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DEVELOPMENT AND TESTING OF THE LUNAR GRAVITY AND EARTH ORBITAL SIMULATOR (PARALLELOGRAM)

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ABSTRACT

This report contains an account of work accomplished in the development and testing of the Lunar Gravity and Earth Orbital Simulator or "Parallelogram" (L/G and E/O).

The L/G and E/O was developed from specifications described within MSFC's Contract NAS8-20821, the Martin-Marietta Corporation, Baltimore, Maryland. Proof testing was accomplished at the contractor's plant under the surveillance of Air Force Inspection. In-house acceptance testing was accomplished in accordance with the requirements set forth by Technical Directive to the MEL Hayes Space Experiment Group. The work reports included in this report describe the events and happenings during development, proof testing, irregularity of achieving balance of the L/G and E/O and the remedy of same.

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SPACE SIMULATION AND ENGINEERING OFFICE
MANUFACTURING ENGINEERING LABORATORY

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DEVELOPMENT AND TESTING OF THE LUNAR GRAVITY AND EARTH ORBITAL SIMULATOR (PARALLELOGRAM)

SUMMARY

This report contains an account of work accomplished in the development and testing of the Lunar Gravity and Earth Orbital Simulator or "Parallelogram" (L/G and E/O).

The L/G and E/O was developed from specifications described within MSFC's Contract NAS8-20821, the Martin-Marietta Corporation, Baltimore, Maryland. Proof testing was accomplished at the contractor's plant under the surveillance of Air Force Inspection. In-house acceptance testing was accomplished in accordance with the requirements set forth by Technical Directive to the MEL Hayes Space Experiment Group. The work reports included in this report describe the events and happenings during development, proof testing, irregularity of achieving balance of the L/G and E/O and the remedy of same.

INTRODUCTION

Development and test of Space Support Equipment requires evaluation of the problems inherent in working under the extraterrestrial gravities of weightless space, the lunar surface, and eventually planetary surfaces in order to identify and evaluate the possible solutions.

Under a contract to NASA, Martin Marietta began practical study of these problems in 1963 with the construction of a 5 degree-of-freedom air bearing-supported frictionless simulator. This simulator was used to evaluate the need for special tools and techniques. Early work showed the need for improvements and simplification in the basic simulator design to make it a more efficient laboratory tool, and several of the improvements were incorporated in a simulator delivered to NASA-MSC in late 1963.

Need for a 6th degree-of-freedom, vertical translation, was apparent, and a concept of vertically translating the subject through a large volume air spring, plus unlimited rotational freedom, was incorporated in a 6 degree-of-freedom simulator installed by Martin Marietta at Wright Patterson Air Force Base in 1964.

A different approach, adapted to the study of work station rather than locomotion problems, was later developed in-house through the use of a frictionless parallelogram in conjunction with a 5 degree-of-freedom simulator. This approach minimized the mass inherent in the 6 degree-of-freedom simulator while allowing almost the same range of motion. It is particularly suited to lunar surface simulation where reduced rather than null gravity is required. This reduces the sensitivity of the simulator to subject balance changing as a result of work motions.

The parallelogram approach was chosen over other alternates on the basis of easy adjustment and the proven low friction capability of ball bearings under proper lubrication and loading conditions. The inherent drag hysteresis of cables and negator springs or other spring type devices plus their lack of adjustability and linearity and the relative expense of servo controlled devices were all considered in the choice of the parallelogram.

An improved 5 degree-of-freedom simulator incorporating improved air bearings and a self-contained blower to reduce drag loads was delivered to NASA-MSFC in 1965.

In 1967, a parallelogram was developed to mate with this simulator and to provide additional flexibility of use through a demountable floor and an air bearing system to enable more sophisticated zero-g testing.

LOW FRICTION PARALLELOGRAM

General Description

The air bearing parallelogram is a parallelogram structure supporting a vertical task panel mount and removable floor and supported in turn on a rigid base on which are mounted three low friction air pads, an electrically powered blower and an air distribution system. The parallelogram structure can be counterweighted to balance the task panel so that low vertical forces will cause motion. Full details of construction can be determined from MSFC approved, Martin Marietta Drawing No. 861-00045.

