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INTERFACE STABILITY DURING LIQUID INFLOW TO INITIALLY EMPTY HEMISPHERICAL ENDED CYLINDERS IN WEIGHTLESSNESS

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16. Abstract

An experimental investigation was conducted in a weightless environment to study the behavior of the liquid-vapor interface during liquid inflow to hemispherical ended cylinders which were initially void of liquid. During inflow, both stable and unstable behavior of the liquid-vapor interface was noted. The stability of the liquid-vapor interface has previously been correlated by a Weber number based on inlet line radius and average inflow velocity. This report extends the correlation to larger tanks and inlet line radii by the use of the 5- to 10-Second Zero Gravity Facility at the Lewis Research Center. As was previously determined, the value of the critical Weber number was again found to be 1.3.

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INTERFACE STABILITY DURING LIQUID INFLOW TO INITIALLY EMPTY HEMISPHERICAL ENDED CYLINDERS IN WEIGHTLESSNESS

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SUMMARY

An experimental investigation was conducted in a weightless environment to study the behavior of the liquid-vapor interface during liquid inflow to hemispherical ended cylinders which were initially void of liquid. During inflow, both stable and unstable behavior of the liquid-vapor interface was noted. The stability of the liquid-vapor interface has previously been delineated by a Weber number based on inlet line radius and average inflow velocity. The objective of this experiment was to extend the Weber number correlation to larger tanks and inlet line radii by the use of the 5- to 10-Second Zero Gravity Facility at the Lewis Research Center. Tests were conducted with two tank sizes (7.5 and 15 cm radii), two inlet line sizes (0.75 and 1.5 cm radii), and two test liquids (ethanol and trichlorotrifluoroethane). Results obtained were consistent with the previous study, and the value of the critical Weber number (the Weber number above which interface instability occurs) was again found to be 1.3.

INTRODUCTION

In-orbit, propellant transfer and the transfer of liquids between containers (as in regenerative life support systems) will be required for future long-range missions. A thorough knowledge of both the outflow characteristics from a storage tank and the subsequent fluid behavior during the filling of the receiver tank in a weightless environment is required for the design of these transfer systems.

An extensive program dealing with liquid transfer in a weightless environment is being conducted at the Lewis Research Center. Most of the work to date has dealt with the liquid-outflow phase of fluid transfer (refs. 1 to 3), and it is only recently that the problems of liquid inflow have been investigated. A previous study (ref. 4) has determined that there is a region in which the behavior of the liquid-vapor interface is stable and another region in which the interface is unstable. In that work, it was found that a Weber number based on inlet radius and average inflow velocity delineated between the two regions and that the value of this critical Weber number was 1.3.

The objective of this experimental investigation is to extend the data of reference 4 to larger tanks (up to a 15-cm radius) and larger inlet line radii (up to a 1.5-cm radius) by the use of the 5- to 10-Second Zero Gravity Facility at Lewis. The behavior of the liquid-vapor interface during inflow and the development of the Weber number criterion are discussed in a manner similar to reference 4. In addition, experimental data are presented and compared with previous results.

SYMBOLS

A_i	cross-sectional area of the inlet line, cm^2
F_{mf}	force due to momentum flux, dynes
F_{st}	force due to surface tension, dynes
R_i	radius of inlet line, cm
R_t	radius of tank, cm
$V_{i,avg}$	average inlet velocity, cm/sec
We	Weber number, $We = \left(V_{i,avg}\right)^2 R_i/2\beta$
β	specific surface tension, σ/ρ, cm^3/sec
μ	absolute viscosity, g/cm-sec
ρ	liquid density, g/cm^3
σ	surface tension, dynes/cm

APPARATUS AND PROCEDURE

A description of the experiment vehicle and the facility employed in this study and the procedure for their operation can be found in the appendix.

Test Tanks and Liquids

The experiment tanks used in this investigation were 7.5- and 15-centimeter-radius cylinders having hemispherical bottoms. A sketch of a typical tank is shown in figure 1. Both tanks were machined from cast acrylic plastic and polished for photographic purposes. Inlet lines were located along the longitudinal axis, were circular in cross section, and were terminated with a sharp edge. The inlet line radius was equal to one-tenth the tank radius.

Tank radius, R_t, cm	Inlet line radius, R_i, cm
15	1.5
7.5	0.75

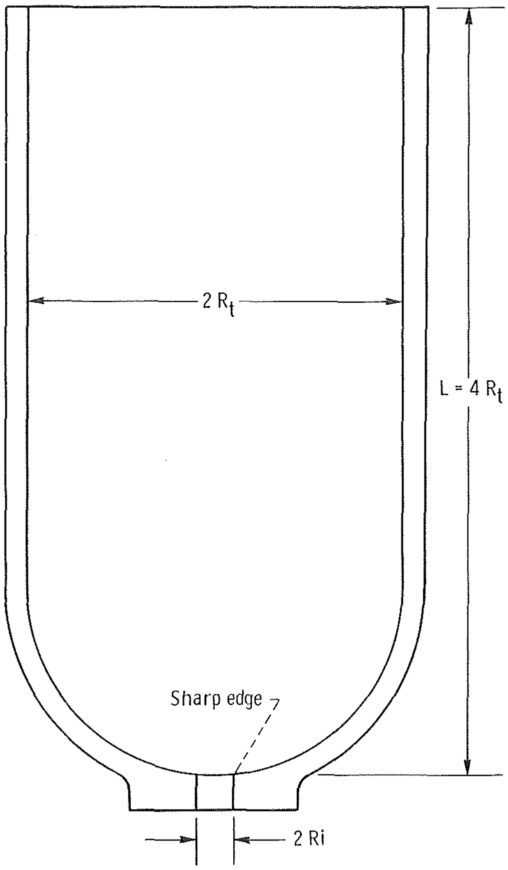


Figure 1. - Experiment tanks.

