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DYNAMIC-MODEL INVESTIGATION OF SOME LANDINGS AND SLIDEOUTS OF A RECOVERABLE BOOSTER

by William C. Thompson

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Langley Station, Hampton, Va.

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SUMMARY

An investigation was made to study the landing and slideout stability characteristics during recovery of a reusable booster. The portion of the recovery operation considered herein deals with the initial landing impact and slideout stability on a hard-surface runway. Model tests were made at touchdown speeds simulating a full-scale horizontal velocity of 135 ft/sec (41 m/s) and a vertical velocity of 10 ft/sec (0.3 m/s).

The four-skid landing system appeared to have very satisfactory stability. Several fixed nose-wheel arrangements were tested with the two-rear-skid configuration and all had a tendency to ground loop. Fairly good stability was obtained with a single free-castering nose wheel.

The maximum longitudinal acceleration varied from 0.9 to 2.2 g units and the maximum normal acceleration varied from 1.6 to 4.6 g units. The slideout distance varied from 8 to 11 booster lengths.

INTRODUCTION

The development of spacecraft and launch vehicles has progressed to a point where it may be economical to recover the launch vehicles and prepare them for reuse. The Saturn I launch vehicle is typical of those expected to be used extensively in the space program. Some developmental work has been undertaken on recovery and landing impact systems for the first stage of this vehicle. One such system employs a paraglider-landing-skid arrangement. The paraglider through a flare maneuver just prior to touchdown can convert most of the vertical-velocity component to horizontal velocity and thus effect an airplane type of landing. The horizontal velocity is dissipated through friction of the landing skids on a hard-surface runway.

The portion of the recovery operation under consideration in the present study deals with initial landing impact and slideout stability. A 1/14-scale dynamic model of the first stage of a Saturn I launch vehicle was used for the present investigation. One of the landing-gear concepts investigated was a four-skid arrangement employing yielding metal shock absorbers. Another arrangement employed an aircraft type of nose wheel in conjunction with two rear skids. Free-body landing tests were made, initial impact accelerations were measured, and stability and behavior were observed during slideout.

The units for the physical quantities used in this paper are given both in the U.S. Customary Units and in the International System of Units (SI) (ref. 1). The appendix presents factors relating these two systems of units. A film supplement (L-901) to this paper shows some of the tests discussed herein.

DESCRIPTION OF MODEL

The general arrangement of the 1/14-scale dynamic model used in the investigation is shown in figure 1. The four-skid landing gear is shown in figure 1(a). The location of the landing skids at the front and rear bulkheads is dictated by the fact that these are the strong points on the full-scale booster. A configuration with two rear skids and a castering nose wheel is shown in figure 1(b). Photographs of the model are shown in figure 2. Full-scale and model-scale relationships applicable to these tests are given in table I. Pertinent model-scale and full-scale dimensions are given in table II.

The model was constructed principally of plastic impregnated fiber glass.

Four-Skid Landing Gear

The four-skid landing gear was constructed principally of welded steel. A detailed sketch of a typical gear is shown in figure 3. The bottom surfaces of the two front skids were covered with teflon which gave a friction coefficient of about 0.25 when the model was landed on a hard-surface runway. The hard-surface runway consisted of a plywood floor attached to a steel subfloor. The bottom surfaces of the two rear skids were covered with leather which gave a friction coefficient of about 0.50, or about twice that of the front skids. The differential coefficient of friction between the front and rear skids provides directional stability. Each gear contained a shock absorbing element or energy strap installed in such a manner that landing loads imposed upon the gear strut were absorbed in tension by the energy strap. When the load reached the yield strength of the strap, it elongated plastically during the strut stroke. Since energy is absorbed by yielding a ductile metal, little energy is stored; thus, rebound is minimized. The energy strap is readily adaptable to high temperatures. Further description and characteristics of the energy strap are given in reference 2.

Nose-Wheel and Two-Rear-Skid Landing Gear

The second landing-gear configuration (fig. 1(b)) was a tricycle arrangement consisting of a nose wheel attached at the forward bulkhead and a pair of skids attached to the rear bulkhead. The rear skids had a leather surface which gave a friction coefficient of about 0.50. The same tension type of energy strap as described previously was used for this gear. A detailed sketch of the rear-skid gear is shown in figure 4. One of the strut assemblies of the four-skid gear was used for the forward gear of the tricycle arrangement. The skid was removed and replaced with an aircraft dual-wheel landing gear; also an energy strap of the proper size was installed to give approximately the same stroke as the four-skid gear.

TEST METHODS AND EQUIPMENT

The investigation was conducted by launching the model as a free body by use of the monorail apparatus of the Langley impact structures facility. The model is shown on the launching carriage in figure 5. Model tests were made at speeds which simulated a full-scale horizontal velocity of 135 ft/sec (41 m/s) and a vertical velocity of 10 ft/sec (0.3 m/s). The horizontal-velocity component was obtained by accelerating the launching carriage to the desired speed. The free-fall distance of the model to the runway was set to obtain the desired vertical-velocity component. In order to have simultaneous contact with all landing gear, the model was launched at 0° pitch attitude for the four-skid tests and at $-2\frac{1}{2}^{\circ}$ pitch attitude for the nose-wheel and two-rear-skid tests. The four-skid configuration was tested at 0° and 5° yaw angle. The configuration with the nose wheel and two rear skids was tested at 0° yaw only.

Impact accelerations were measured by strain-gage accelerometers rigidly mounted to the model structure. Longitudinal acceleration was measured near the center of gravity with a $\pm 6g$ accelerometer which had a natural frequency of 93 cycles per second and was damped to about 60 percent of critical damping. Normal accelerations were measured near the front and rear gear attachment points with $\pm 15g$ accelerometers; each accelerometer had a natural frequency of 160 cycles per second and was damped to about 60 percent of critical damping.

RESULTS AND DISCUSSION

A motion-picture film supplement (L-901) showing some of the tests discussed in this paper is available on loan. A request card form and a description of the film are found at the back of this paper. All data presented are converted to full-scale values by use of the scale relations given in table I. A summary of the test results is given in table III.