The parallelogram exhibits low breakout forces of under 3 ounces (0.83 N) in the vertical and horizontal directions. This permits the simulator to be used for zero-g testing as well as for reduced gravity testing.

Enough lead weight to counterbalance the platform and give 40 pounds (178-N) upward force to the test subject was supplied with the simulator. Requirements specified enough extra weight to counterbalance the 200-pound (890-N) dead load during acceptance testing. Three 70-pound (312-N) lead pigs were supplied by the contractor for this purpose.

Only one problem was encountered with the hardware at Huntsville. One of the air pads was cocked so that one edge was 1/4 inch (0.635 cm) higher than the other. Removal of the air pad and examination of the system revealed the damage. The threaded rod supporting the pad had been bent. This was replaced and the acceptance tests were performed. The simulator performed satisfactorily in all respects.

Technical Notes

NASA requested that curves be drawn showing the motor-blower time/temperature relations to determine the relationship between air flow and temperature of motor with voltage control. These are included as Figures 1 through 4 of this report.

There is one minor peculiarity in the operation of this type of simulator. When the simulator is balanced vertically to any point in its operating range, it will remain at that point as expected. As little as 1 1/2 ounces (0.4 N) of force is required to break the static friction and initiate vertical motion. However, there is a slight restoring force which tends to return the platform to its initial balance position when the displacement force is removed.

Examination of the application of this simulator shows that this restoring action is not a problem and in most cases is a convenience. For instance, when used in the earth orbital mode a slight force will drive the

