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NASA Lewis Research Center Low-Gravity Fluid Management Technology Program

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NASA LEWIS RESEARCH CENTER LOW-GRAVITY

FLUID MANAGEMENT TECHNOLOGY PROGRAM

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SUMMARY

A survey is presented of the reduced gravity fluid management technology program sponsored by the NASA Lewis Research Center over the past 2 decades. The program yields experimental and analytical solutions of general reduced gravity fluid management problems with a few studies pointed specifically at the improvement of the Centaur vehicle. In-house experimental studies which use scale model propellant tanks are conducted in drop towers that provide up to 5 sec of reduced gravity test time. Recent experimental and numerical modeling efforts conducted to establish the dynamics associated with the separation of the Centaur vehicle from the Shuttle cargo bay are highlighted.

The current focus of the fluid management technology program is on the development of experimentally verified analytical models which describe the fluid dynamic and thermodynamic processes associated with the on-orbit transfer of cryogenic liquids. A number of future space missions have been identified that will require or could benefit from this technology. A Shuttle attached reusable test bed, the Cryogenic Fluid Management Facility, is being designed to provide the experimental data necessary for the technology development effort.

INTRODUCTION

Approximately 25 yr ago Lewis initiated a research program intended to provide the technology base for the design and operation of fluid systems in the reduced gravity environment of space. The early emphasis of this program involved the use of small transparent tanks and the Lewis drop tower to experimentally study the behavior of liquid-vapor interfaces in response to changes in gravity level, disturbances, and liquid draining from the tank. Particular attention was placed on identifying dimensionless parameters which characterized the fluid phenomena observed and allowed the prediction of fluid behavior in full size spacecraft tankage (ref. 1).

The Lewis reduced gravity fluid management program was subsequently enhanced by the construction of the Zero-Gravity Facility which increased the available test time from 2.2 to 5.1 sec. The experimental program was expanded and included studies of liquid-vapor interface configuration, sloshing and settling in larger tank sizes and a variety of tank shapes. In addition,

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liquid flow into tanks, the use of baffles to reduce liquid residuals during outflow, boiling, venting, bubble motion, the impingement of gas jets on liquid surfaces, and the axial-jet mixing of liquids were experimentally examined. This in-house experimental program has been complimented over the years by contracted mathematical and numerical modeling studies of low-g fluid behavior.

The current emphasis of the Lewis program is directed toward the development of technology for the design of fluid management systems for in-space heat exchange, liquid acquisition, thermal control of cryogenic tankage, and fluid transfer. To achieve this goal the program has been expanded to include experimental apparatti flown in the Lewis Lear Jet aircraft which has been equipped to provide a near weightless environment for up to 20 sec. Also, a Shuttle attached reusable test bed, the Cryogenic Fluid Management Facility (CFMF), is being designed to provide the experimental data necessary for the development of in-space cryogenic liquid transfer technology.

In May 1974, Lewis initiated a contract with General Dynamics Convair to perform a "Low-G Fluid Transfer Technology Study." The first task of this effort involved an extensive literature search, screening, and compilation of document summaries in the areas of low-g fluid behavior (ref. 2), cryogenic thermal control (ref. 3), and fluid management systems (ref. 4). Approximately 40 percent of the documents summarized describe work either performed at or sponsored by Lewis. This paper presents a review of the Lewis reduced gravity fluid management program using these documents as a starting point. It is not intended to be an exhaustive review, but rather a broad treatment to acquaint the reader with the Lewis program and the general state-of-the-art. Many of the references cited contain extensive bibliographies with which particular subjects may be pursued in more detail.

During the early 60's, the Centaur vehicle development effort was transferred to Lewis. In support of this project, experiments were conducted to assist in the improvement of the Centaur; specifically, studies of propellant sloshing, settling and draining in Centaur configuration tank models were undertaken. Also, the use of cryogenic propellants, liquid hydrogen and oxygen, in the Centaur vehicle triggered an interest in the improvement of thermal control systems both for the Centaur and for advanced chemical propulsion systems. Both in-house and contractual efforts were initiated to develop filament wound feed lines and tank supports, multi-layer insulation, shadow shields, lightweight vacuum jackets, and tank pressure control techniques. In addition, advanced fluid management system studies (ref. 5) were undertaken which may ultimately provide direction for future evolutionary improvements to the Centaur vehicle.

The Centaur has recently been modified to make it compatible with the Shuttle for the launch of the Galileo and Ulysses spacecraft, as well as for other spacecraft missions. The separation of the Centaur from the Shuttle cargo bay may cause the Centaur propellants to move with a resulting effect on the Centaur motion and the reduction of clearance between the two vehicles. This liquid motion has been observed in scale model spheroidal oxygen tank tests conducted in the Lewis Zero-Gravity Facility. In addition, numerical modeling techniques have been employed to predict the liquid motion in both the scale model tank and the Centaur liquid oxygen tank. This paper will highlight this experimental and analytical effort as an example of the kind of in-space operations problem solutions the Lewis low-g fluid management program can provide.

FUTURE APPLICATIONS AND BENEFITS

Both NASA and DOD mission models include spacecraft which will be boosted to orbit without fluids to minimize weight and optimize thermal performance. The required fluids will be separately transported to orbit and then must be transferred in the low-gravity environment of space. In other applications liquids will be periodically resupplied to extend the useful life of space experiments, satellites, and Space Station subsystems.

Space Station auxiliary propulsion, electrical energy storage, life support, and thermal control subsystems are all potential users of resupplied liquids. In addition, the Space Station is anticipated to eventually have the capability to service Orbit Maneuvering Vehicles, satellites, and Orbit Transfer Vehicles (OTVs), providing both cryogenic coolants and propellants. Potential military applications also include cryogenically fueled upper stages as well as space based weapon systems which may employ resupplied liquids as reactants, coolants, and propellants. These large future spacecraft will also require advanced technology thermal control systems primarily to accommodate the anticipated increase in electrical power requirements and the corresponding need for improved heat transfer and heat rejection techniques. Advanced technology heat transfer and heat rejection techniques will yield significant benefits in the form of lighter, more compact spacecraft.

The Johnson Space Center is currently sponsoring a program to develop the capability to resupply noncryogenic liquids in-space. Lewis is responsible for the development of advanced power and propulsion technology for future space applications. Consequently, the Lewis reduced gravity fluid management technology program is currently focused on thermal control system improvement and the resupply of the cryogenic liquids that will be required for future missions such as the space-based OTV. Because of the unique properties of helium, the Ames and Goddard Research Centers are responsible for a parallel in-space liquid helium transfer technology development program.