Four-Skid Landing Gear

The landing and slideout stability for the four-skid system appeared to be very satisfactory for the conditions tested (0° and 5° yaw angle). Deviation from the runway center line is illustrated in figure 6. The maximum deviation was about 7 feet (2.1 m) (full scale) from the runway center line. The model veered to the starboard or port side at random, and landing at the 5° yaw angle appeared to have little effect on the slideout stability. The data presented in reference 2 show that a friction coefficient ratio less than 1 resulted in some instability, and a ratio greater than 1 always resulted in good slideout stability. The friction coefficient ratio of 2 between front and rear skids used in these tests appears to be the major contributing factor to the good slideout stability. The sequence photographs presented in figure 7 illustrate a typical landing runout for the four-skid configuration. The total slideout distance was about 8 or 9 booster lengths. For 0° yaw angle the maximum longitudinal accelerations ranged from 1.0 to 1.3 g units while the maximum normal accelerations over the front skids ranged from 1.8 to 2.6 g units and over the rear skids from 2.3 to 2.8 g units. For the 5° yaw angle the maximum longitudinal accelerations ranged from 0.9 to 1.2 g units while the maximum normal accelerations over the front skids ranged from 2.0 to 3.1 g units and over the rear skids from 1.6 to 2.8 g units.

Nose-Wheel and Two-Rear-Skid Landing Gear

The nose-wheel and two-rear-skid gear was not as inherently stable as the four-skid landing gear. The fixed dual-wheel aircraft nose gear was not satisfactory on the model because no steering mechanism was employed. When the model diverged drastically from a straight course, a rather severe ground loop usually resulted. Sometimes the model turned over, sometimes it hit the protective barrier alongside the runway, and at other times it turned 180° and slid backwards for about one-half a booster length. Several other fixed-nose-wheel designs were investigated and were not stable. The best stability was obtained with a free-castering single wheel, wherein the wheel rotation axis was located just aft of the vertical pivot axis. Deviation from the runway center line as a function of slideout distance for the free-castering nose-wheel and two-rear-skid configuration is shown in figure 8. The deviation shown in this figure is about four times as large as that for the four-skid gear shown in figure 6.

Sequence photographs showing a typical slideout are presented as figure 9. The booster with the castering-nose-wheel configuration maintained a nearly straight course and the slideout distance was about 11 booster lengths. The maximum longitudinal accelerations ranged from about 1.0 to 2.2 g units. The maximum normal accelerations over the front wheel ranged from 1.7 to 3.7 g units and over the rear skids from 3.2 to 4.6 g units, which is somewhat more than for the four-skid configuration. (See table III.) These higher accelerations are due to the fact that the rear-skid shock absorbers used a shorter stroke and heavier yield strap than the shock absorbers on the four-skid arrangement.

CONCLUDING REMARKS

Results of the dynamic model investigation of the landing and slideout during recovery of a reusable booster show that the four-skid configuration gave consistently small deviations from the center line during slideout. Maximum longitudinal acceleration for the four-skid gear was about 1.3 g units and the maximum normal acceleration was about 3.1 g units. The slideout distance was about 8 booster lengths.

The nose-wheel and two-rear-skid arrangement had a tendency to ground loop with the fixed nose wheels. A free-castering single nose wheel gave fairly good stability and the slideout distance was about 11 booster lengths. The maximum longitudinal acceleration was about 2.2 g units and the maximum normal acceleration was about 4.6 g units.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., April 14, 1966.

APPENDIX

CONVERSION OF U.S. CUSTOMARY UNITS TO SI UNITS

The International System of Units (SI) was adopted by the Eleventh General Conference on Weights and Measures, Paris, October 1960, in Resolution No. 12 (ref. 1). Conversion factors for the units used herein are given in the following table:

Physical quantity	U.S. Customary Unit	Conversion factor (*)	SI Unit
Length	in.	0.0254	meters (m)
	ft	0.3048	meters (m)
Mass	lbm	0.454	kilograms (kg)
Moment of inertia . . .	slug-ft^2	1.35582	kilogram-$meter^2$ (kg-m^2)
Velocity	ft/sec	0.3048	meters per second (m/s)

*Multiply value given in U.S. Customary Unit by conversion factor to obtain equivalent value in SI unit.

Prefixes to indicate multiples of units are as follows:

Prefix	Multiple
milli (m)	10^{-3}
centi (c)	10^{-2}
kilo (k)	10^{3}
mega (M)	10^{6}

REFERENCES

1. Mechtly, E. A.: The International System of Units – Physical Constants and Conversion Factors. NASA SP-7012, 1964.
2. Blanchard, Ulysse J.: Landing Characteristics of a Winged Reentry Vehicle With All-Skid Landing Gear Having Yielding-Metal Shock Absorbers. NASA TN D-1496, 1962.

TABLE I.- SCALE RELATIONSHIPS

[λ = Scale of model]

Quantity	Full size	Scale factor	Model
Length	l	λ	λl
Mass	W	λ^3	$\lambda^3 W$
Moment of inertia	I	λ^5	$\lambda^5 I$
Time	t	$\sqrt{\lambda}$	$\sqrt{\lambda}\ t$
Velocity	V	$\sqrt{\lambda}$	$\sqrt{\lambda}\ V$
Linear acceleration . . .	a	1	a