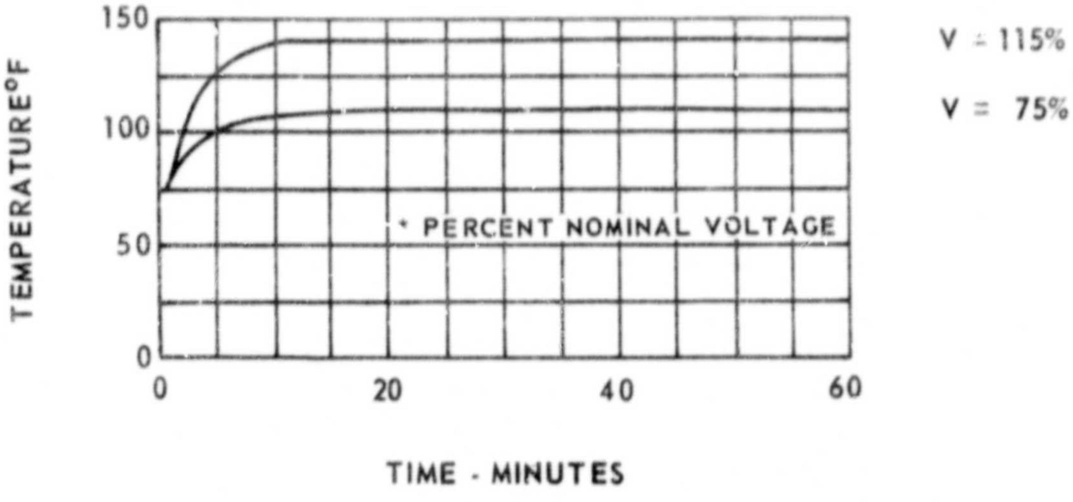


FIGURE 1. BLOWER SHROUD TEMPERATURE CURVES

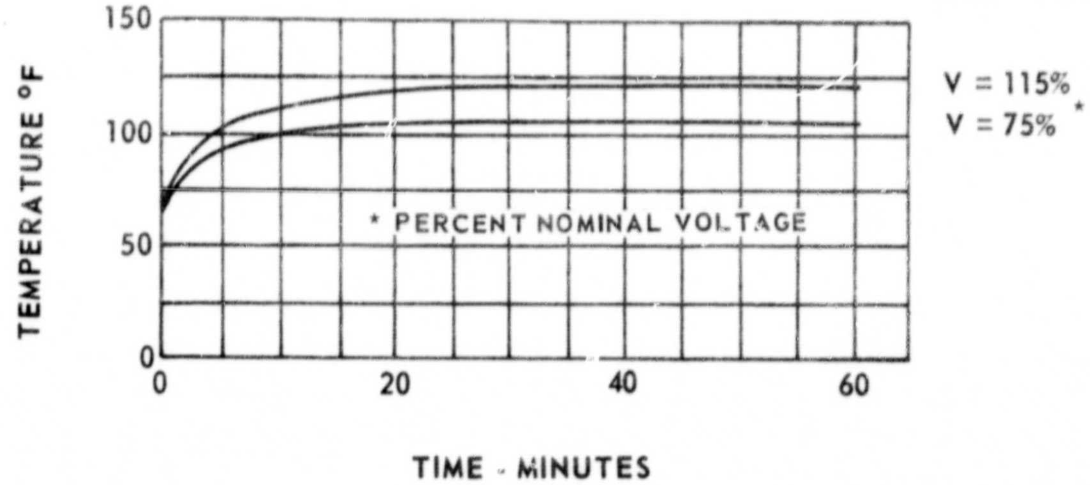


FIGURE 2. MOTOR STATOR TEMPERATURE CURVES

work panel out of reach vertically, at which time the purpose or usefulness of the test has been fulfilled. The work panel will slow down and gradually return to its neutral position and testing can resume.

In the lunar gravity mode, the difference of a few ounces in the simulated weight of the test subject from the standing to the stooping position will have virtually no effect on the simulation.