TABLE I. - PROPERTIES OF TEST LIQUIDS

[Contact angle with cast acrylic plastic in air, 0^{o}]

Liquid	Surface tension at 20^{o} C, σ, dynes/cm (or 10^{-5} N/m)	Density at 20^{o} C, ρ, g/cm^3	Viscosity at 20^{o} C, μ, g/cm-sec	Specific surface tension, β, cm^3/sec^2
Anhydrous ethanol	22.3	0.79	1.2×10^{-2}	28.3
Trichlorotri-fluoroethane	18.6	1.58	$.7\times10^{-2}$	11.8

The liquids used in this investigation were trichlorotrifluoroethane and ethanol. Properties of the test liquids pertinent to the study may be found in table I. To improve photographic quality, a small amount of dye was added to the liquid. This dye had no measurable effect on the fluid properties.

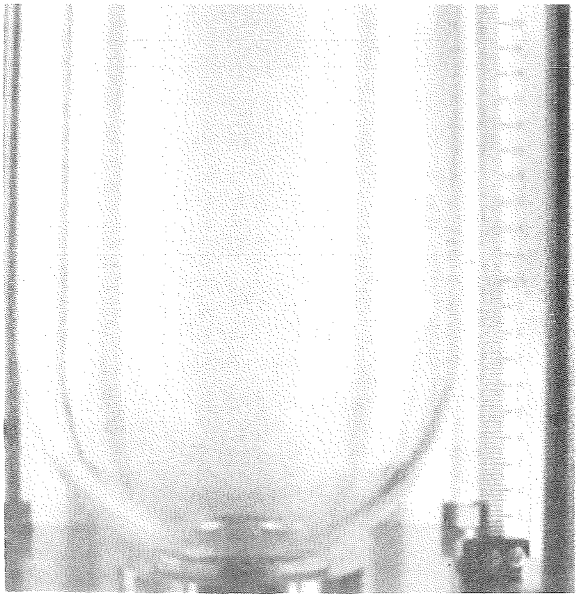
Data Reduction

The behavior of the liquid-vapor interface during inflow was recorded on 16-millimeter color film. Flow rates were determined by calibration tests at normal gravity and checked by monitoring the pressure during the experiment by means of telemetry. Since the flow rate was known, the average inflow velocity was calculated.

RESULTS AND DISCUSSION

Description of Interface Behavior

As in the previous study (ref. 4), both stable and unstable interface behavior were observed. A photographic sequence, typical of the data obtained in this study, showing both regions of interface behavior is presented in figure 2. In the stable region (fig. 2(a)), the incoming liquid formed a small geyser above the inlet line. This geyser initially grew in height with respect to the lowest point on the liquid-vapor interface and then became stabilized, apparently by surface tension. After reaching some maximum height (in all observed cases, less than one tank radius), the geyser either remained at that height or decreased in height with respect to the lowest point on the interface for the duration of the test.



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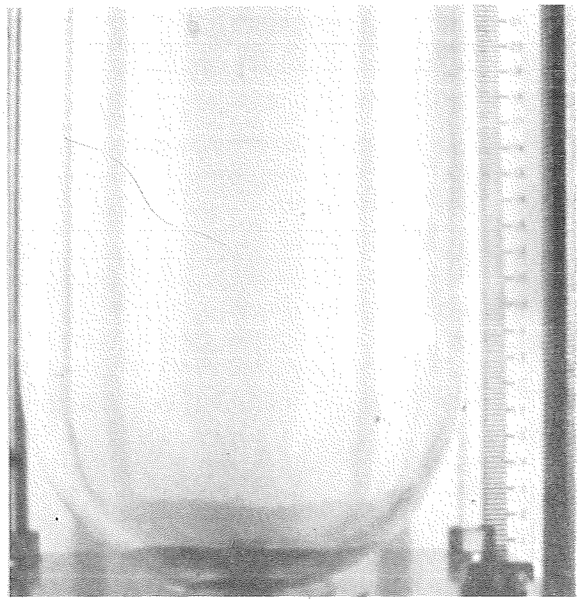

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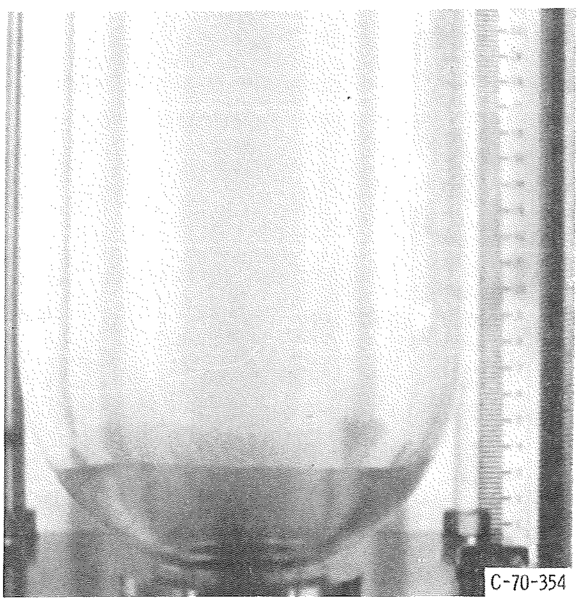
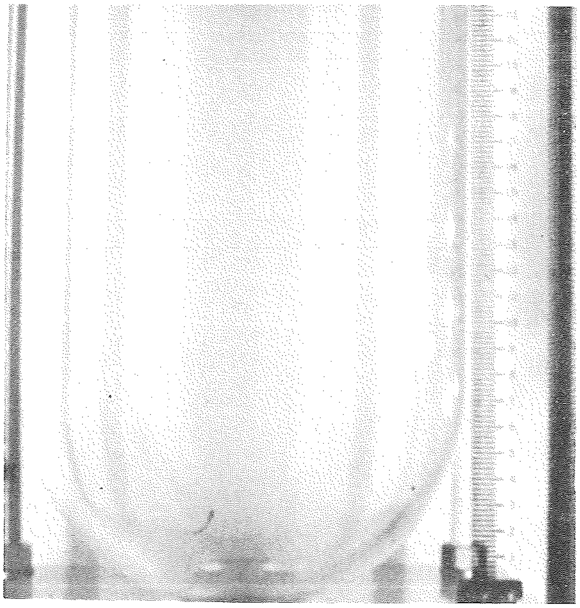


Time, 5.00 second.