The orbit-to-orbit payload transportation requirements are anticipated to grow with the evolution of the Space Station. On orbit (Space Station) topping of ground based Centaur propellant tanks can be used to increase satellite/payload placement capability. This method can be employed to replace cryogenic propellant boiloff and/or to overcome Shuttle launch weight restrictions. Eventually, space-based reusable OTVs having higher energy capability will be required to meet the payload placement capability demands envisioned for the mid-1990's time frame and beyond.

The space-based OTV is an example of a weight critical spacecraft which benefits from relaxed structural requirements. In contrast to ground-based OTV concepts which must be designed to withstand the Shuttle multi-g launch environment fully loaded with propellants, the space-based OTV can be transported to orbit empty and be structurally designed to withstand only the relatively low thrust imposed by its own engine system. A much lighter structural design results for the space-based OTV with a corresponding one to one increase in payload placement capability. The space-based OTV will also have a lighter, more efficient thermal control system due to the fact that fewer tank support struts will be required and the insulation system needs to be designed only for the space environment.

Of potentially much greater impact is the projected operational cost savings associated with space-based OTV concepts. A large percentage of the anticipated operating cost for any space-based OTV concept is associated with the expense of transporting propellants to orbit (ref. 6). For ground-based vehicles, which are fully loaded with propellants prior to Shuttle ascent, the earth to orbit propellant transportation cost is the same as for any dedicated Shuttle payload. However, space-based OTVs are to be fueled at the Space Station from cryogenic storage tanks which can be replenished on an as-available basis. The possibility exists for propellants to be at least partially supplied to the Space Station by scavenging unused propellants from the Shuttle external tank and main propulsion system (refs. 7 and 8). In addition, the transporting of propellants in Shuttle mounted tanks on a space- and weight-available basis could greatly reduce the cost associated with operating the space-based OTV.

LOW-G FLUID MANAGEMENT TECHNOLOGY REQUIREMENTS

Based on the review of future NASA and DOD mission plans, in-space cryogenic fluid management technology requirements were grouped into the three general categories of liquid supply, liquid transfer, and thermal control. The thermal control category was further subdivided into the areas of cryogenic liquid storage and heat transfer/rejection.

Liquid Supply

Propulsive settling. - During vehicle maneuvers to provide propellant settling, large safety factors are generally applied to the selection of settling rocket thrust level and duration. This operational philosophy yields correspondingly large settling rocket hardware and propellant weight penalties. Utilizing an empirical analysis and data obtained from a Lewis drop-tower program, Sumner (ref. 9) developed estimates of the minimum velocity increment required to achieve liquid settling. The results of this study indicate that the weight penalties associated with propulsive settling could be significantly reduced. However, additional experimental verification of the analysis should be undertaken prior to utilizing this technique for vehicle design.

Capillary acquisition. - When propellant settling is not practical, other methods must be considered for delivery of single-phase liquid from a tank. The idea of using the liquid retention characteristics of fine mesh screen materials to acquire liquids in a reduced gravity environment was introduced in the early 1960's. The first use of screen materials for liquid acquisition was to cover the propellant sump at the bottom of propulsive vehicle tanks. The liquid trapped in the sump was used to provide on-orbit engine restart capability regardless of the bulk liquid position in the tank. Once the engine ignited, the resulting thrust settled the propellants refilling the sump and allowing continued engine firing. This general class of liquid positioning device is commonly referred to as a partial acquisition system or start basket.

For applications that require continuous feed of liquids under reduced gravity conditions, it is necessary to design the liquid acquisition device so that it contacts the liquid bulk no matter where the liquid is positioned in the tank. These acquisition devices generally consist of a complete screen liner or multiple channels, with screen on one face of the channel, which are positioned circumferentially inside the tank. This general class of liquid positioning device is commonly referred to as a total communication system.

Fluid dynamic analysis and modeling techniques are well developed for capillary acquisition devices for storable propellants. Systems for cryogenic liquids require the same fluid dynamic analysis; however, concern must also be given to thermal effects since cryogenic liquids will be stored near their boiling point. It may be necessary to avoid heat addition to capillary liquid acquisition devices in order to prevent vapor formation and displacement of liquid. The explusion efficiency (residual determination) and sensitivity to heat addition of fine mesh screen liquid acquisition devices designed for cryogenic applications needs to be established experimentally.

Liquid expulsion. - A pressure differential is required to cause liquid flow between two systems. Common techniques employed involve pressurization of the liquid supply tank or the use of mechanical pumps. For cryogenic systems some pressurization of the supply tank may be required, even if pumps are employed, in order to preclude boiling and subsequent outflow of two-phase fluid.

Inert noncondensible pressurant gases, such as helium, are typically employed for cryogenic systems. However, for space applications involving tanks which will be resupplied prior to being completely drained, a means for removing the noncondensible gas is required in order to avoid over pressurization of the tank during refill. Autogenous pressurization, using stored liquid which has been vaporized and possibly heated, would elminate this problem. Since the heat and mass transfer phenomena associated with either helium or autogenous pressurization is expected to be highly gravitational dependent, in-space experimentation is required to establish the quantity of pressurant required and the impact of pressurization on the thermodynamic state of the outflowing liquid.

Liquid Transfer

Several analytical studies have been completed which specifically addressed the problem of reduced-gravity fluid transfer with particular emphasis on systems for managing cryogenic liquids. Reference 10 analyzed a "fluid dynamic" filling technique based on maintaining separation of the liquid and vapor phases within the receiver tank during the entire fill process. For this liquid transfer technique, extremely low liquid transfer flow rates are generally required in order that the capillary stability of the liquid-vapor interface is maintained. A low acceleration environment to enhance phase separation could be provided by atmospheric drag, but only at relatively low orbital altitudes, or by using tethers between the Space Station and a Space Vehicle Servicing Facility (ref. 11). In contrast to the the "fluid dynamic" technique, references 12 and 13 present the analysis of a "thermodynamic" technique for the on-orbit filling of receiver tanks. This approach is based on the concept of alternately chilling and venting cryogenic tankage until the receiver tank is cold enough that the tank can be filled without venting. Because the "thermodynamic" liquid transfer technique is anticipated to be suitable for all identified applications, it was selected as the preferred approach and consequent focus of the Lewis low-g fluid management technology program.