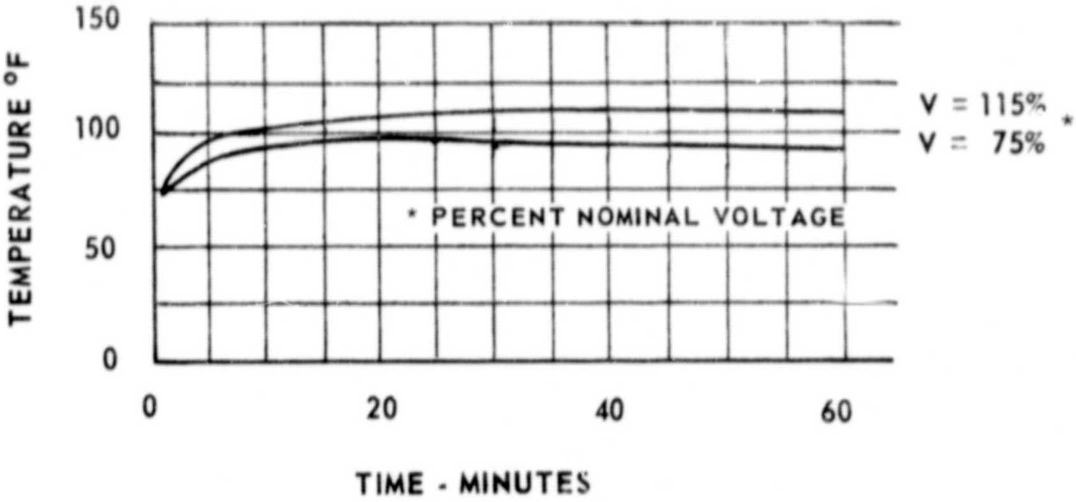


FIGURE 3. MOTOR SHROUD TEMPERATURE CURVES

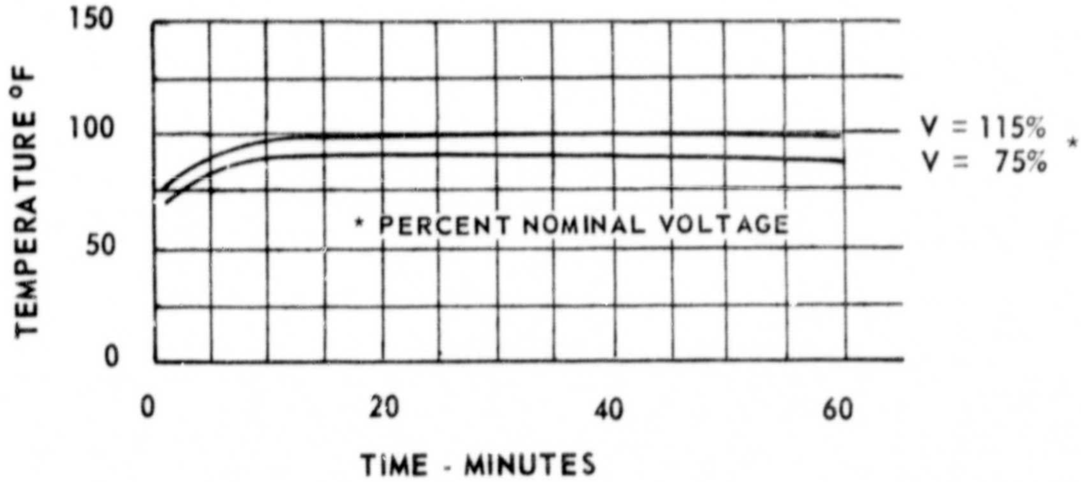


FIGURE 4. MOTOR TOP-BEARING TEMPERATURE CURVES

Preliminary analysis of the simulator geometry shows that a deflection as little as 0.010 inches (0.0254 cm) in the parallelogram arms, due to the weight of the counterbalanced load, will cause about 1 percent of the load to appear as a restoring force at the extremes of vertical travel. At the platform this force is proportional to the displacement from the neutral balance point. Hence, it is extremely low in the normal operating range.

PROOF TESTING OF THE PARALLELOGRAM

Purpose

The purpose of the proof testing procedure was to establish and demonstrate the capabilities of the air bearing parallelogram to meet the requirements of stability and breakout force specified in Contract NAS8-20821, Article I (Work Statement) and final acceptance test as specified herein.

Test Equipment

Test equipment included:

1. Parallelogram structure, P/N 861-0045
2. Spring Balance 0-2 pound (0-8.9 N) horizontal and vertical reading
3. Lead Weights - Total 200 pounds (890 N)
4. Maintenance and Instruction Manual (MI)

Test Procedure

1. Vertical Friction Force Test

   a. Set up.

      (1) Using M&I Manual, install semi-circular platform.

      (2) Balance by adjusting counterweight until floor remains in position to which it is set.

b. Test.

(1) With a spring balance, measure maximum force required to initiate motion upward (Table I). Record 1 1/2 ounces (0.4 N).

(2) Repeat for downward motion. Record 1 1/2 ounces (0.4 N).

TABLE I. FORCE REQUIRED TO INITIATE MOTION

Trial No.	Force			
	Up		Down	
	Ounces	Newtons	Ounces	Newtons
1	1 1/2	0.4	1 1/2	0.4
2	1 1/2	0.4	1 1/2	0.4
3	1 1/2	0.4	1 1/2	0.4
4	1 1/2	0.4	1 1/2	0.4
5	1 1/2	0.4	1 1/2	0.4

NOTES: One of front air pads slightly out of parallel with floor due to bent threaded leg. However, this did not adversely affect performance of the simulator.

Trials performed with 70 percent Blower Motor Power, except when simulator was loaded with 200 pounds (890 N) weight. Motor Power of 100 percent was then required for air pads to have sufficient lift. This much power probably will not be required when out of parallel air pad is corrected.

(3) Repeat steps (1) and (2) five times each and compute average value. Acceptable value is any force less than 2.0 pounds (8.9 N). Record average value 1 1/2 ounces (0.4 N).

2. Horizontal Friction Force Test

a. Set up.

(1) Using M&I manual, install semi-circular platform.

(2) Balance by adjusting counterweight until floor remains in positions to which it is set.

(3) Assure that 115 VAC, 60 Hz power source is connected to blower power connector.

b. Test.

(1) Turn power on.

(2) Adjust the variable transformer until the air pads inflate and lift assembly approximately 1/4 inch (0.635 cm).

(3) If required, adjust air pad valves to balance lift.