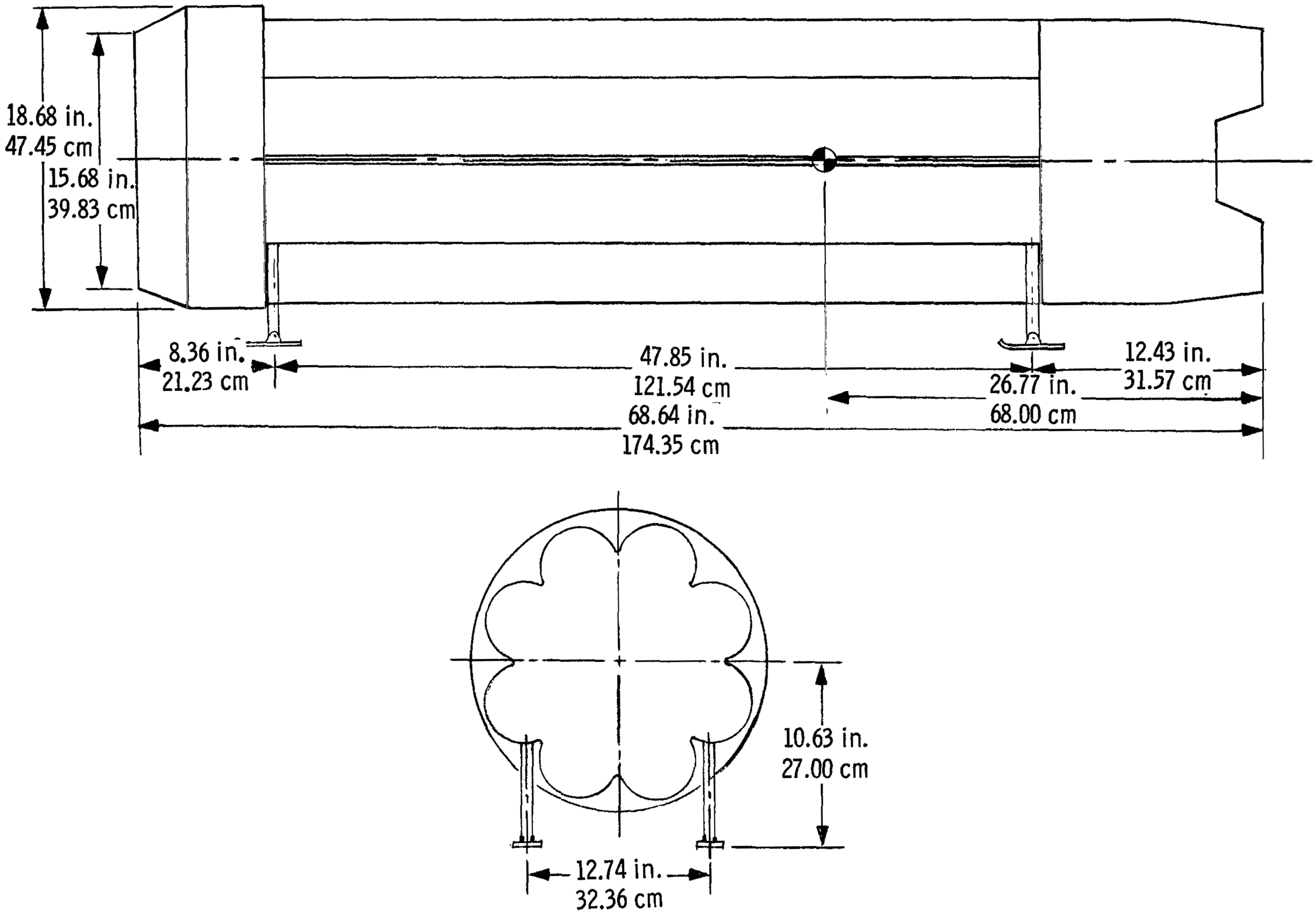
TABLE II.- PERTINENT FULL-SCALE AND MODEL-SCALE VALUES FOR BOOSTER

	1/14-scale		Full scale	
Total mass	36.44 lbm	(16.6 kg)	100 000 lbm	(45.4 Mg)
Overall length	68.64 in.	(1.74 m)	961 in.	(24.41 m)
Maximum diameter	18.68 in.	(0.47 m)	262 in.	(6.65 m)
Horizontal velocity	36.0 ft/sec	(11.0 m/s)	135 ft/sec	(41.0 m/s)
Vertical velocity	2.7 ft/sec	(0.8 m/s)	10 ft/sec	(3.0 m/s)
Moment of inertia:				
Roll axis	0.40 slug-ft^2	(0.54 kg-m^2)	215 000 slug-ft^2	(291 Mg-m^2)
Pitch axis	3.70 slug-ft^2	(5.00 kg-m^2)	2 000 000 slug-ft^2	(2 700 Mg-m^2)

TABLE III.- SUMMARY OF RESULTS OF HARD-SURFACE LANDING TESTS OF 1/14-SCALE DYNAMIC MODEL OF A RECOVERABLE BOOSTER

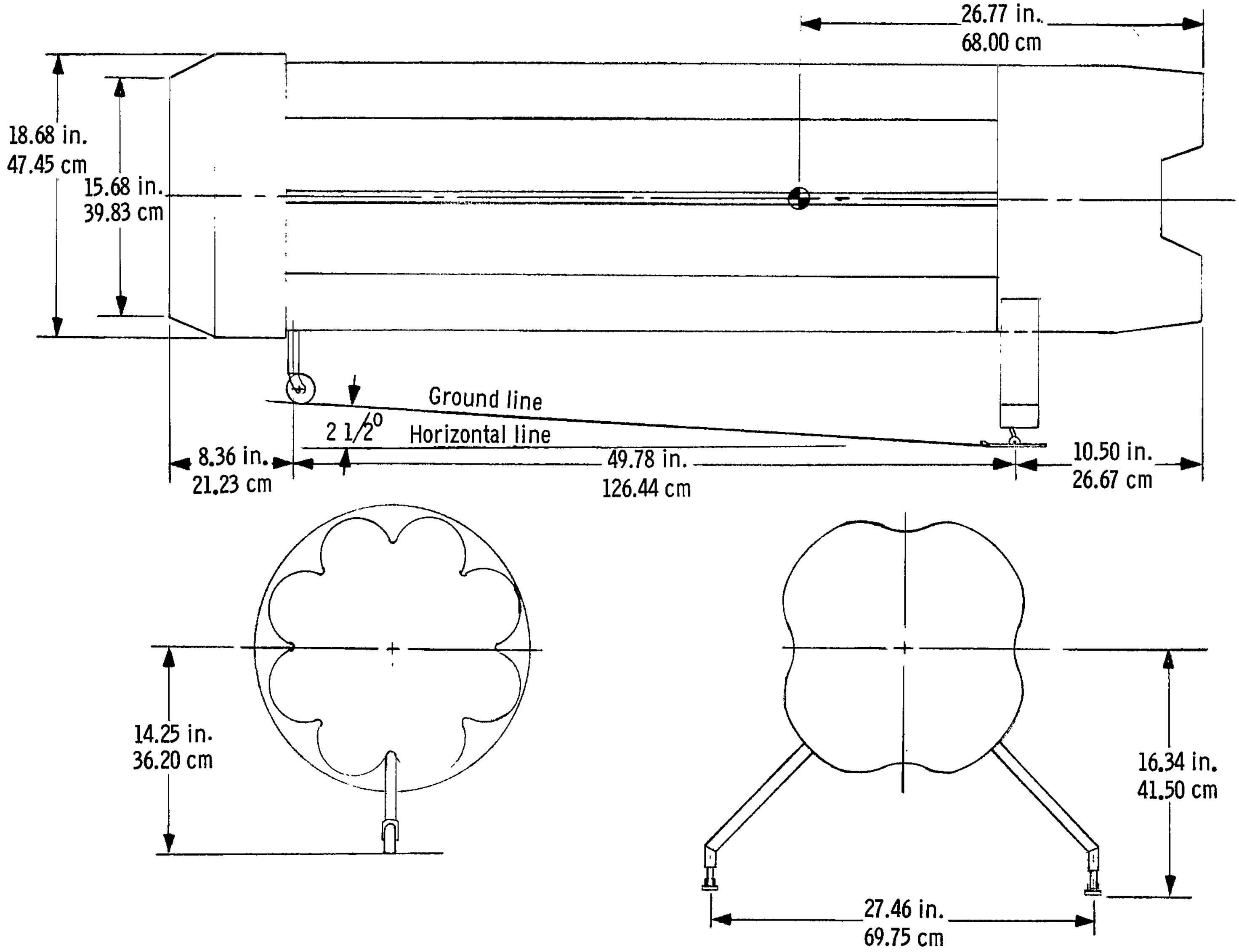
[All values are converted to full scale. Vertical velocity, 10 ft/sec (3 m/s); horizontal velocity, 135 ft/sec (41 m/s); mass, 100 000 lbm (45.4 Mg).]