Receiver tank chilldown. - When the tank to which cryogenic liquid is to be transferred is initially empty and warm, the first step in the procedure is to cool the tank down to an acceptable temperature for the transfer to begin. A small quantity of liquid cryogen is admitted to the previously evacuated tank. This charge is held in the tank allowing transfer of heat from the tank to the cryogenic fluid to take place. All of the cryogenic liquid will be vaporized and the resulting warm vapor is vented to space. This process may be repeated as necessary, depending on the initial temperature and thermal mass of the tank. The temperature to which the tank must be pre-chilled is determined by the fluid conditions that are desired to exist at the end of the subsequent no-vent fill process. If the transfer is started with the receiver tank at too high a temperature, the final pressure will be excessive or significantly less than a full tank of liquid will result. In addition, a high tank temperature prior to the start of the liquid transfer will yield a higher temperature, lower density liquid in the receiver tank and a reduction in the mass of cryogenic liquid transferred.

During the receiver tank chilldown several heat transfer processes will occur. Initially, the liquid will partially vaporize as it comes into equilibrium with the reduced pressure in the tank. The remaining liquid will tend to break into drops and spatter against the hot tank wall, being repelled by the vaporization that occurs during the brief period of contact. The drops of liquid moving through the tank will absorb heat from the vapor and will vaporize as a result. Finally, vapor generated by the initial flashing and by subsequent vaporization will exchange heat with the tank wall by free or forced convection and by conduction. These heat transfer processes are expected to be highly influenced by the gravitational environment and will also be governed by the fluid properties, liquid injection technique, tank wall temperature and tank size.

Receiver tank no-vent fill. - Examination of the thermodynamics in the receiver tank during a no-vent fill liquid transfer process can be considered in two phases. The first phase, starting at the beginning of transfer, involves vaporization of part of the incoming liquid, or flashing. This occurs because the pressure in the tank is lower than the vapor pressure of the incoming liquid. During this phase, additional vaporization may occur if the walls and internal hardware have not been prechilled to liquid temperature.

Flashing of the liquid continues until the incoming liquid is in equilibrium with the tank pressure. At that point, the second phase begins. Continued inflow of liquid causes compression of the vapor, and the tank pressure will rise above the vapor pressure of the incoming liquid. As the pressure increases, vapor will begin to condense at the liquid-vapor interface. When the receiver tank pressure reaches its specified maximum operating limit, further transfer into the tank can occur only as condensation of vapor makes room for more liquid.

Condensation of vapor is the most important process in the no-vent fill procedure. The liquid-vapor interfacial area available for condensation as well as the rate at which condensation occurs at the interface will limit the rate at which transfer can proceed. During the highly transient no-vent fill operation, whenever the liquid interface is at a temperature that is below the saturation temperature corresponding to the tank pressure, vapor will condense at the interface. However, this condensation deposits the heat of condensation into the interface layer, and quickly raises its temperature to the saturation point. Further condensation is dependent on transfer of heat from the interface into the bulk of the liquid. Consequently, to enhance this heat transfer, means for promoting mixing should be considered.

Under reduced-gravity conditions the liquid-vapor interface configuration is established primarily by surface tension forces. However, the interface position and area will also be influenced by the flow of liquid into the tank. The interface area is expected to increase due to mixing induced generation of vapor bubbles within the liquid. The bubbles may not separate from the liquid or coalesce due to the lack of buoyancy. Consequently, determining the effectiveness of mixing methods and the resulting prediction of condensation rates is expected to be more difficult than would be anticipated for earth based experiments.

As the quantity of liquid transferred increases, the volume of the vapor decreases, and as the tank approaches a nearly full condition the total interfacial area, regardless of the mixing mode, decreases. Therefore, it is possible that the rate of liquid transfer will be severely reduced as the tank becomes filled to approximately the 90 percent level.

If on-the-wall or internal Thermodynamic Vent System (TVS) concepts (discussed in the following "Thermal Control" section) are used for pressure control of the receiver tank they could also be employed to aid in the condensation of vapor during the no-vent fill operation. In addition, TVS designs for the supply tank may include provisions to cool the liquid as it leaves the supply tank to improve the effectiveness of the receiver tank no-vent fill operation.

Both the fluid dynamic and the thermodynamic processes associated with the transfer of cryogenic liquids are expected to be highly influenced by the gravitational environment. Consequently, development of on-orbit cryogenic fluid transfer capability is dependent on obtaining data on the no-vent filling process in space.

Thermal Control

Cryogenic liquid storage. - Heat reaches cryogenic tanks through the tank insulation, the support system, the fluid lines attached to the tank and any other conduction paths such as instrumentation lead wires. Most of the thermal analysis is straightforward and based on adequate experimental data. An exception is heat transfer through thick multilayer insulation systems (MLI). The impact of the Shuttle launch environment on thick MLI blanket performance and the degradation of MLI resulting from long-term exposure to the space environment has not been determined.

Most NASA liquid propellant upper stages control tank pressure by periodic venting. This method of pressure control requires the use of settling rockets to position propellants prior to venting to prevent the loss of liquid. Settling rockets may also be required for propellant acquisition prior to engine start. An approach for management of the effects of heat addition to cryogenic tankage which has potentially much wider application is the use of the TVS concept.

In the TVS a small amount of the stored cryogenic liquid is sacrificially evaporated to offset the unavoidable heat addition to the tank. Cryogenic liquid is withdrawn from the tank and passed through a Joule-Thompson valve with a resultant pressure and temperature reduction. This cold two-phase fluid is then introduced into a heat exchanger where evaporation continues and heat absorption takes place before the resulting vapor is vented overboard.

The heat exchanger is typically located either within the tankage insulation (vapor cooled shield), inside the tank or on the tank wall. In the first option, most of the incoming heat is intercepted before it reaches the liquid contained in the tank. For the second option, the cryogenic liquid and vapor in the tank are the heat exchanger hot side fluid. This fluid is cooled during operation of the TVS, thus controlling the tank pressure. In the third option, both heat interception and energy removal from the stored cryogen is provided to control tank pressure.

Flow of the cold side fluid in the TVS heat exchanger is not expected to be significantly affected by the gravitational environment, regardless of location, because the required tube size is small, leading to capillary dominated fluid flow phenomena. However, the in-the-tank heat exchanger option introduces the additional requirement of circulating the hot side fluid (i.e., the fluid in the tank) so that effective liquid cooling can take place. Fluid circulation experiments conducted in the Lewis Zero-Gravity Facility have established that the gravitational environment has a significant effect on the liquid motion (refs. 14 and 15).

<u>Heat transfer/rejection</u>. - In many cases, heat transfer dealing with propulsion applications involves two-phase flow phenomena. For instance, initially warm lines which cryogenic propellants travel through, require two-phase flow heat transfer analysis. This situation can occur for several different space operations, including propellant transfer or resupply. Heat exchangers which use two-phase flow may also provide thermal control for spacecraft instruments subjected to the extreme temperatures of a space environment.

