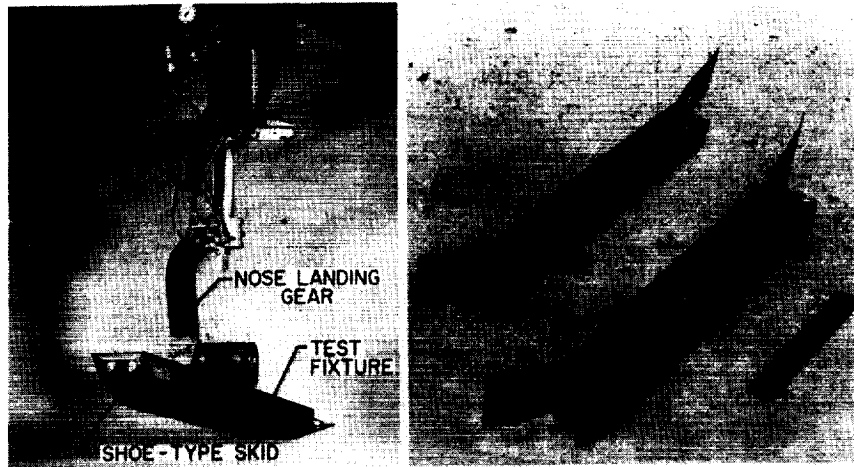


Figure 10

SKID CONFIGURATIONS



(a)

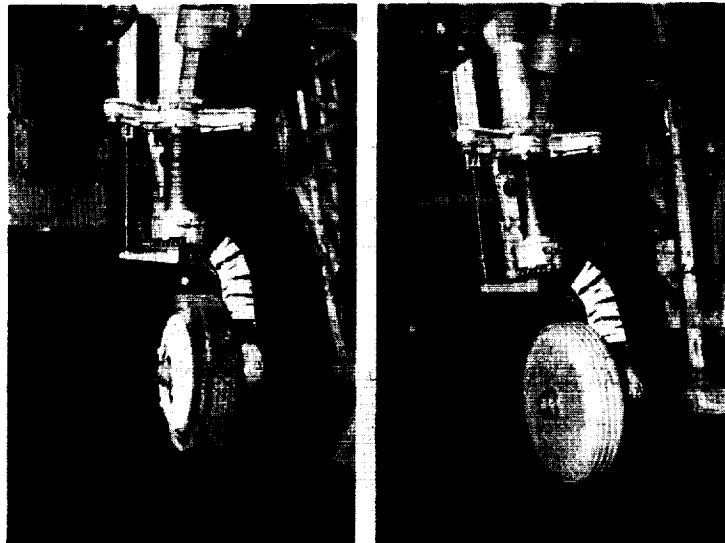
(b)

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Figure 11

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ALL-METAL WHEELS



(a)

(b)

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Figure 12

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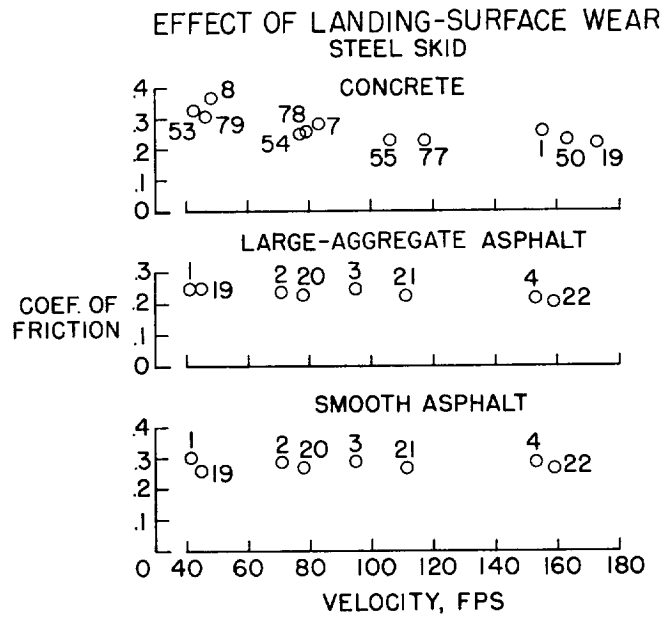