(4) With a spring balance, apply horizontal forces to floor assembly or work panel mounting structure to initiate motion.

(5) Verify that horizontal force is well below 2.0 pounds (8.9 N). Record value 2 ounces (0.6 N). Note: Depending upon floor levelness, the force should be less than 4 ounces (1.1 N). Assembly may move of its own accord, coasting to lowest point on the floor.

3. Vertical Load 200 Pound (890 N) Proof Test

a. Set up.

(1) Using M&I manual, set up on smooth floor.

(2) Assure that blower power is off.

(3) Install semi-circular platform.

(4) Assure that support legs are fully extended.

(5) Remove weights in counterweight to assure that platform is at lowest point.

b. Test.

(1) Apply a 200 pound (890 N) weight to rear center of platform.

(2) Attach counterweights until platform legs just lift off floor.

(3) Turn on air pad blower and adjust variable transformer until air pads inflate and lift assembly 1/4 inch (0.635 cm).

(4) Apply horizontal force to move parallelogram across floor.

(5) Observe that structure is stable under load and moves horizontally with no interference. If interference is noted, check air pad flotation height and adjust air pad valves to balance lift.

IRREGULARITIES OF THE SIMULATOR

As indicated previously in this report, true balance of the simulator had not been achieved. Since true balance is necessary to achieve earth orbital simulation, the irregularity was undesirable. An investigation was made to determine the true cause of the irregularity.

Manufacturing Engineering Laboratory personnel optically aligned and measured the simulator. All measurements were verified by Quality and Reliability Assurance Laboratory personnel. The optical measurement findings indicated that the simulator was out of tolerance to a minor degree.

The Martin Corporation's analysis for the simulator's peculiarity in that a deflection of 0.010 inches (0.0254 cm) in the parallelogram arms due to the weight of the counterbalance load will cause 1 percent of the load to appear as a restoring force at the extremes of vertical travel (either the ultimate top or bottom locations). Assuming this analysis was correct and with the additional information of optical measurements taken, the following testing and conclusion were offered for consideration.

The parallelogram was tested for restoring forces. Maximum restoring forces for parallelogram from bottom to top or top to bottom is 2 pounds (8.9 N) for the balanced parallelogram without platform. Assuming that 1 percent of the counterbalanced beam weight is included in these 2 pounds (8.9 N), 2 pounds minus (1 percent of 70 pounds) = 1.3 pounds (5.8 N) restoring force. The 2 percent additional restoring force was believed due to the parallelogram being slightly out of parallel with some dimensions being slightly out of tolerance.

These test data were analyzed and further calculations resulted in a modification to the L/G and E/O which was totally effective in resolving the balancing peculiarity.