(a) Stable interface; inflow velocity, 4.64 centimeters per second.

Figure 2. - Regions of liquid-vapor interface behavior during inflow. Tank radius, 7.5 centimeters; inlet line radius, 0.75 centimeters; test liquid, trichlorotrifluoroethane.



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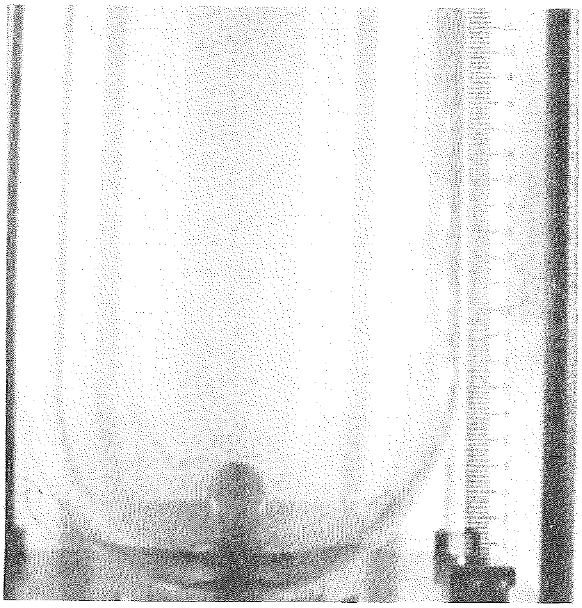

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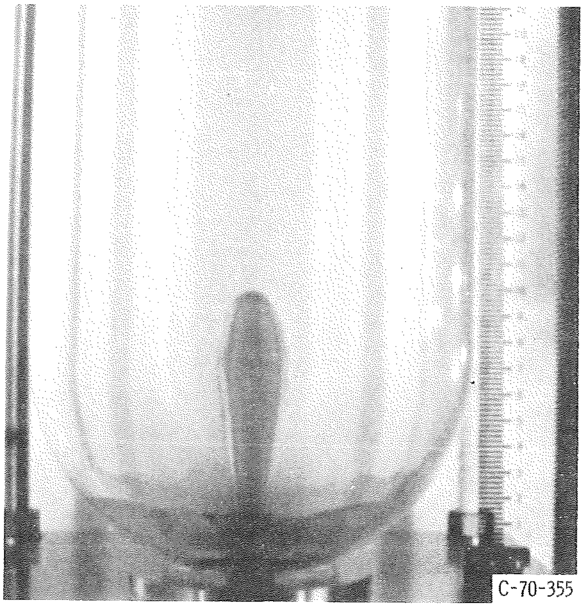

Time, 5.00 second.

(b) Unstable interface; inflow velocity, 7.24 centimeters per second.

Figure 2. - Concluded.

In the unstable region (fig. 2(b)), the incoming liquid again formed a geyser above the inlet line. However, in this region, the geyser continued to grow in height with respect to the lowest point on the liquid-vapor interface. In this region, only a small amount of incoming liquid is collecting at the inlet end of the tank and continuation of the inflow process would result in liquid impinging on the opposite or vent end of the tank.

Weber Number Criterion

According to reference 4, the only forces considered to be significant in delineating between the regions of stable interface behavior and unstable interface behavior are those due to momentum flux and the surface tension. When the incoming momentum flux is small compared to surface tension, the liquid-vapor interface is stable, and conversely, when the momentum flux reaches a magnitude large enough to overcome the surface tension, the interface is unstable. Therefore, the ratio of these two forces should delineate the regions of stability and instability of the interface during liquid inflow.

To determine the momentum flux of a given jet, it is essential to know the exact velocity profile of the liquid as it exits the inlet line. The shape of the velocity profile determines the constant which precedes the terms in the momentum flux equation. For example, if the velocity profile of the liquid exiting the inlet line is parabolic, the momentum flux could be written as

$$F_{mf} = \frac{4}{3}\rho A_i V_{i,avg}^2 = \frac{4}{3}\rho\pi R_i^2 V_{i,avg}^2 \tag{1}$$

while for a velocity profile which is flat or square headed, the momentum flux may be written as

$$F_{mf} = \rho A_i V_{i,avg}^2 = \rho\pi R_i^2 V_{i,avg}^2 \tag{2}$$

Because it was impossible to determine the exact velocity profile of the liquid jets in this experiment, we employ the equation for momentum flux in the form

$$F_{mf} \propto \rho\pi R_i^2 V_{i,avg}^2 \tag{3}$$

The surface tension force may be given as

$$F_{st} \propto 2\pi R_i \sigma \tag{4}$$

Taking the ratio of these two forces then yields

$$\frac{F_{mf}}{F_{st}} \propto \rho \frac{V_{i,avg}^2 R_i}{2\sigma} \tag{5}$$

which is the Weber number based on an average inflow velocity and the inlet radius. This equation may be simplified by substitution of β for σ/ρ

$$We = \frac{F_{mf}}{F_{st}} \propto \frac{V_{i,avg}^2 R_i}{2\beta} \tag{6}$$

From reference 4, the value of the critical Weber number (the value of the Weber number at which the liquid vapor interface became unstable) was found to be

$$We = \frac{F_{mf}}{F_{st}} \propto \frac{V_{i,avg} R_i}{2\beta} = 1.3 \tag{7}$$

Verification of Weber Number

In order to verify that the Weber number expressed in equation (7) is the proper scaling parameter for liquid inflow during weightlessness, inflow velocity is plotted against the ratio of specific surface tension to inlet line radius as shown in figure 3. Note that the data obtained in this experiment agree favorably with previous data, and that the value of the critical Weber number is again shown to be 1.3.