Figure 13

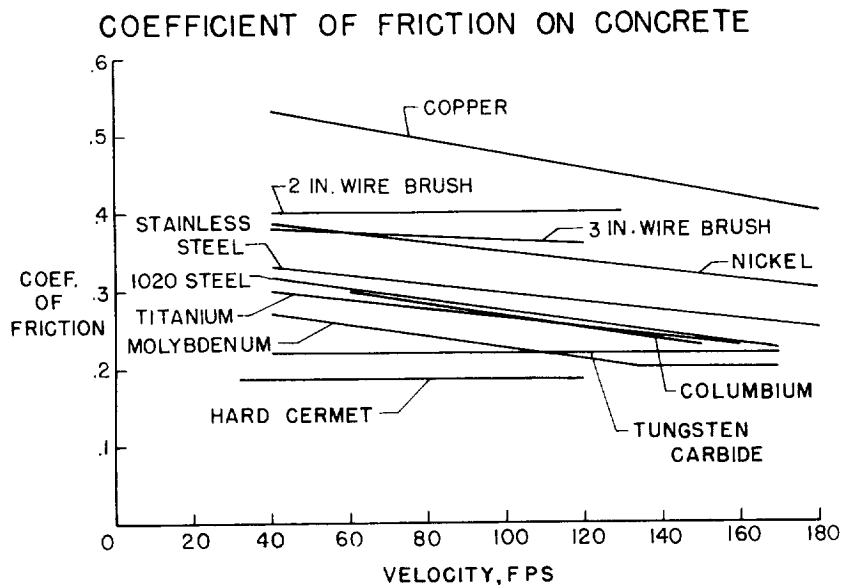


Figure 14

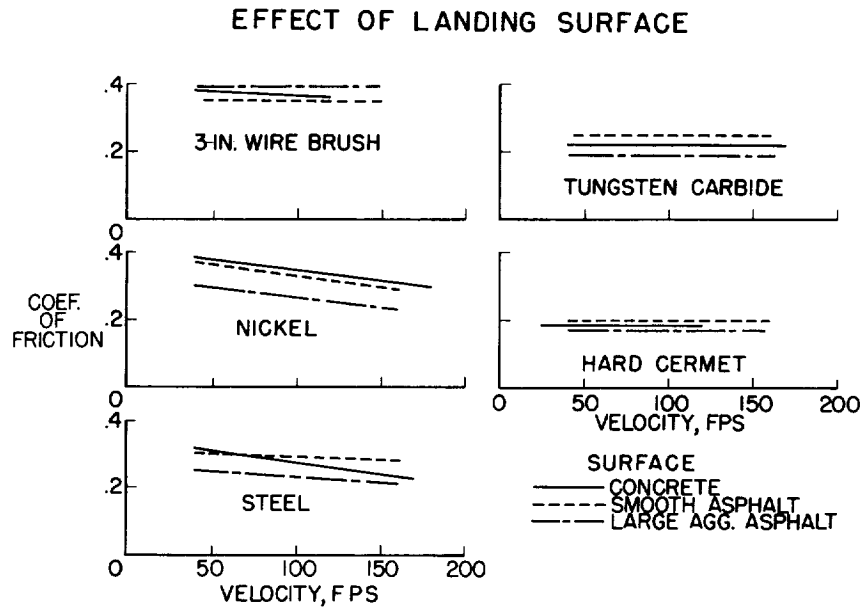


Figure 15

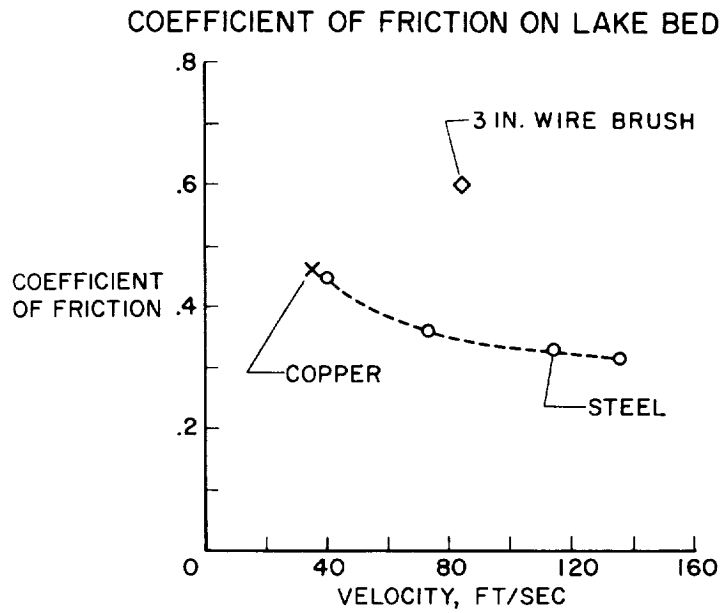


Figure 16

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ROLLING FRICTION COEFFICIENTS