Thermal control of the Space Station is another major application where two-phase heat transfer analyses will be helpful. In a two-phase coolant loop system, the cooling fluid vaporizes as it absorbs heat. This vapor then flows to condensers, where it returns to a liquid phase and continues through the loop back to the heat sources. Such two-phase cooling loops could be maintained at specific pressures and temperatures in order to control the temperature and humidity of various Space Station modules. This is a more efficient method than the conventional liquid cooling systems, where the liquid coolant is heated from one temperature to another.

Although two-phase flow has been studied in a 1-g environment, much more work is needed to determine the effect gravity has on two-phase flow heat transfer. Past work has indicated three areas of two phase flow that appear to be sensitive to gravity: flow regime definition, pressure drop, and flow boiling heat transfer (ref. 16). Specific flow regimes, such as stratified flow, exist solely because of a gravity field. Thus, in a low gravity environment, it would be expected that this type of flow regime would change. As the flow regime changes, the pressure drop should also change. Preliminary work shows this to be the case; however, additional data is required in order to better understand how gravity influences the heat transfer effects of two phase flow systems.

Space Station electrical power requirements are anticipated to eventually reach hundreds of kilowatts. Some planned military space systems may even require megawatts of electrical power. Associated with these high power requirements are equally demanding needs for waste thermal energy rejection. A unique space energy rejection concept, the liquid droplet radiator, has the potential of providing a significantly smaller and lighter thermal control system when compared with current state-of-the-art radiator designs. This advanced technology radiator concept involves the spraying of liquid drops through space where they are cooled by radiation. The liquid drops must then be collected and returned to the heat source; obviously introducing the requirement for new low-gravity fluid management technology.

EXPERIMENTAL RESEARCH FACILITIES

A large part of the research investigating zero-g fluid management problems has been, and is currently being, conducted at the Lewis Research Center. The Center has two drop facilities to produce low-gravity environments for short periods of time. One allows 2.2 sec of free-fall or zero-gravity time, while the other, called the Zero Gravity Facility, has a free-fall time of 5.16 sec. Lewis personnel also use a Lear jet flying Keplerian trajectories as another method of collecting low gravity data. In addition to these in-house facilities, Lewis is responsible for the development of the CFMF, a shuttle attached reusable test bed for studying on-orbit cryogenic liquid transfer.

2.2 Sec Drop Tower

This facility (fig. 1) provides a usable drop distance of 26 m. By allowing an experimental package to free-fall this distance, approximately 2.2 sec of drop time or zero gravity time is available. An experiment is a completely self-contained unit and is enclosed inside a drag shield during the drop. Figure 1 illustrates a drag shield assembly in a predrop position at the top of the tower. A typical experimental package is shown in figure 2(a) prior to enclosing it in the drag shield (fig. 2(b)). Allowing the experiment package to fall inside this shield reduces air drag on the package to less than 10^{-5} g. During the drop, the experiment and drag shield fall simultaneously but are independent of each other. Thus, the experiment falls freely with no guides or electrical wires connected to it.

Prior to dropping an experiment, the package is balanced about its vertical axis to ensure an accurate drop trajectory. The entire drop package (the experiment placed inside the drag shield) is then supported at the top of the tower with a wire that is fixed to the drag shield assembly. Initiation of free-fall is accomplished by pressurization of an air cylinder that forces a knife edge into the support wire causing the wire to fail. The drop package decelerates during the penetration of deceleration spikes (attached to the bottom of the drag shield) in a sandbox at the bottom of the tower. From the sandbox, the package is recovered and returned to ground level. Due to this simple operation, turnaround time in this facility is short, and, 6 to 8 drops per day are possible.

Zero-Gravity Facility

The Zero Gravity Facility (fig. 3) consists of a concrete-lined 8.7 m diameter shaft that extends 155 m below ground level. A steel vacuum chamber, 6.1 m in diameter and 142 m high, is contained within the concrete shaft. By utilizing the Lewis wind tunnel exhaust system in series with vacuum pumps located in the facility, the pressure in the vacuum chamber is reduced to 13.3 N/m^2 (1.3×10^{-4} atm). Dropping a vehicle from the top of this chamber results in approximately 5 sec of free-fall time.

As in the case with the 2.2 sec drop tower, the vehicle falls with no guides or electrical lines connected to it. Unlike the smaller tower, however, the package falls in an evacuated environment, and therefore, a drag shield is not required. The residual air that is left in the drop chamber after pumpdown does produce a very low drag on the package; but this force results in an equivalent acceleration acting on the vehicle which is estimated to be no greater than 10^{-5} g.

A typical test vehicle (fig. 4) consists of a cylindrical body where the experiment assembly, direct-current power and control systems are housed. Again, similar to the smaller drop tower, the entire experimental package is balanced about the vertical axis prior to a drop. After preparation of the experiment is complete, the test vehicle is suspended at the top of the vacuum chamber by a support shaft (connected to the cylindrical section of the vehicle) on a hinge plate assembly. Once chamber pumpdown is completed, the vehicle is released by pneumatically shearing a bolt that holds the hinged plate in a closed position. Following the free-fall period, the vehicle is decelerated at the bottom of the chamber in a cart filled with small pellets of expanded polystyrene. After the drop, the vacuum chamber is vented to the atmosphere and the experiment is returned to ground level.

Since the operation of this facility is more complex than the smaller tower due to the required vacuum environment, only 1 or 2 drops can be made per day. Consequently, the Zero Gravity Facility is used only when the additional free-fall time is critical for a successful experiment.

Lear Jet Aircraft

The Lear jet is a small passenger jet capable of flying a parabolic trajectory between 3.4 and 5.5 km (11 000 and 18 000 ft (fig. 5)). The aircraft passenger compartment has been modified to allow installation of low-gravity fluid management experiment packages. The scientist or engineer responsible for the experimental program can also fly in the aircraft, thus providing real time control of the experiment and observation of the experimental results. Instrumentation developed by Lewis personnel aids the pilots in flying the required Keplerian trajectories which provide test intervals up to 20 sec at gravitational levels of approximately 10^{-2} g. Multiple Keplerian trajectories may be flown, providing up to 6 data points per flight.