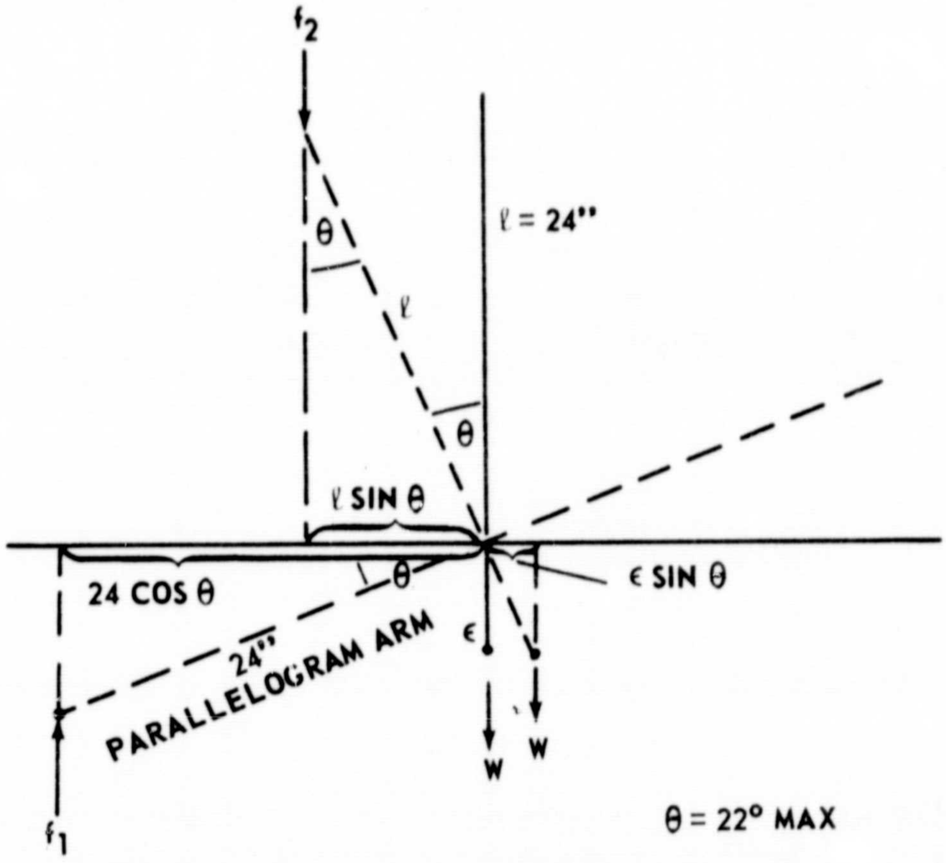
CALCULATIONS FOR SIMULATOR MODIFICATION

Figure 5 shows the geometry of the restoring force problem and the corrections applied. It is assumed that the restoring forces is a pendulous effect due to the effective center of gravity of the parallelogram and counterweights being below the center of the bearings by some distance, ϵ. When the platform is moved to either limit the arms rotate to about 22 degrees from horizontal. The weight, W, creates a restoring moment, M_r, as it moves through an angle, Θ, which is:

$$M_r = W \epsilon \sin \Theta .$$

It is this moment which we must balance out. A force, f_2, applied vertically to arm 1 will give a cancelling moment M_c of:

$$M_c = - f_1 \, l \sin \Theta .$$



$$W \epsilon \sin\theta = f_1 \times 24 \cos\theta = -f_2 \ell \sin\theta$$

FIGURE 5. CANCELLATION MECHANISM GEOMETRY

Assume we wish to cancel a six-pound (26.7 N) restoring force f_1 on the platform. The simulator moment arms are 24 inches (0.61 m) long so that the moment on the parallelogram at the maximum 22 degree angle is:

$$f_1 \times 24 \cos 22 \text{ degrees} = 6 \times 24 \cos 22 \text{ degrees} = 132 \text{ inch-pounds } (14.9 \text{ Nm}).$$

If we choose an arbitrary length of 24 inches (0.61 m) for the cancelling arm l (based on available space and loading considerations) the weight, f_2, required will be:

$$f_2 = \frac{132 \text{ inch-pounds}}{24 \sin 22 \text{ degrees inches}} = \frac{132}{9.0} = 14.6 \text{ pounds } (65.0 \text{ N}).$$

Since lead has a volume of about 2.44 cubic inches per pound (88.2 cm^3/kg), about 35.5 cubic inches (581 cm^3) of lead are required for the weight. Figure 6 shows the dimensions chosen for the weight. The length of the aluminum tube was chosen to be 26 inches (0.66 m) to allow the center of the weight to be placed above the 24-inch (0.61 m) level for additional connection, if required. Note that the length l used in the calculations would be measured from the center of the bearing to the combined center of mass of the tubing and the weight.

ADJUSTMENT OF CANCELLING DEVICE

The cancelling device should be adjusted in accordance with the following steps:

1. The weight should be removed. The simulator and its load should then be balanced as per the maintenance manual instructions, but with the parallelogram arms horizontal. The weight should be replaced on the cancelling device at about its correct height for the load.

2. Rotate the weight to a point where the arms remain horizontal.

3. The parallelogram floor should then be pressed down to its bottom position and the cancelling weight moved up or down until the restoring force is just cancelled. (A +, -, or 0 force may be achieved.)

4. At this point the parallelogram should be returned to horizontal position and step 2 repeated.

5. Check for minimum unbalances through the range of vertical motion of the parallelogram and repeat steps 2, 3, and 4 for optimum results.