Furthermore, because the inlet line size of 0.75-centimeter radius for the 7.5-centimeter-radius tank is close to the inlet line size of 0.80-centimeter radius for the 4-centimeter-radius tank investigated in reference 4, no effect of tank radius (size) is evident. Therefore, the results of this experiment indicate that the Weber number as defined in equation (7) is indeed a useful nondimensional scaling parameter for delineating between the regions of stable and unstable behavior of the liquid-vapor interface during inflow to a hemispherical ended tank which is initially void of liquid and in a weightless environment.

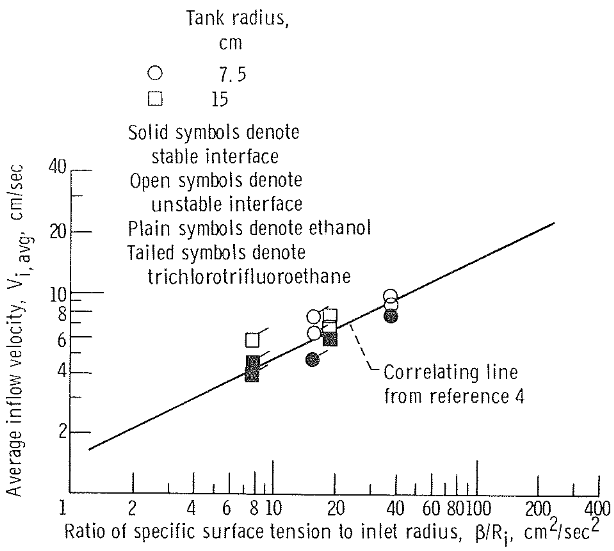

Figure 3. - Delineation of interface behavior by Weber number criterion.

SUMMARY OF RESULTS

An experimental investigation of the behavior of the liquid-vapor interface during liquid inflow to hemispherical ended cylinders was conducted in a weightless environment. At the initiation of inflow, the tanks were void of liquid. Tests were conducted with two tank sizes (7.5- and 15-cm radii), two inlet line sizes (0.75- and 1.5-cm radii), and two test liquids (ethanol and trichlorotrifluoroethane). The results indicate the following:

1. Both stable and unstable regions of interface behavior were found to exist in larger tanks than previously investigated.

2. The validity of the Weber number as the proper nondimensional scaling parameter for delineating between these two regions has been extended to larger inlet and tank sizes. The value of the critical Weber number was again 1.3.

3. The stability of the interface was again found to be independent of the tank size.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, January 23, 1970,
124-08.

APPENDIX - APPARATUS AND PROCEDURE

Test Facility

The experiment data for this study were obtained in the 5- to 10-Second Zero Gravity Facility at the Lewis Research Center. A schematic diagram of this facility is shown in figure 4. The facility consists of a concrete-lined 8.5-meter-diameter (28-ft-diam) shaft that extends 155 meters (510 ft) below ground level. A steel vacuum chamber, 6.1 meters (20 ft) in diameter and 143 meters (470 ft) high, is contained within the concrete shaft. The pressure in this vacuum chamber is reduced 13.3 newtons per square meter (1.3×10^{-4} atm) by utilizing the Center's wind tunnel exhaust system and an exhauster system located in the facility.

The ground-level service building has, as its major elements, a shop area, a control room, and a clean room. Assembly, servicing, and balancing of the experiment vehicle are accomplished in the shop area. Tests are conducted from the control room (see fig. 5) which contains the exhauster control system, the experiment vehicle predrop checkout and control system, and the data retrieval system. Those components of the experiment which are in contact with the test fluid are prepared in the facility's class 10 000 clean room. The major elements of the clean room are an ultrasonic cleaning system (fig. 6(a)) and a class 100 laminar-flow work station (fig. 6(b)) for preparing those experiments requiring more than normal cleanliness.

Mode of operation. - The Zero Gravity Facility has two modes of operation. One is to allow the experiment vehicle to free-fall from the top of the vacuum chamber, which results in nominally 5 seconds of free-fall time. The second mode is to project the experiment vehicle upwards from the bottom of the vacuum chamber by a high pressure pneumatic accelerator located on the vertical axis of the chamber. The total up-and-down trajectory of the experiment vehicle results in nominally 10 seconds of free-fall time. The 5-second mode of operation was used for this experimental study.

In either mode of operation, the experiment vehicle falls freely; that is, no guide wires, electrical lines, etc. are connected to the vehicle. Therefore, the only force (aside from gravity) acting on the freely falling experiment vehicle is due to residual air drag. This results in an equivalent gravitational acceleration acting on the experiment which is estimated to be of the order of 10^{-5} g maximum.