Test configuration	Number of runs	Pitch attitude, deg	Yaw angle, deg	Range of strut deflections				Range of acceleration, g units, for-			Distance of slideout, booster lengths	Deviation from center line	
				Front		Rear		Longitudinal	Normal				
				in.	cm	in.	cm		Front	Rear		ft	m
Four skid	13	0	0	8.6 to 12.8	21.9 to 32.5	13.7 to 15.4	34.8 to 39.1	1.0 to 1.3	1.8 to 2.6	2.3 to 2.8	8	7.0	2.1
Four skid	10	0	5	9.4 to 12.0	23.9 to 30.4	12.8 to 15.4	32.5 to 39.1	0.9 to 1.2	2.0 to 3.1	1.6 to 2.8	9	7.0	2.1
Castering nose wheel and two rear skids	12	$-2\frac{1}{2}$	0	7.4 to 12.3	18.8 to 31.2	7.0 to 9.8	17.8 to 24.9	1.0 to 2.2	1.7 to 3.7	3.2 to 4.6	11	28	8.5
Fixed nose wheel and two rear skids	4	$-2\frac{1}{2}$	0	6.3 to 12.6	15.7 to 32.0	9.8 to 9.8	24.9 to 24.9	1.0 to 2.0	2.1 to 3.8	1.5 to 4.6	8	120	36.6



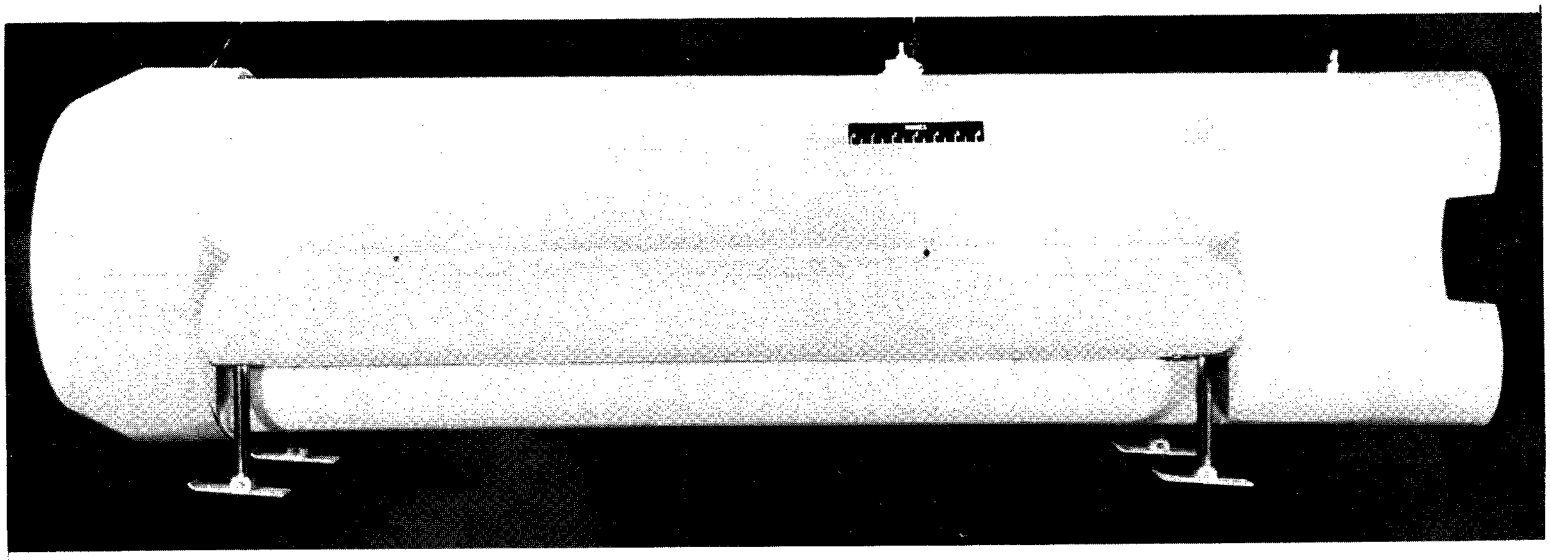
(a) Four-skid landing gear.

Figure 1.- Landing-gear arrangements tested on the 1/14-scale model. Dimensions are model size.