Cryogenic Fluid Management Facility

NASA committees, composed of representatives from each field center with an interest in low-gravity fluid management, have periodically reviewed the

Lewis program and aided in the formulation of a plan for the acquisition of the required technology. The variety of cryogenic liquid technology requirements that were identified led to the recommendation that a complete transfer system should be employed to provide the experimental data. Because the fluid dynamic and thermodynamic processes associated with the orbital transfer of cryogenic liquids are expected to be highly dependent on the acceleration environment, Shuttle attached experimental transfer systems were conceptually designed (refs. 17 and 18). Based both on anticipated technological return and funding availability, the Cryogenic Fluid Management Facility (CFMF) concept (ref. 19) was selected for subsequent development.

The preliminary design and mission planning for three flights of the CFMF have been completed by Martin Marietta Denver Aerospace under contract to Lewis. The CFMF is a Shuttle attached reusable test bed which consists of six major elements: (1) a cryogenic liquid storage and supply system, (2) the fluid transfer line and receiver tank, (3) both hydrogen and helium pressurization systems, (4) plumbing to provide cryogen loading, dumping and venting capability, (5) a facility control and data acquisition system, and (6) the supporting structure including a subpallet which is attached to a Spacelab pallet for mounting the CFMF in the Shuttle Orbiter cargo bay (fig. 6).

Liquid hydrogen has been selected as the CFMF experimental fluid for several reasons: (1) its prominent planned use for future NASA and DOD missions, (2) it presents challenging in-space fluid management requirements due to its low temperature, density and surface tension properties, and (3) technology developed with liquid hydrogen should be applicable to all other cryogens planned for extensive use in space with the exception of liquid helium which has unique fluid and thermal properties. Each flight of the CFMF will employ common hardware with the exception of interchangeable receiver tanks thus allowing parametric investigation of the primary technology requirement, the on-orbit transfer of cryogenic liquids.

TECHNOLOGY DEVELOPMENT STATUS

Liquid Supply

The obvious starting point for any study of orbital liquid supply systems is an understanding of low-g fluid behavior. The low-g fluid behavior technology area is adequately summarized in reference 2 with the exception of the mathematical and computational work of Dr. Paul Concus. These studies provided an analytical prediction of liquid-vapor interface configuration (ref. 20) and stability (ref. 21). Also developed was a software package for calculating axisymmetric liquid-vapor interface configuration as a function of container shape and acceleration environment (ref. 22).

A key objective of the liquid supply portion of the Lewis fluid management program is to develop the technology necessary for acquisition or positioning of liquid and vapor within a tank in reduced gravity to enable liquid outflow or vapor venting. Liquid acquisition techniques can be divided into two general categories: (1) Active liquid acquisition by the creation of a positive acceleration environment resulting from the propulsive thrust of small rocket engines, and (2) Passive liquid acquisition utilizing the liquid capillary forces provided by using solid baffles (refs. 23 and 24) or liquid traps made of fine mesh screen material.

Propulsive settling. - Most NASA liquid propellant upper stages have used or are using settling rockets to position propellants prior to venting or main engine start. The criteria for sizing the settling rockets was based on early drop tower programs that studied liquid-vapor interface stability and liquid settling phenomena (refs. 25 and 26). Reference 26 established that liquid rebounding or geysering and liquid circulation can occur during the settling process causing very low rates of liquid collection. A later experimental program (ref. 27) using scale model Centaur tanks simulated the real vehicle acceleration environment and established liquid settling times as a function of the tank fill level. A numerical code utilizing the marker and cell techniques (ref. 28) has been developed to simulate settling of propellants by both intermittent thrust and continuous thrust in the Centaur vehicle. Utilizing an existing empirical analysis and employing data obtained from earlier Lewis drop-tower programs, Sumner (ref. 9) developed estimates of the minimum velocity increment required to achieve liquid reorientation. The results of this study indicate that significant reductions in the weight penalties associated with propulsive settling could be realized by optimizing settling system design. A Shuttle mid-deck or Spacelab experiment, which would generate the data necessary to verify this analysis, has been conceptually designed (ref. 29).

Capillary acquisition. - The idea of using the liquid retaining property of fine mesh screen materials to position liquids in a reduced gravity environment was introduced in the early 1960's. The first use of screen materials for liquid acquisition was to cover the propellant sump at the bottom of propulsive vehicle tanks. The liquid trapped in the sump was used to provide on-orbit engine restart capability regardless of the bulk liquid position in the tank. Although screened sumps performed their intended function flawlessly, a general lack of design information existed for more complicated liquid acquisition device geometries. During the early 1970's Lewis initiated a program to establish fine mesh screen-liquid interaction characteristics with emphasis on extending the available design information to include the cryogenic liquids hydrogen and oxygen.

The liquid retention capability of fine mesh screen materials is experimentally determined by measuring the resistance of the wetted screen to penetration by vapor, commonly referred to as the screen bubble point. The screen bubble point is the pressure differential that must be applied across the wetted screen material to cause vapor to penetrate into the liquid acquisition device and thus destroy its liquid retention capability.

In order to successfully design fine mesh screen liquid acquisition systems, it is necessary to account for all the sources of pressure differential between the inside of the acquisition device and the surrounding vapor. The objective of this analytical accounting procedure is to insure that most of the liquid can be removed from the tank prior to penetration of the screen material by vapor bubbles. The pressure differential across the screen results from the sum of the hydrostatic head in the reduced gravity environment, the liquid flow losses within the screen acquisition device, the flow loss through the screen material, and from external sources; for example, pressure variations caused by vibration.

The first study in this area supported by Lewis established the bubble point and flow losses both parallel and perpendicular to a variety of fine mesh screen materials using liquid hydrogen as the test fluid (ref. 30). This reference also contains an extensive catalog of types and suppliers of fine mesh screen materials. The program was later expanded to establish the effect of transient liquid flow, such as would result from opening and closing valves in the outlet lines, on the liquid retention characteristics of screen materials (ref. 31). The effect of vibration on the liquid retention characteristics of screen materials was experimentally established as reported in reference 32.

An interest in the fluid dynamic phenomena associated with the refilling of start baskets following engine ignition led to both experimental (ref. 33) and analytical (ref. 34) studies of liquid jet impingement on screen materials. These two studies served as building blocks for the experimental evaluation and analysis of the refilling of capillary devices with settled fluid (ref. 35).