Recovery system. - After the experiment vehicle has traversed the total length of the vacuum chamber, it is decelerated in a 3.6-meter- (12-ft-) diameter, 6.1-meter- (20-ft-) deep container which is located on the vertical axis of the chamber and filled with small pellets of expanded polystyrene. The deceleration rate (averaging 32 g's) is controlled by the flow of pellets through the area between the experiment vehicle and the

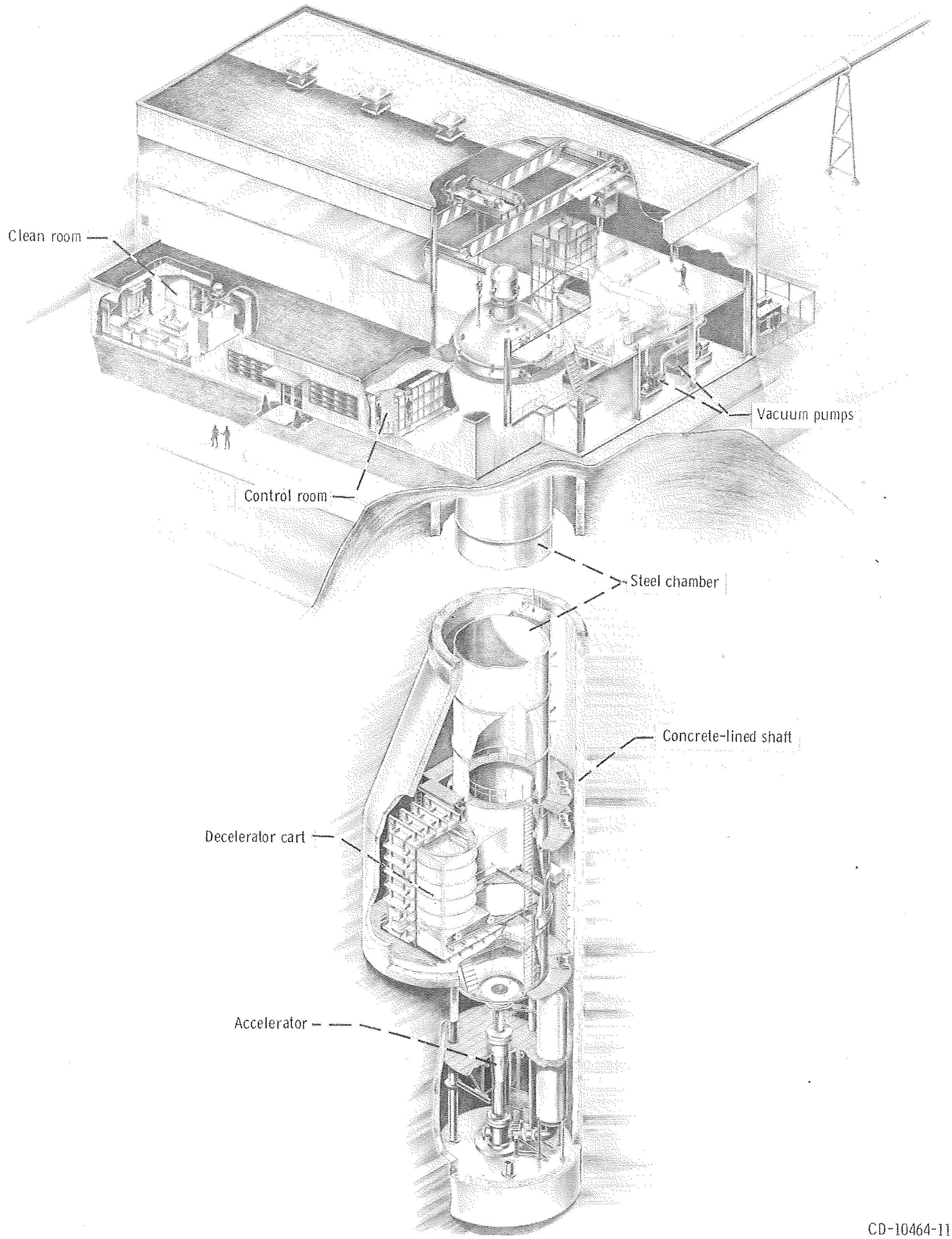

Figure 4. - Schematic diagram of 5- to 10-Second Zero-Gravity Facility.