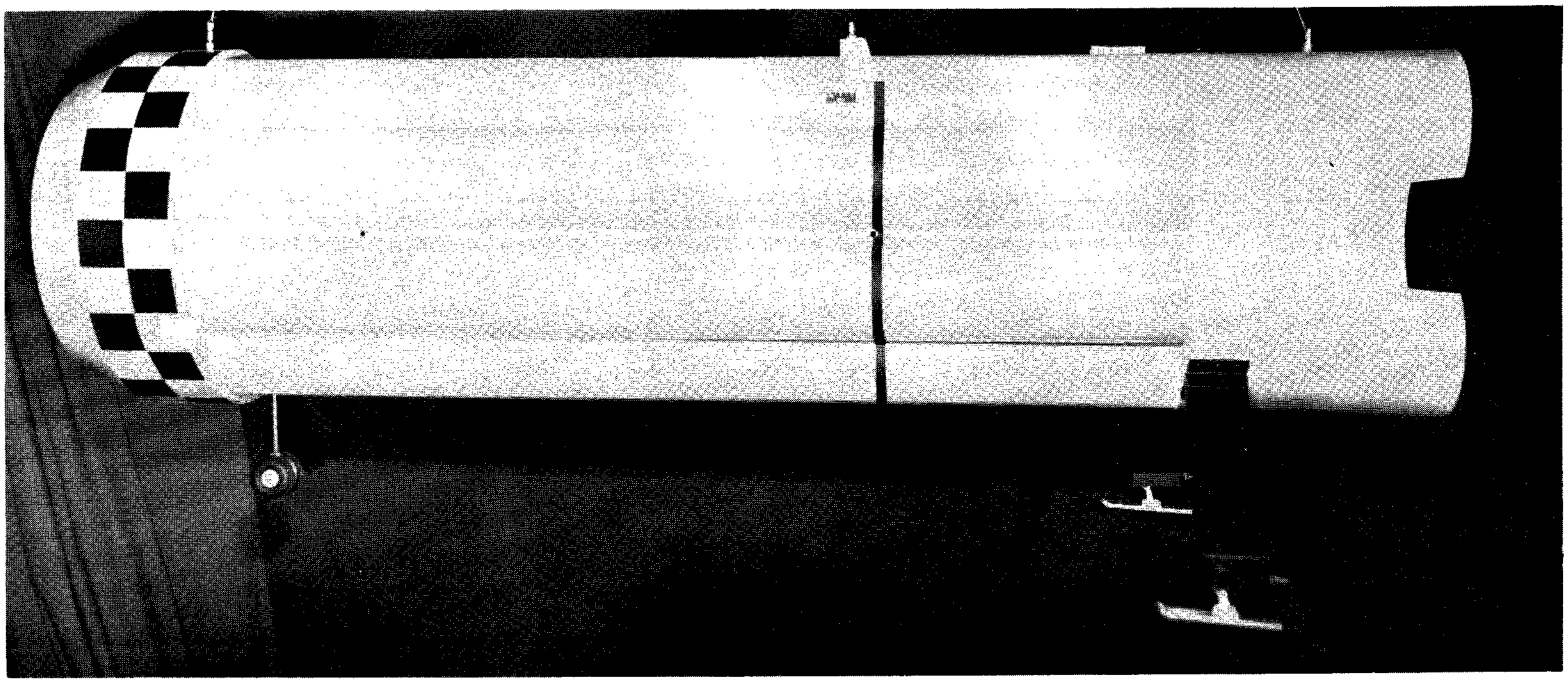
(b) Free-castering nose gear and twin rear skids.

Figure 1.- Concluded.



(a) Four-skid landing gear. L-62-831

Figure 2.- Photographs of 1/14-scale model.



(b) Fixed nose wheel and two rear skids. L-62-3828

Figure 2.- Concluded.

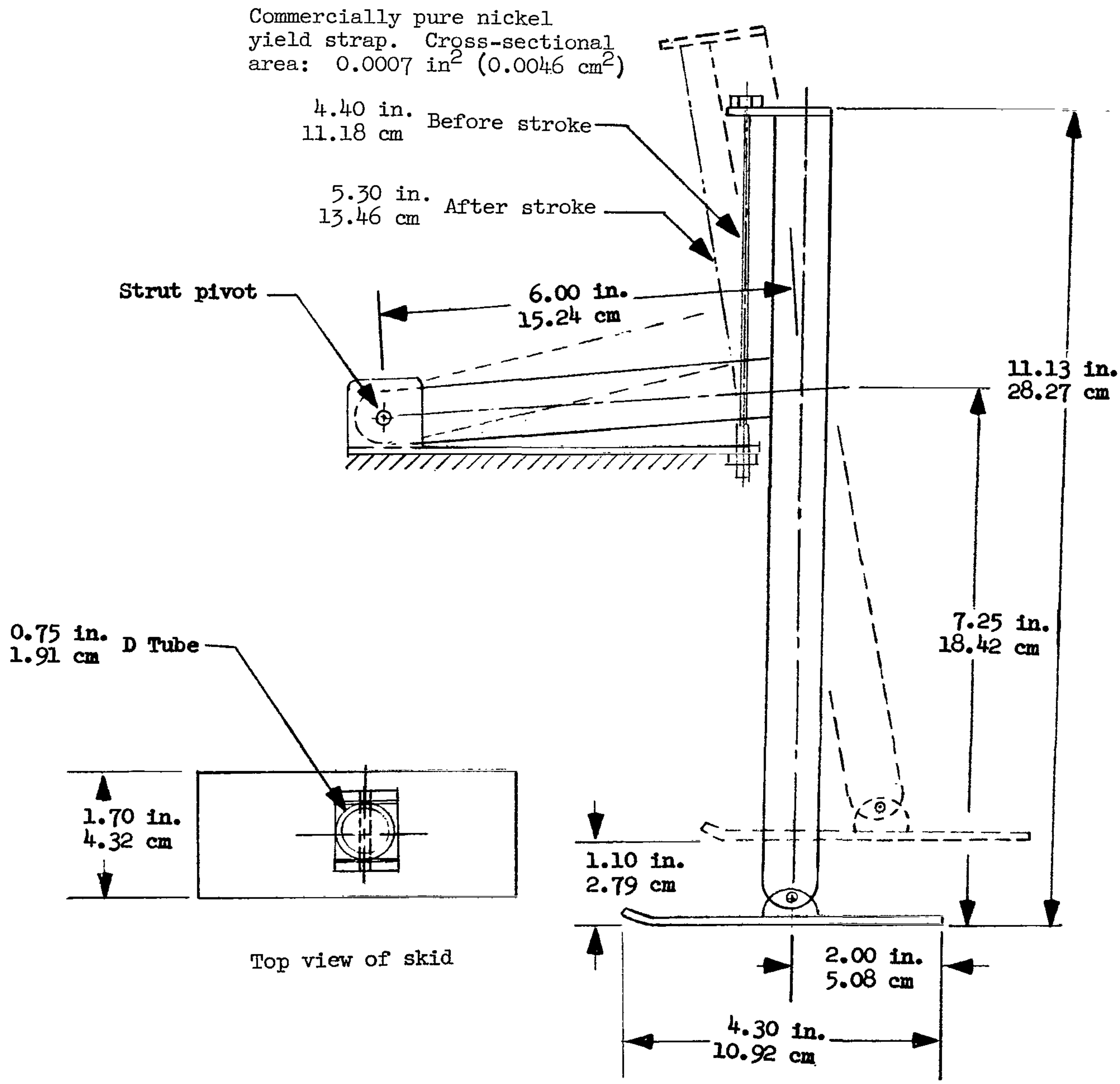


Figure 3.- Typical mechanism for four-skid installation. Dimensions are model size.