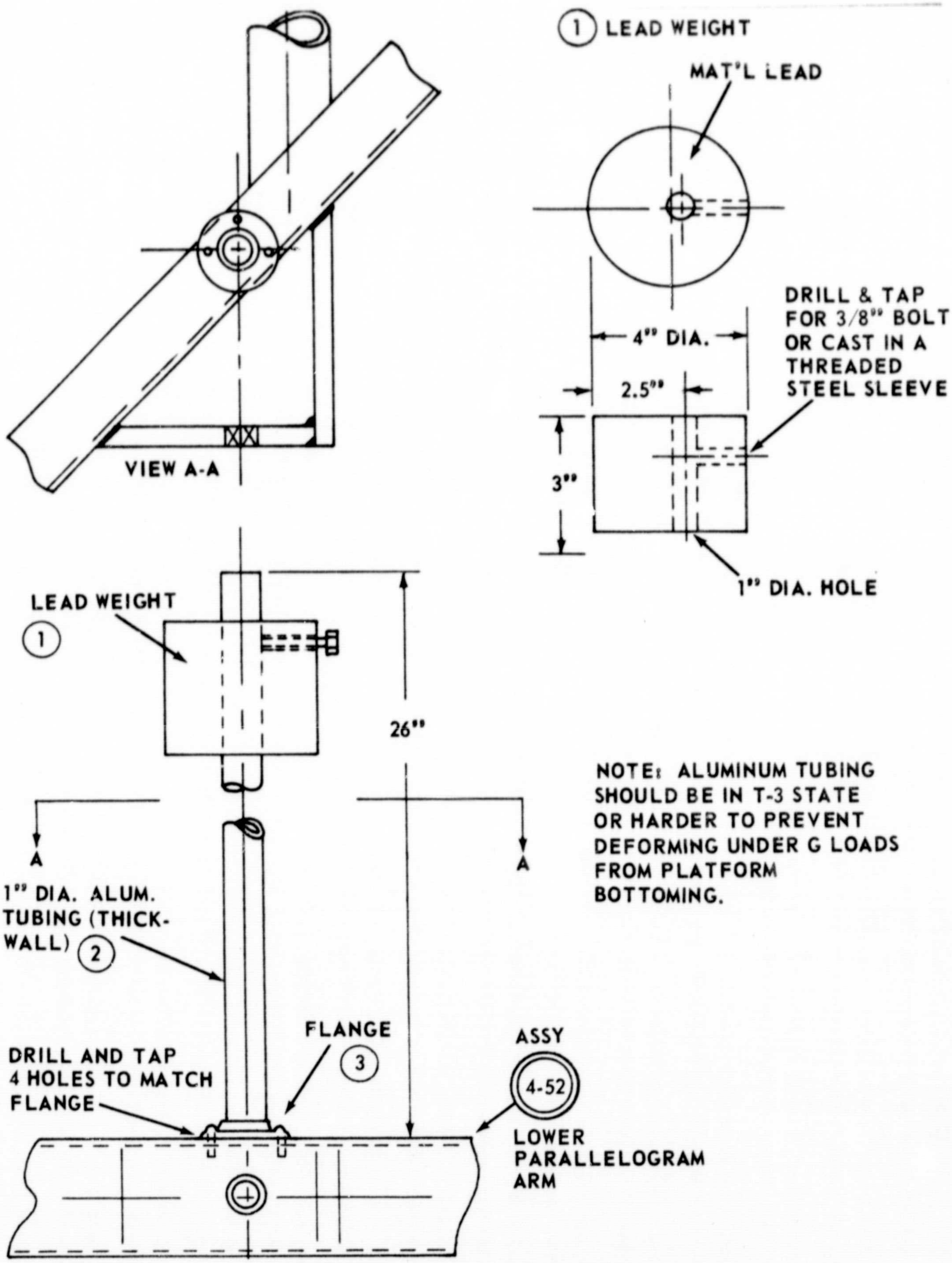


FIGURE 6. CANCELLATION MECHANISM