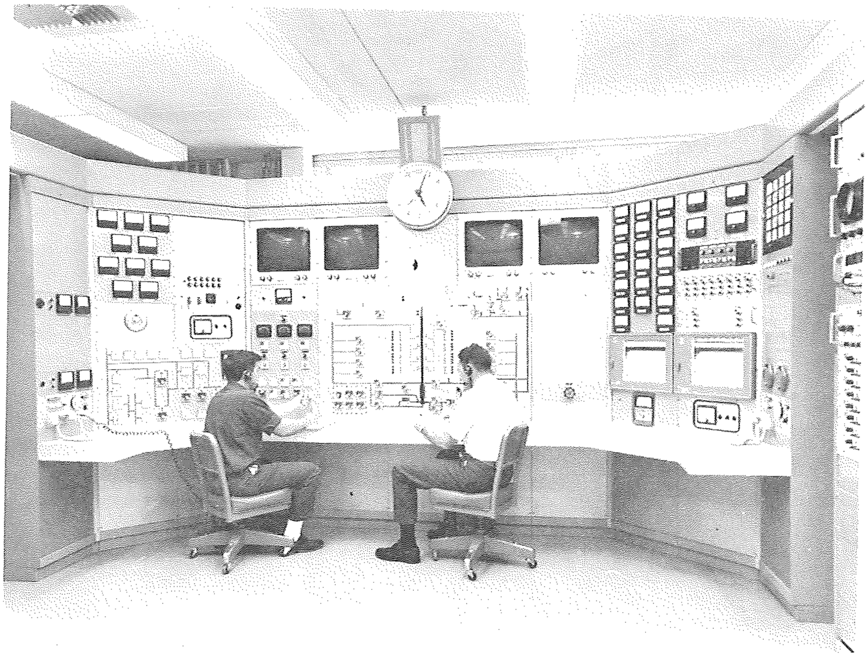

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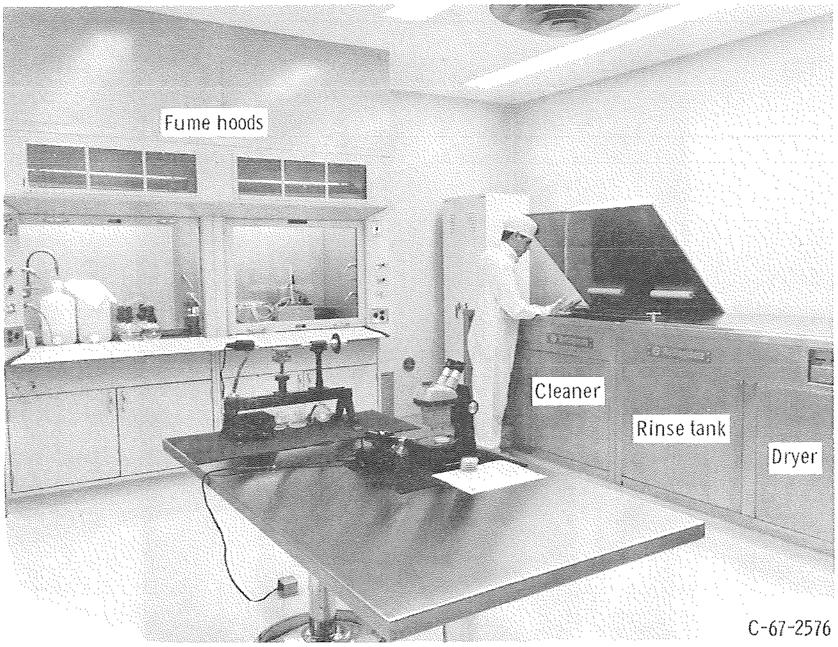
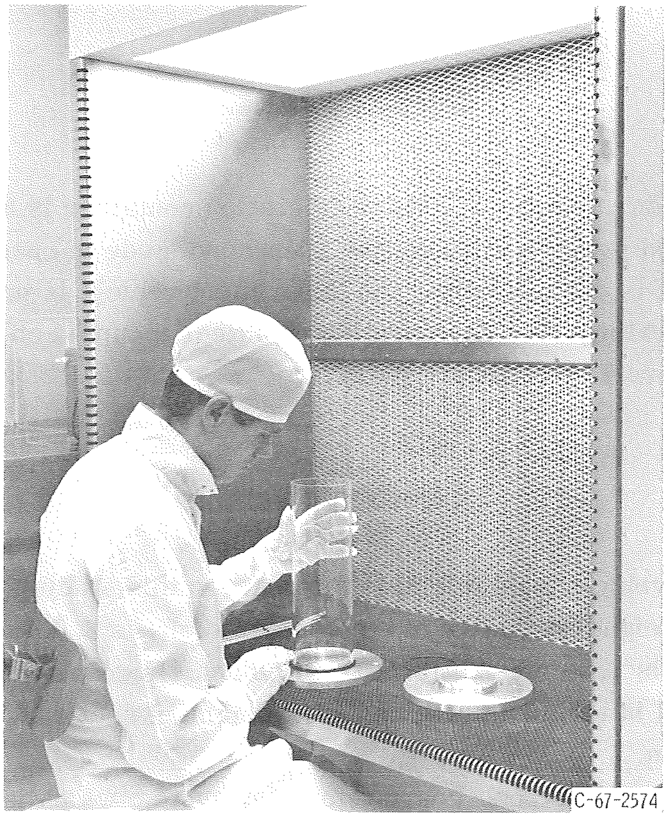
Figure 5. - Control room.



(a) Ultrasonic cleaning system.



(b) Laminar-flow work station.

Figure 6. - Clean room.

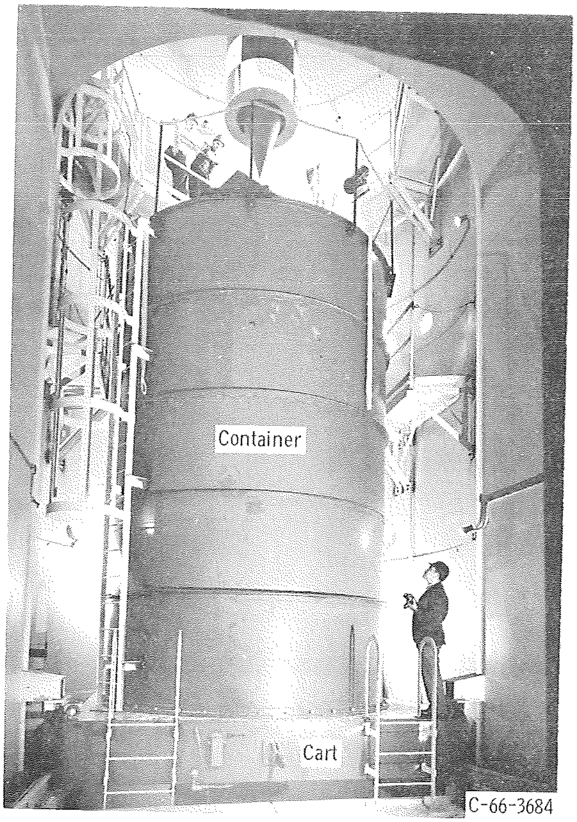


Figure 7. - Deceleration system.

wall of the deceleration container. This deceleration container is mounted on a cart which can be retracted prior to utilizing the 10-second mode of operation. In this mode of operation, the cart is deployed after the experiment vehicle is projected upward by the pneumatic accelerator. The deceleration container mounted on the cart is shown in the photograph of figure 7.