The interest in cryogenic propellants adds an additional consideration to start basket design. For cryogenic liquids, heat addition to the propellant tank and ultimately to the liquid acquisition device is inevitable during prolonged orbital coast. Reference 36 presents the experimental results of a program which determined the degradation of the liquid hydrogen bubble point for a variety of screen materials and heat fluxes; very little bubble point degradation was observed for heat fluxes up to 9.5 kW/m^2 (3000 $Btu/hr\text{-}ft^2$). However, these tests were conducted with the screen material in direct contact with the liquid bulk on one side. Start baskets designed for cryogenic liquids will often have portions of the screen surface of the device exposed to vapor on both sides. Since evaporation will take place from the screen surface, the ability of the screen material to stay wet by wicking liquid from those portions of the device in contact with the liquid bulk becomes important. The wicking characteristics of screen materials (ref. 37) and multiple screens in combination with support materials (ref. 38) have been experimentally established and analytically correlated. An analytical model that specifies the conditions needed to cause a flow of vapor through the wetted screens of a partial acquisition device has been developed (ref.39). Vapor flow into the acquisition device, to replace the evaporated liquid, must be accomplished without causing screen dryout. Reference 39 also presents experimental results which verify the trends predicted by the analytical model.

Study efforts intended to identify desirable modifications to the Centaur vehicle included analytical comparisons of propellant acquisition concepts (ref. 40). The Centaur hydrogen peroxide settling system was compared with several passive liquid acquisition system concepts. Although the acquisition systems were specifically configured for the Centaur vehicle, it is the author's contention that the general results of the study are applicable to any cryogenic upper stage of similar size. Specifically, the following conclusions were reached; (1) Start baskets are the most attractive passive liquid acquisition system concept, (2) Start baskets become more attractive than propulsive settling when multiple engine burns are required for a particular mission, and (3) The use of cooling coils on start baskets to prevent screen dry-out yields prohibitive weight penalties. Liquid evaporated from the screen surfaces of a start basket must be replenished by providing adequate liquid wicking paths. The currently planned third mission of the CFMF will incorporate a scale model OTV receiver tank containing a start basket, thus allowing evaluation of a fine mesh screen partial liquid acquisition device.

For applications that require continuous feed of liquids under reduced gravity conditions, it is necessary to design the liquid acquisition device so that it contacts the liquid bulk no matter where the liquid is positioned in the tank. Trade studies were performed to evaluate alternate total communication system configurations which could be integrated with cryogenic thermal control systems (refs. 30 and 31). These studies led to the selection of two circumferential screen-channels to provide liquid acquisition and a vapor-cooled-shield for thermal control. A more detailed discussion of cryogenic thermal control systems appears in a following section.

Using the screen-channel/vapor-cooled-shield concept, the McDonnell Douglas Corporation performed a preliminary design of the Cryogenic Fluid Management Experiment (ref. 41) which has subsequently been integrated into the CFMF concept (ref. 19) as the liquid hydrogen storage and supply tank. Data will be obtained during each mission to establish the expulsion efficiency (liquid hydrogen residuals) of the supply tank fine mesh screen total liquid acquisition device as a function of the liquid outflow rate and the heat flux to the storage tank.

The "Low Thrust Chemical Orbit to Orbit Propulsion System Propellant Management Study" (ref. 42) determined that a combination of propulsive settling prior to engine start and fine mesh screen bubble traps over the tank outlets was preferred for this application. The bubble traps work to minimize propellant residuals in the low-g environment that is associated with a low-thrust vehicle even when the main engines are under full power. This study considered the use of partial and total communication fine mesh screen liquid acquisition devices in addition to the selected approach and thus provides a good introduction to the analytical techniques available for comparing liquid acquisition concepts.

Liquid Expulsion. - Pressurant gas requirements for the expulsion of liquid oxygen and hydrogen propellants from high thrust vehicle tanks has been established experimentally (ref. 4). Simple thermodynamic models, which assume no heat and mass transfer between the pressurant gas and the propellant, provide very good correlations of the experimental data because the high-g environment maintains the pressurant/propellant separation and the liquid outflow times are relatively short.

Transportation of orbit-to-orbit liquid propulsion systems in the Shuttle Orbiter cargo bay has led to the requirement for propellant dump capability in the event of a mission abort (ref. 43). These propellant dump scenarios involve high liquid outflow rates, but may be accomplished under orbital, low-g conditions. The low-g environment may cause the pressurant inlet to be covered with propellant. The normal-gravity experimental data presented in reference 44 indicates that the use of a submerged helium gas injection technique results in less pressurant being required. Whether these normal-gravity results can be applied to the low-gravity situation is yet to be proven experimentally.

The on-orbit transfer of cryogenic liquids requires that the supply tank fluid expulsion take place in the low-g environment. In addition, the liquid flow rates are expected to be orders of magnitude lower than the flow rates that are typical of chemical propulsion systems. Consequently, the heat and mass transfer between the stored liquid and pressurant gas is expected to be appreciable and simple thermodynamic analysis will be inadequate. The CFMF will provide experimental data to establish both helium and hydrogen pressurant requirements during the on-orbit transfer of liquid hydrogen.

Liquid Transfer

Over a period of many years, NASA has been producing the technology which will be necessary for the development of large orbit transfer vehicles and manned space platforms that would remain permanently in space. The need to periodically replenish the liquid supply systems on these vehicles and spacecraft led Lewis, in the early 1970's, to include on-orbit fluid transfer as a part of the reduced gravity fluid management program. The specific objective of this portion of the program is to develop the technology to permit efficient transfer of liquids from a supply tanker to a receiver vehicle or spacecraft while in the reduced gravity environment of space.

The "Low-G Fluid Transfer Technology Study," (refs. 45 and 46) mentioned earlier, provided conceptual designs of supply tankers for the on-orbit fueling of an orbit transfer vehicle, the in-space resupply of another Shuttle Orbiter and the orbital resupply of a variety of spacecraft. These potential supply tanker designs were used to help identify technology gaps and system characteristics critical to both cryogenic and noncryogenic on-orbit fluid transfer. The potential problem areas identified included chilldown of cryogenic receiver tanks, filling of both cryogenic and noncryogenic receiver tanks without excessive liquid loss or pressure rise, and the complete filling of fine mesh screen liquid acquisition devices.

Tank draining. - Two experimental and analytical studies of reduced gravity draining from cylindrical tanks were completed at Lewis in the late 1970's. The first of these studies (ref. 47) provides an analytical correlation of the experimental data which relates liquid residuals to the outflow rate and acceleration environment for hemispherically bottomed tanks. The second study (ref. 48) presents experimental verification of an analytical technique which was developed to indicate how tank outlets should be shaped or contoured in order to minimize liquid residuals. The contouring analysis was applied to the design of tanks that could be used for the on-orbit fueling of a cryogenic orbit transfer vehicle. Another recent analytical and experimental study was conducted at Lewis to establish minimum liquid hydrogen levels required to prevent vapor ingestion in the feed line when restarting the Centaur engines in space (ref. 49).