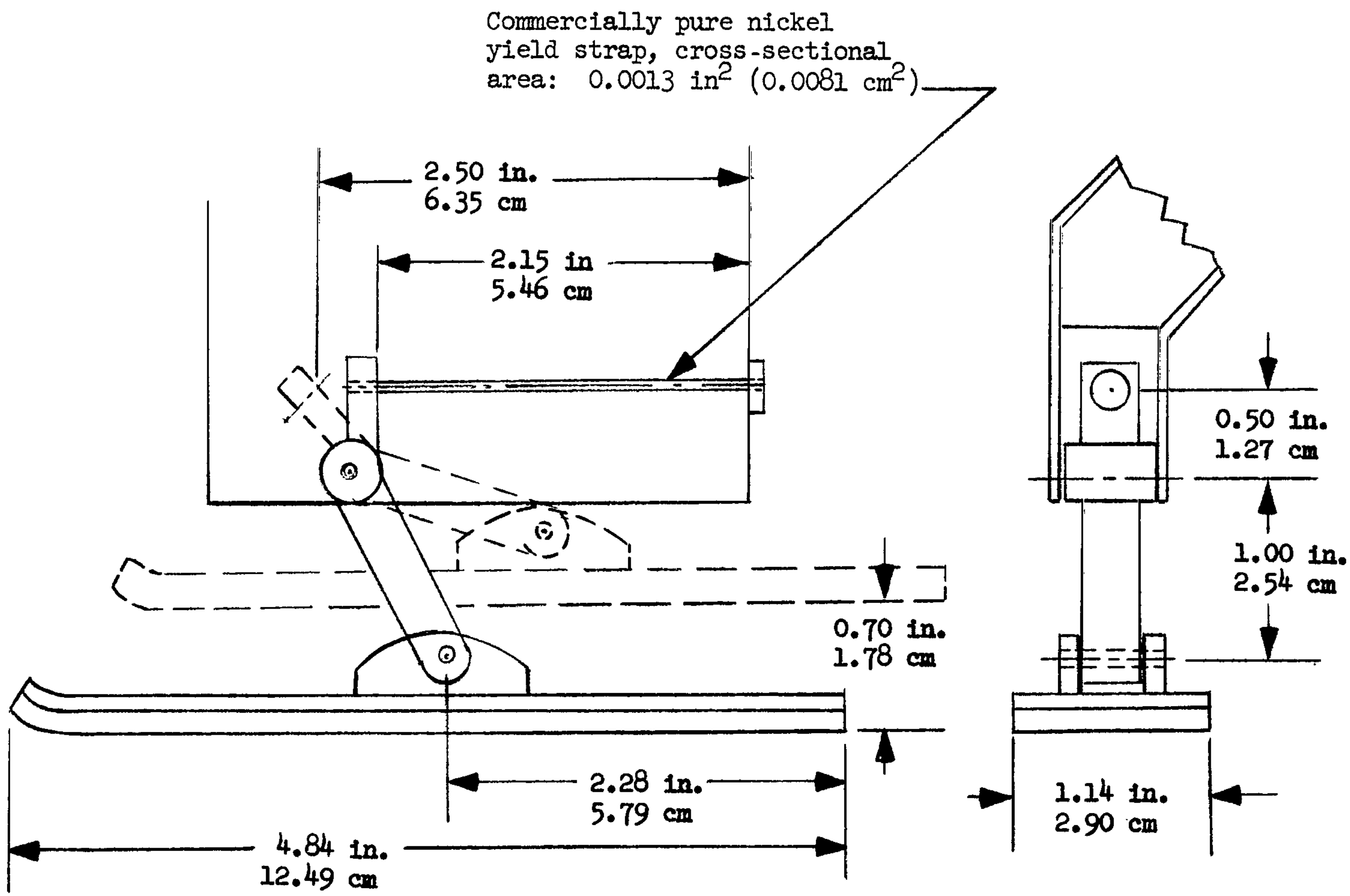


Figure 4.- Typical mechanism for two-rear-skid installation. Dimensions are model size.

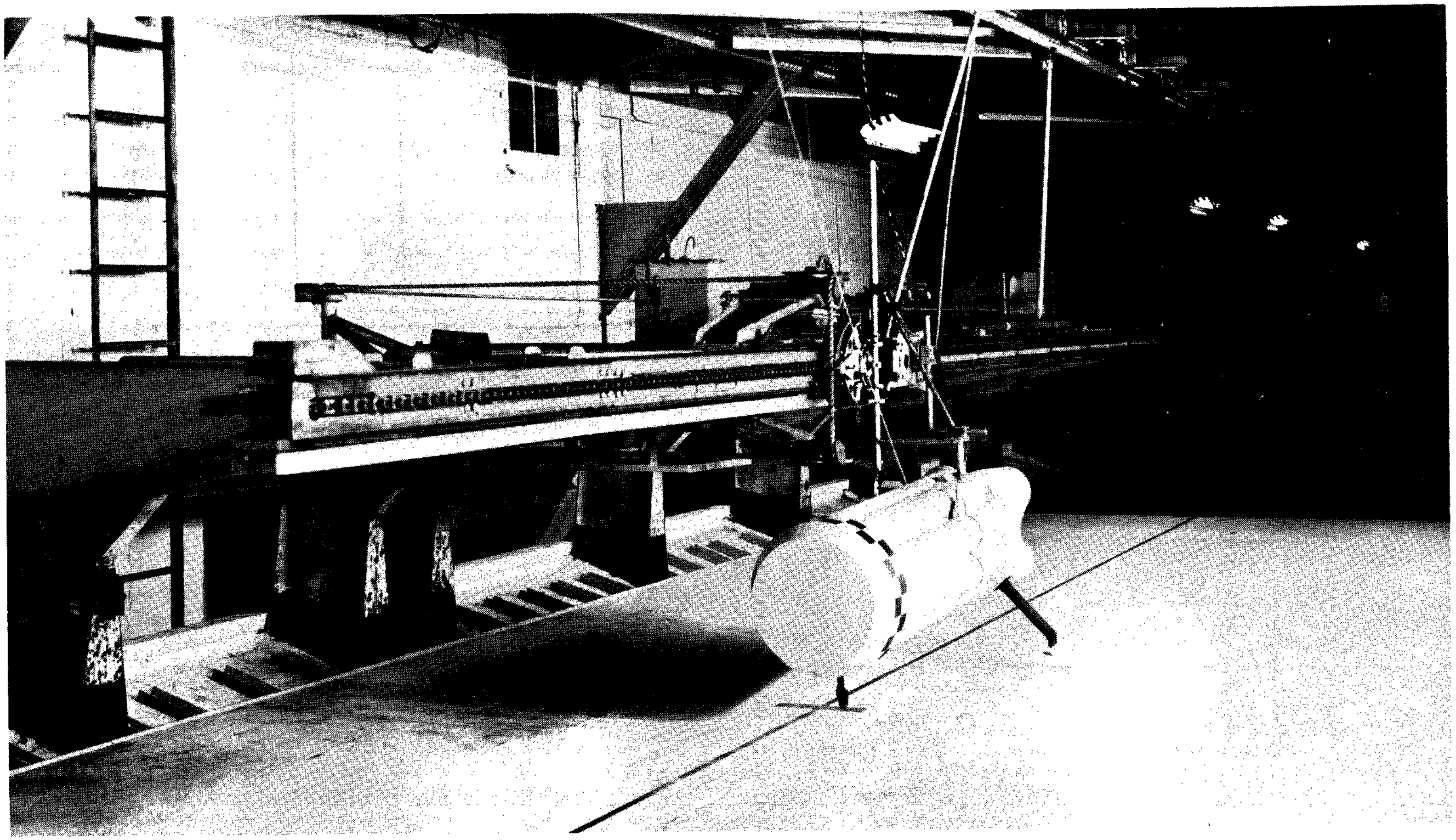


Figure 5.- Model on launching carriage.