Experiment Vehicle

The experiment vehicle used to obtain the data for this study is shown in figure 8. The overall vehicle height (exclusive of the support shaft) is 3.0 meters (9.85 ft) and the largest diameter is 1.06 meters (3.5 ft). The vehicle consists of a telemetry system section contained in the aft fairing and an experiment section which is housed in the cylindrical midsection.

Telemetry system. - The one-board telemetry system which is used to record pressure data is a standard Inter-Range Instrumentation Group (IRIG) FM/FM 2200-megahertz telemeter. It is used during a test drop to record up to 18 channels of con-

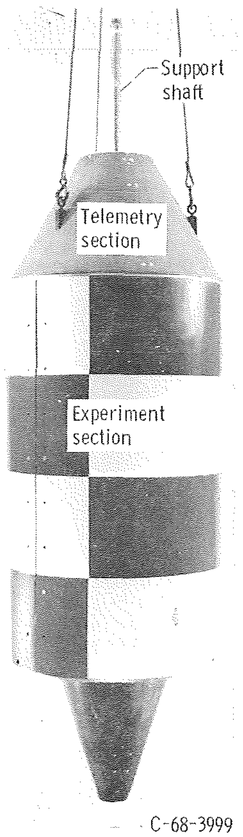


Figure 8. - Experiment vehicle.

tinuous data. The system has a frequency range up to 2100 hertz. The telemetered data are recorded on two high-response recording oscillographs located in the control room.

Experiment. - The experiment section consists of the test tank, the pressurization and flow control system, and the necessary photographic equipment. The details of the experiment section are shown in figure 9. The experiment tank is mounted in such a way so that the motion of the liquid-vapor interface behavior during inflow can be recorded by means of a high-speed motion picture camera. Both a sweep hand clock having an accuracy of ±0.005 second and a centimeter scale are positioned in the field of view of the camera. In order to provide adequate lighting for the photography, the experiment is lighted with an array of spotlights. Differential pressure is maintained by the pressure regulator during the inflow process and is continuously recorded by telemetry.

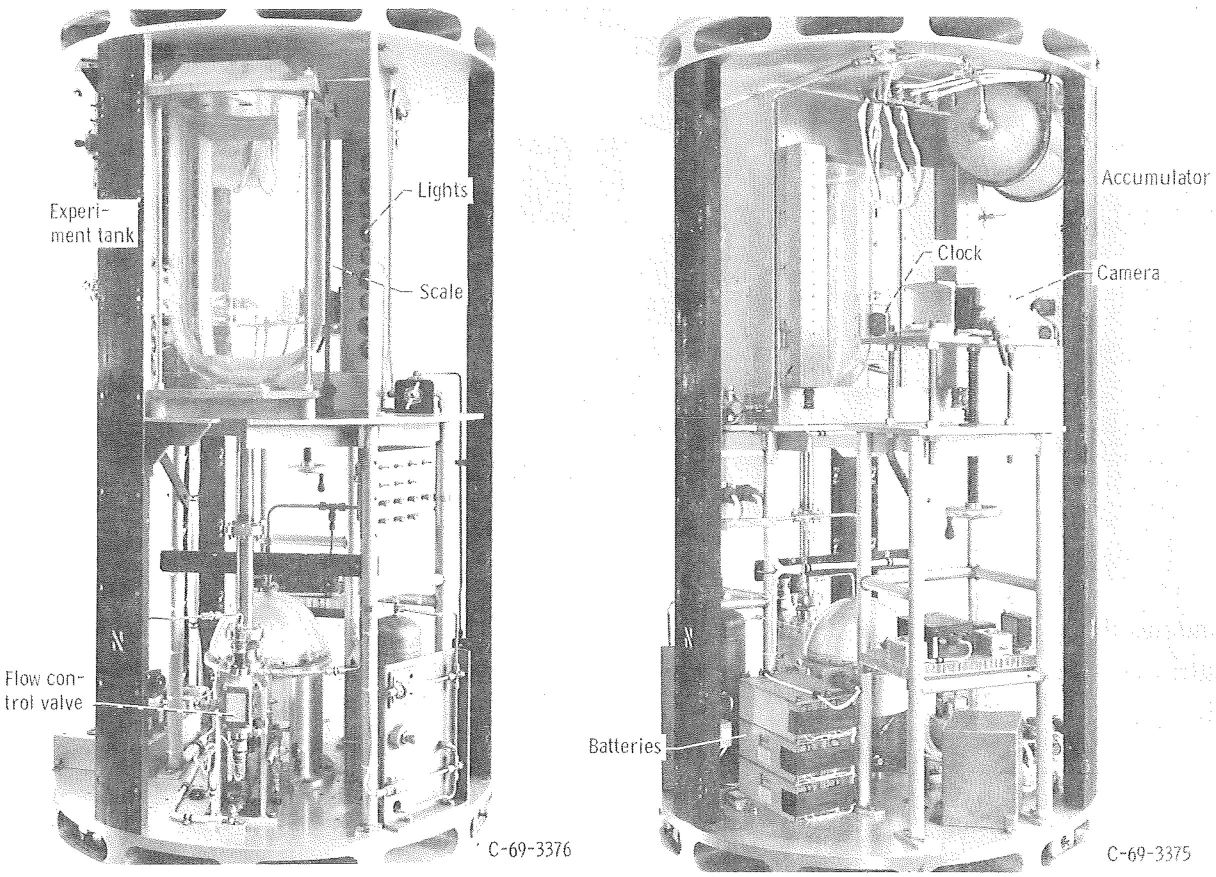


Figure 9. - Experiment section details.

Test Procedure

Prior to every experiment, the test tank was thoroughly washed, ultrasonically cleaned, dried in a warm air dryer, and assembled in the clean room. The clean tank was then installed in the experiment vehicle.