Several contractual efforts have been sponsored by Lewis to develop numerical techniques to study the reduced-gravity tank draining phenomena (refs. 50 to 52). The last of these three studies resulted in the development of a two-dimensional exportable computer program (NASA SOLA-VOF) utilizing the marker and cell technique to solve the Navier-Stokes equations with surface tension. This computer code has been installed on the Lewis computer system. Excellent agreement between the experimental results of reference 47 and the analytical results of reference 52 has been achieved. Although the original capability of this reference 52 program was restricted to simulation of reduced-gravity tank draining phenomena, the basic analytical and computational method employed can be applied to a wide variety of fluid dynamic problems. Lewis is continuing to support the further development of the SOLA computer codes via an interagency agreement with the DOE Los Alamos National Laboratory. The resulting improved numerical modeling capability will include curved boundaries, better treatment of the liquid-vapor-container interfaces, complex internal tank geometries including screen baffles, and three-dimensional nonaxisymetric fluid flow situations.

Receiver tank filling. - The studies of bare receiver tank filling mentioned earlier (refs. 10 and 12), included analysis of the on-orbit filling process for tanks containing fine mesh screen total communication liquid acquisition devices. These two parallel studies employed different analytical approaches based on the "fluid dynamic" technique (ref. 10) and the "thermodynamic" technique (ref. 12) for the on-orbit filling of receiver tanks. The "thermodynamic" technique includes pressurization following tank filling to subcool the bulk liquid and condense any vapor bubbles trapped in the fine mesh screen liquid acquisition device. Once again, these two studies led to the conclusion that the "thermodynamic" approach to the on-orbit filling of any receiver tank was the preferred technique, especially for cryogenic liquid systems.

Both the fluid motion and the thermodynamic processes associated with the transfer of cryogenic liquids are expected to be highly influenced by the gravitational environment. Because several future space missions will require cryogenic liquid resupply, the current focus of the Lewis fluid management technology program is on the development of experimentally verified analytical models which describe the liquid transfer process. The experimental time required for this type of investigation greatly exceeds any ground based facility capability. Consequently, development of on-orbit cryogenic fluid transfer capability is dependent on obtaining data in space. The CFMF development activity is intended to provide this low-g experimentation capability.

The currently planned experimental hardware for the initial mission of the CFMF includes a spherical, vacuum jacketed, 0.62 m^3 (22 ft^3) liquid hydrogen storage tank and a 0.37 m^3 (13 ft^3) receiver tank. The cryogenic storage tank assembly, which will provide approximately 41 kg (90 lb) of liquid hydrogen for the experimentation, incorporates: (1) a vacuum jacket, multilayer insulation and a vapor cooled shield thermodynamic vent system for thermal control, (2) a fine mesh screen total communication device for liquid acquisition and (3) both helium and hydrogen (autogenous) pressurization capability. The receiver tank is a scale model OTV liquid hydrogen propellant tank which employs two on-the-wall thermodynamic vent systems for pressure control. Two liquid hydrogen injection or spray systems are contained within the receiver tank to facilitate the chilldown and filling operation: (1) a set of four tangential spray nozzles mounted on the girth rings which separate the barrel section from the end domes of the tank and (2) a combined ring and central spiral tube which has multiple holes to provide small axial and radial liquid jets.

The highest priority technology objectives for the first CFMF mission are: (1) receiver tank chilldown, (2) no-vent fill of an empty receiver tank, (3) refill of a partially full supply tank and (4) refill of a partially full receiver tank. The planning and preliminary hardware design for two additional CFMF missions has been completed. The primary technology requirements addressed by these missions parallel the first mission with the emphasis on providing additional parametric data on the in-space transfer of cryogenic liquids (ref. 53). This objective will be achieved by replacing the mission one receiver tank with: (1) a larger tank and (2) a tank which contains a partial acquisition device. This approach provides parametric variation of both receiver tank size and mass, the two key variables identified by the analytical modeling effort.

A computer code, the Cryogenic System Analysis Code (CSAM), is being developed to provide predictive capability for the performance of the CFMF as well as for full scale spacecraft employing cryogenic liquids. CSAM defines cryogenic liquid storage and transfer systems by a conductor/node network. It includes a transient heat transfer network analysis, internal tank fluid dynamics and a heat exchanger routine which can simulate thermodynamic vent systems. Events and boundary conditions are programmable, permitting simulation of an entire mission. CSAM is useful in modeling many of the fluid management systems of interest, with the current focus on the analysis of receiver tank chilldown and no-vent fill fluid transfer processes.

Thermal Control

This portion of the Lewis fluid management program has as its objective the development of the required technology for the efficient design of thermal control systems for in-space applications. In the past, Lewis was involved in the development and evaluation of cryogenic tankage insulation systems. The current program is primarily concerned with developing advanced heat exchanger and thermodynamic vent system technology.

<u>Cryogenic liquid storage</u>. - Multilayer insulation (MLI) systems composed of alternate layers of reflective foil and low conductivity spacer material have proven to be highly effective in minimizing heat addition to cryogenic tankage in the high vacuum environment of space. Reference 54 provides a comparison of three "Reusable Insulation Systems for Cryogenic Earth-Based Space Vehicles." The two MLI systems included in the comparison had significantly better thermal performance and lower weight than the microsphere system that was also evaluated. The MLI system tested at Lewis initially had a slightly greater effective thermal conductivity than the other MLI system, but showed significantly less degradation due to thermal cycling.

A Lewis managed study entitled "Evaluation of Propellant Tank Insulation Concepts for Low-Thrust Chemical Propulsion Systems" (ref. 55) has indicated significant advantages for a combined MLI/foam concept. Any Shuttle transported cyrogenic tankage will likely benefit from this combined insulation system concept since tankage weight and volume, as compared to an all MLI system, are reduced for the same quantity of cryogenic liquid delivered to low-earth-orbit.

Another recently completed study (refs. 56 and 57) was conducted to identify and plan the technology improvements needed to enable large quantities of cryogenic liquids to be stored in space for periods up to seven years. The NASA Lewis and Marshall field centers are currently supporting parallel contracted studies which will provide definition of Space Station technology development missions to demonstrate long term cryogenic storage system performance.

The simplest technique for controlling cryogenic tank pressure is to install a vent line in the top of the tank and bleed off vapor as required. Reference 58 presents the results obtained from a venting study conducted in the Lewis Zero-Gravity Facility where only capillary forces were available for positioning the liquid in the bottom of the tank. As the tank pressure decreased boiling took place in the bulk liquid region with the resulting vapor bubbles expanding and pushing the liquid toward the vent. Ultimately, the undesirable condition of dumping liquid would result.