L-62-4453

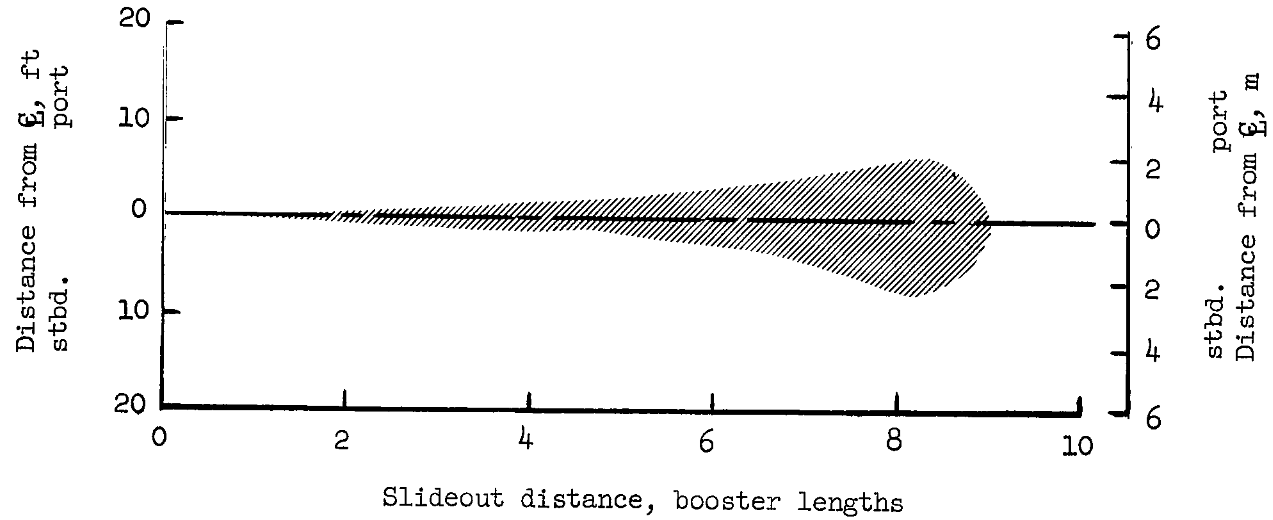
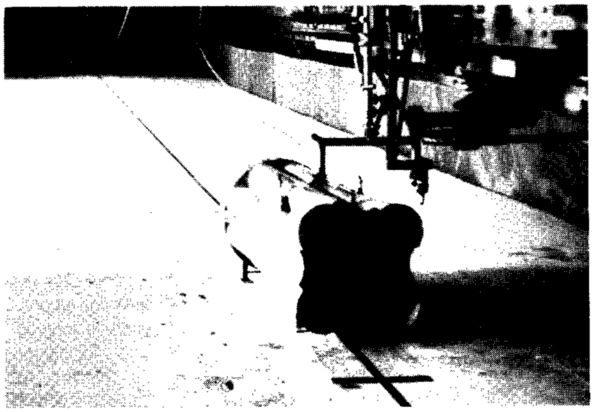


Figure 6.- Deviation from runway center line during typical slideout tests of four-skid configuration. All values are full scale.

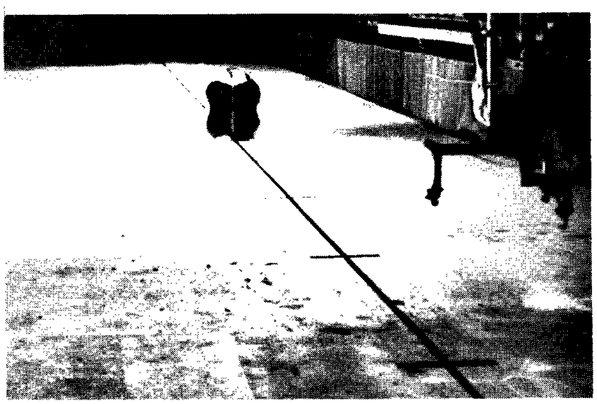


Near touchdown

2 booster lengths

3

4



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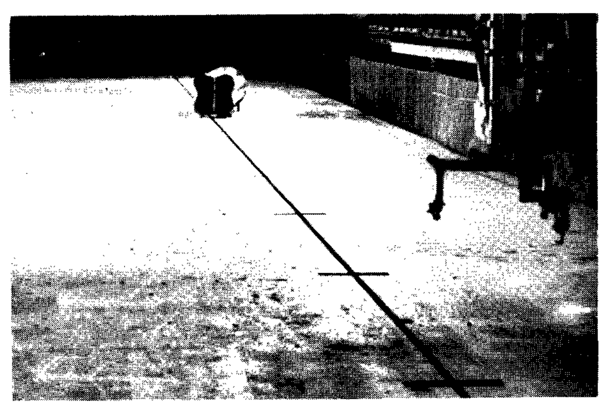

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Figure 7.- Sequence photographs of representative landings of four-skid configuration. Slideout distances are shown in booster lengths.