The liquid velocity was set for each test drop by a normal gravity calibration check. The desired velocity was obtained by regulating the pressure across an orifice and then opening a fast acting solenoid valve to initiate flow into the experiment tank. A calibration curve which gave flow range against pressure for a given orifice size was used to determine approximate settings and verified for each drop by measuring the volume of liquid pumped into the tank in a given period of time. Effects of static head were negligible, and inflow to the experiment was started at the initiation of weightlessness.

The vehicle was positioned at the top of the vacuum chamber as shown in figure 10. It was suspended by the support shaft on a hinged-plate release mechanism. During vacuum chamber pumpdown and prior to release, monitoring of experiment vehicle systems was accomplished through an umbilical cable attached to the top of the support shaft. Electrical power was supplied from ground equipment. The system was then

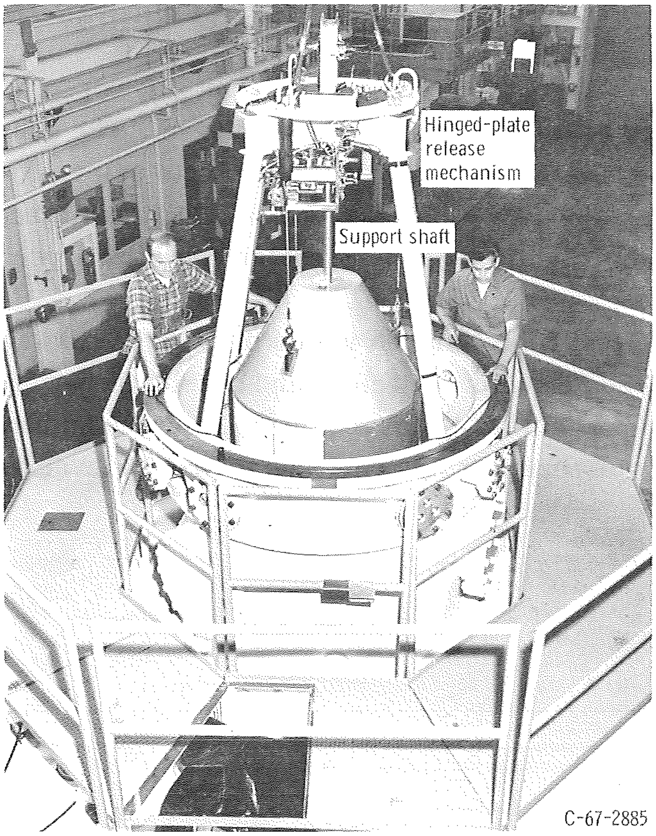


Figure 10. - Vehicle position prior to release.

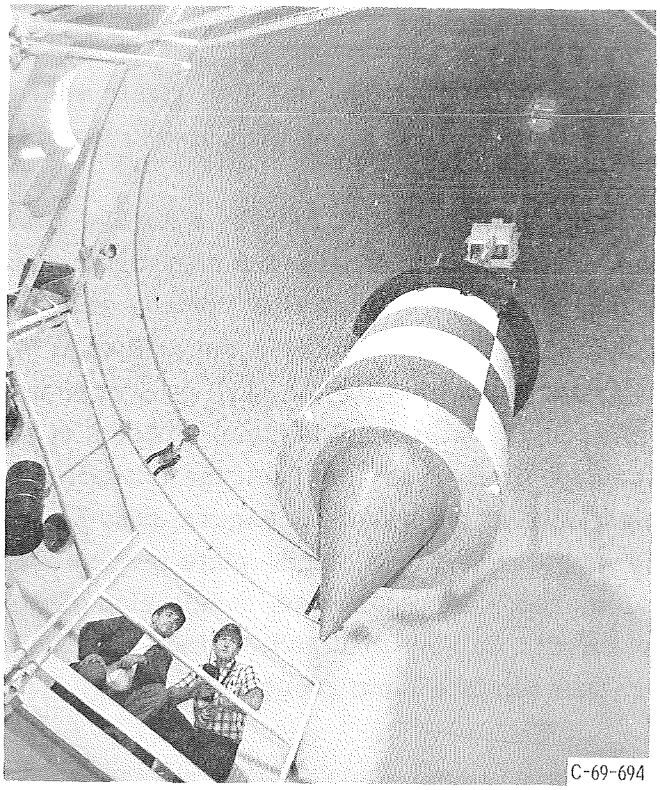


Figure 11. - Experiment vehicle being returned to ground level.

switched to internal power a few minutes before release. The umbilical cable was remotely pulled from the support shaft 0.5 second prior to release. The vehicle was released by pneumatically shearing a bolt that was holding the hinged plate in the closed position. No measurable disturbances were imparted to the experiment vehicle by this release procedure.

The total free-fall test time obtained in this mode of operation is 5.16 seconds. During the test drop, the vehicle's trajectory and deceleration were monitored on closed-circuit television. Following the test drop, the vacuum chamber was vented to the atmosphere and the experiment was returned to ground level (see fig. 11).

REFERENCES

1. Nussle, Ralph C.; Derdul, Joseph D.; and Petrash, Donald A.: Photographic Study of Propellant Outflow from a Cylindrical Tank During Weightlessness. NASA TN D-2572, 1965.

2. Derdul, Joseph D.; Grubb, Lynn S.; and Petrash, Donald A.: Experimental Investigation of Liquid Outflow from Cylindrical Tanks During Weightlessness. NASA TN D-3746, 1966.

3. Abdalla, Kaleel L.; and Berenyi, Steven G.: Vapor Ingestion Phenomenon in Weightlessness. NASA TN D-5210, 1969.

4. Symons, Eugene P.; Nussle, Ralph C.; and Abdalla, Kaleel L.: Liquid Inflow to Initially Empty, Hemispherical Ended Cylinders During Weightlessness. NASA TN D-4628, 1968.

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