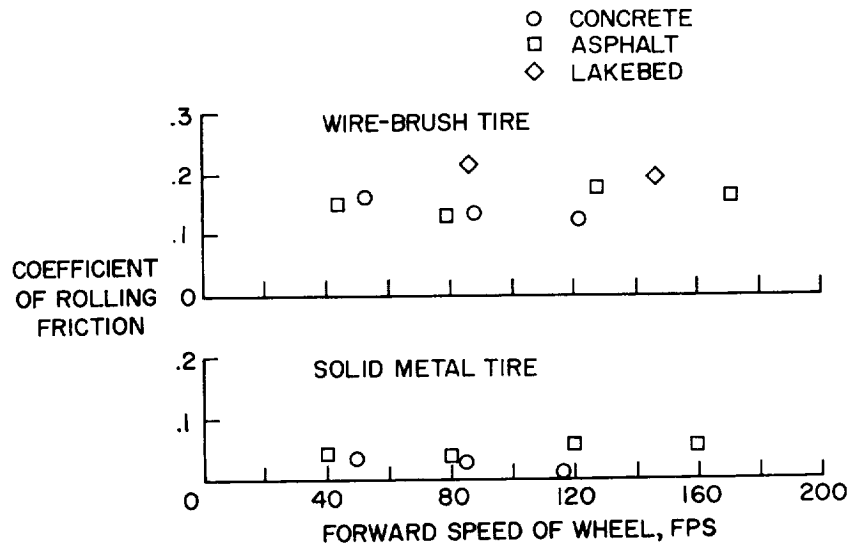


Figure 17

COEFFICIENT OF FRICTION DURING SPIN-UP ON CONCRETE

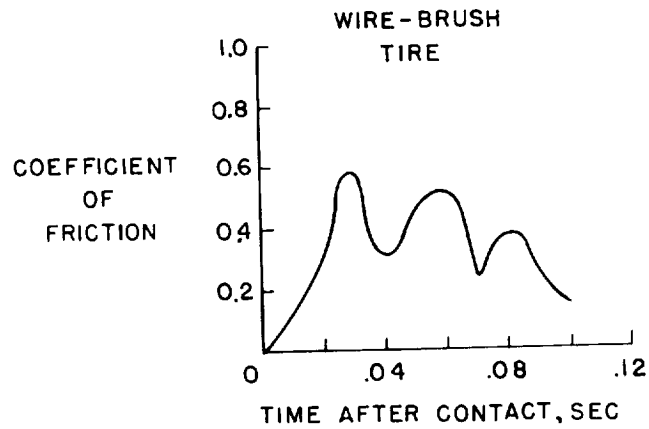


Figure 18

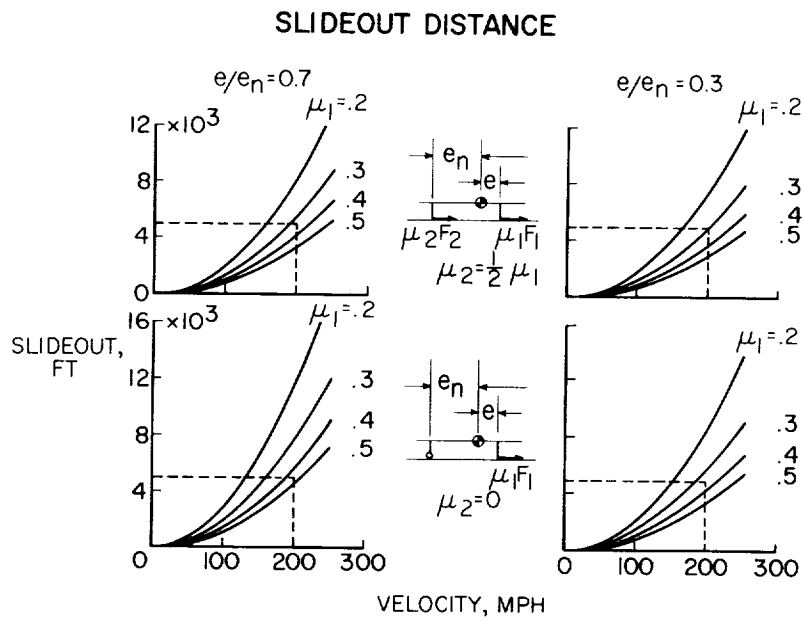


Figure 19

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<p>NASA TN D-448 National Aeronautics and Space Administration. SOME LANDING STUDIES PERTINENT TO GLIDER-REENTRY VEHICLES. John C. Houbolt and Sidney A. Batterson. August 1960. 22p. OTS price, \$0.75. (NASA TECHNICAL NOTE D-448)</p> <p>The results presented may serve as guidelines for consideration of landing problems of glider-reentry configurations. The effect of the initial conditions of sinking velocity, angle of attack, and pitch rate on impact severity and the effect of locating the rear gear in various positions are discussed. Some information is included regarding the influence of landing-gear location on effective masses. Preliminary experimental results on the slide-out phase of landing include sliding and rolling friction coefficients that have been determined from tests of various skids and all-metal wheels.</p> <p>(Initial NASA distribution: 3, Aircraft; 51, Stresses and loads.) Copies obtainable from NASA, Washington</p>	<p>I. Houbolt, John Cornelius II. Batterson, Sidney A. III. NASA TN D-448</p>
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