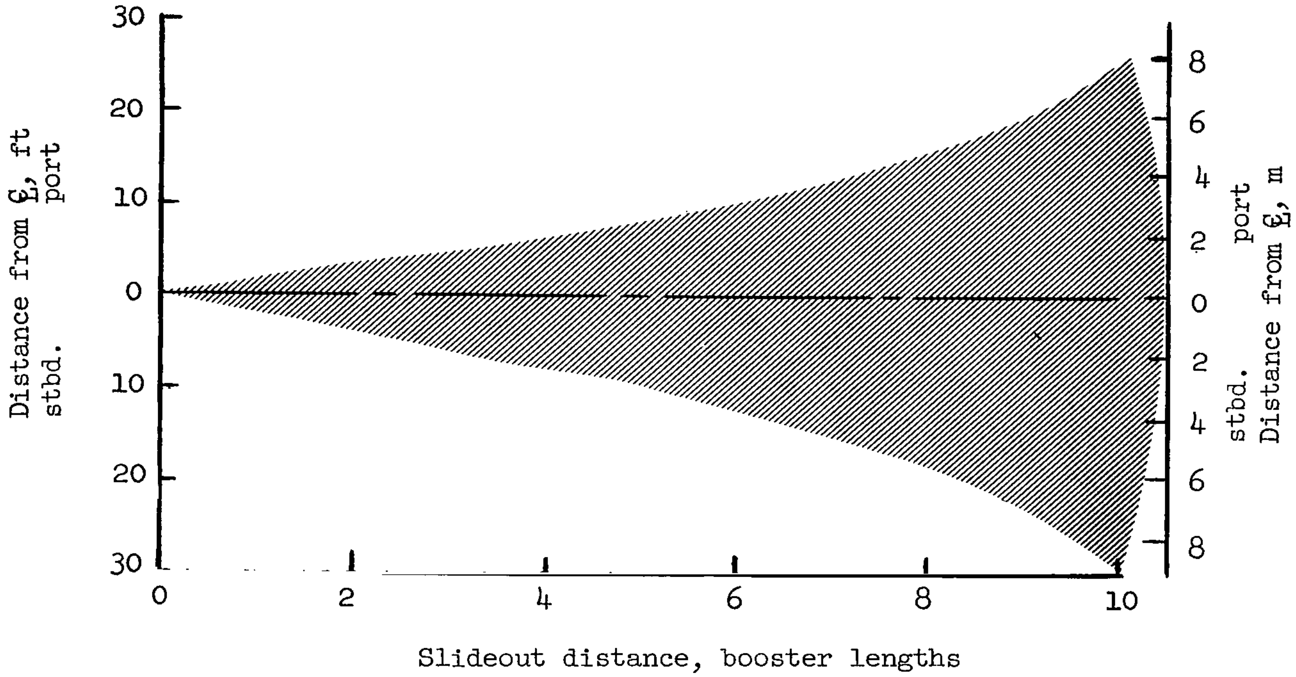

Figure 8.- Deviation from runway center line during typical slideout tests of the free-castering nose-wheel and two-rear-skid configuration. All values are full scale.

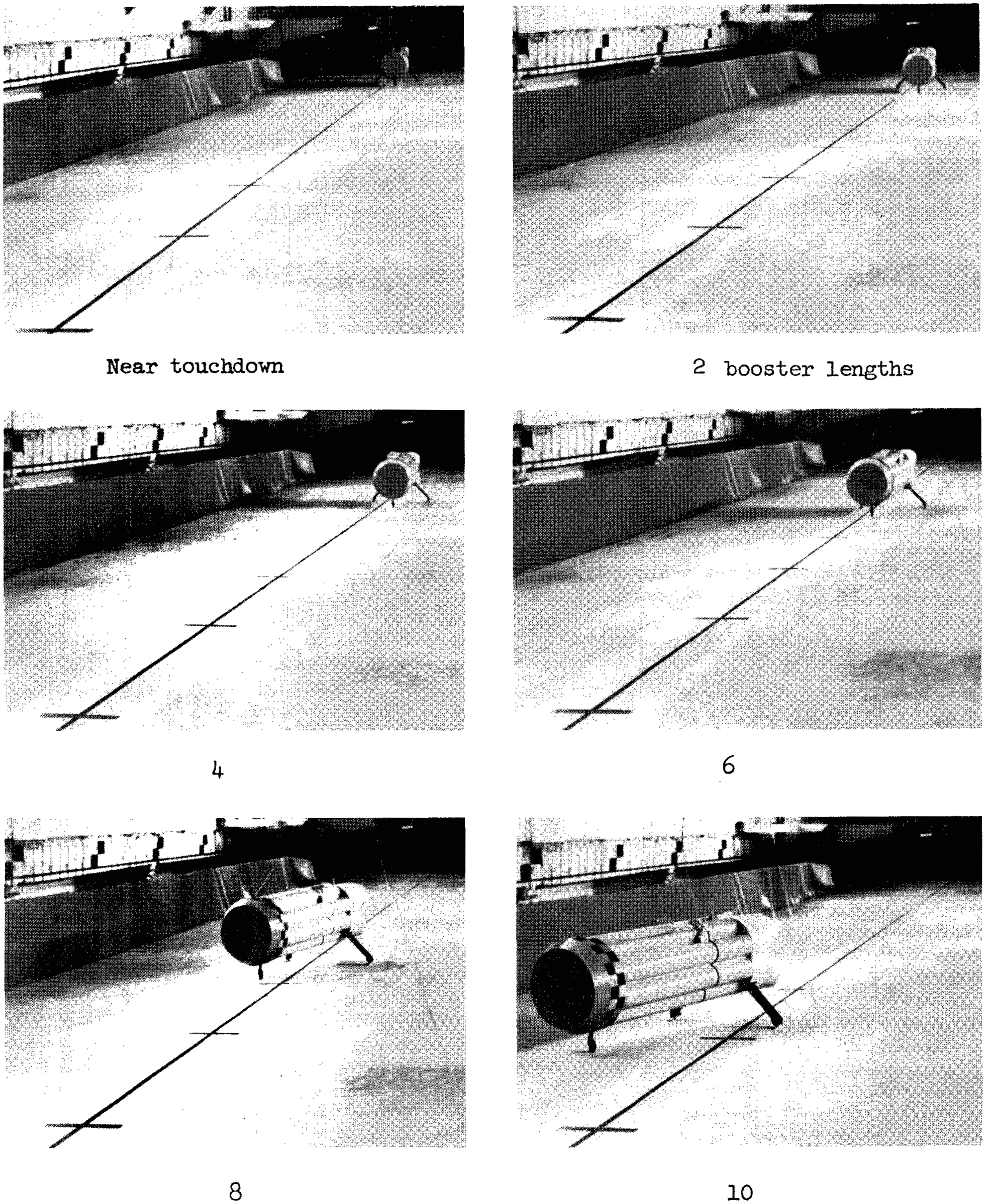

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Figure 9.- Sequence photographs of representative landings of the free-castering-nose-wheel and two-rear-skid configuration. Slideout distances are shown in booster lengths.

NASA-Langley, 1966 L-4101

A motion-picture film supplement L-901 is available on loan. Requests will be filled in the order received. You will be notified of the approximate date scheduled.

The film (16 mm, 3 min, color, silent) shows representative free-body dynamic model landing and slideout tests with various landing-gear configurations.

Requests for the film should be addressed to:

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