For propulsive vehicles like the Centaur, the same settling rockets that are used to acquire propellants for on-orbit engine restart can be used to position the propellants prior to venting. This technique has the disadvantage of utilizing settling rocket propellant for each vent cycle, thus reducing the vehicle's payload placement capability. Efforts to improve the performance of propulsive stages has introduced the concept of the internal thermodynamic vent system (TVS), as previously discussed in the "Low-G Fluid Management Technology Requirements" section. TVS concepts are particularly attractive when cryogenic payloads for the Space Shuttle are considered. Under many normal operating conditions and all abort modes, payload requirements cannot dictate Shuttle operations so settling to relieve tank pressure would be impossible. The Centaur in Shuttle will utilize an in-the-tank TVS to control the liquid hydrogen tank pressure.

Techniques for designing in-the-tank TVS have not been verified experimentally in-space. Specifically, the design of the required mixer is strongly influenced by the acceleration-dependent fluid dynamics necessary to mix the tank contents in a predictable manner. The difference between normal-gravity and weightlessness will influence not only the liquid-vapor configuration before mixing, but also the liquid momentum or velocity required to establish the desired liquid flow pattern and degree of mixing. Based on zero-gravity experimental work (refs. 14, 15, and 59) conducted at Lewis, axial liquid jets were selected as the preferred techniue for providing the desired fluid mixing.

The experimental program was continued (ref. 60) by examining the liquid flow patterns that resulted when an axial liquid jet was used to mix the contents of partially filled spherical, cylindrical and Centaur scale model hydrogen tanks under reduced-gravity conditions. Acceleration levels were chosen which simulated the atmospheric drag that would exist on a full-scale propellant tank in low Earth orbit. Four distinct liquid flow patterns were observed: dissipation of the liquid jet in the bulk-liquid region, geyser formation, liquid collection at the end of the tank opposite the jet outlet, and complete circulation of the liquid along the tank walls. Dimensionless parameters were developed that characterized the liquid flow patterns and the bulk-liquid mixing phenomena.

Computational modeling of axial-jet induced mixing of liquids under low-gravity conditions has been accomplished (ref. 61). The SOLA-ECLIPSE computer code, a derivative of the NASA-SOLA-VOF code (ref. 52), provides prediction of the axial-jet induced bulk liquid velocity fields which compare favorably with the available scale model experimental data presented in reference 60. Computational analysis of a full scale liquid hydrogen tank for a typical OTV is presented in reference 61 with the conclusion that coupling an axial mixing jet with a TVS appears to be a viable concept for the control of tank pressure. Further development of the SOLA-ECLIPSE computer code is continuing with the objective of providing temperature gradient and pressure prediction capability in addition to the fluid motion analysis now available.

Liquid thermal conditioning. - Chemical propulsion systems which utilize cryogenic propellants generally require that the liquids be subcooled prior to introduction into the engine feed system. This liquid subcooling, typically provided by pressurizing the propellant tanks, is required in order to preclude cavitation in the engine pumps. However, liquid subcooling could also be provided by cooling the propellants with heat exchanger systems that utilize the same technique as thermodynamic vent systems; the sacrificial evaporation of a small amount of propellants to provide the required cooling. Propellant subcooler conceptual design studies have been completed for both the Centaur vehicle (ref. 40) and low thrust chemical propulsion orbit transfer vehicles (ref. 43). Both of these study efforts indicated small advantages, in terms of increased vehicle payload placement capability, for the subcooler heat exchanger concept when compared to typical helium pressurization systems. However, no work to develop subcooler heat exchanger technology is currently being supported by NASA.

The filling or refilling of a cryogenic tank is expected to be highly influenced by the temperature of the liquid entering the tank. The temperature of the inflowing liquid will be primarily determined by the storage conditions at the liquid source. However, the liquid temperature will also be influenced by the pressurization technique employed, the heat absorbed in the transfer line between the two tanks and any liquid cooling that may be provided.

Both CFMF mission one tanks will have thermodynamic vent systems intended to maintain the liquid hydrogen experimental fluid saturated at 30 psia prior to any transfer operation. Pressurization of the liquid source tank to 40 or 50 psia will be accomplished prior to the initiation of all chilldown, filling and refilling operations. The transfer line will be well insulated so that heat addition to the flowing cryogenic liquid will be negligible.

The CFMF supply tank TVS, although previously described as a vapor cooled shield, is actually a unique design. The TVS consists of two flow legs and multiple heat exchangers; one leg is designed to operate continuously and absorb the majority of the projected system heat flux while the second has approximately twice the cooling capacity of the first and is designed to operate on-demand based on tank pressure. The cold fluid for both TVS legs is first used to cool the outlet region of the supply tank to ensure that no heat reaches the liquid acquisition device where it could cause vapor formation. The number one TVS flow is routed from an outlet cooling manifold to the vapor cooled shield. The number two TVS flow is routed through a heat exchanger mounted directly on the outside of the supply tank wall and then to the vapor cooled shield. During the receiver tank refilling operation both supply tank heat exchangers will be activated to experimentally evaluate their effect on the temperature of the liquid leaving the supply tank.

Heat transfer. - Two phase fluid flow heat transfer depends strongly on the gravitational environment and the resulting fluid flow regime. References 16 and 29 present summaries of the current status of technology development in this area. Very little low-gravity experimental data exists for two phase fluid flow phenomena. Consequently, Lewis is presently conducting in-house experimental work in order to verify theoretical models under development which predict flow regimes in a low gravity environment. The theoretical modeling is currently being completed through grant work that is managed from Lewis. Preliminary tests have been completed in the 2.2 sec drop tower and analysis of the data is in progress. This data includes information on the flow regime and the pressure drop. A Lear jet experiment is also being fabricated and is scheduled to fly in 1986.

Heat rejection. - Work is currently proceeding in the Lewis Zero-Gravity Facility in support of the liquid droplet radiator concept (fig. 7). This work involves an experimental investigation with the objective of determining the technology needed to produce uniform droplets in zero-gravity, spraying these droplets through space in a straight trajectory, and collecting the droplets after they have traveled some distance. Fabrication of the experimental hardware required to perform this investigation is nearly complete, with testing to be initiated early in 1986.

SHUTTLE/CENTAUR SEPARATION DYNAMICS

During the past year, concern has arisen over the dynamics associated with separation of the Centaur vehicle from the Shuttle Orbiter cargo bay. Prior to separation, the Centaur is rotated out of the cargo bay (fig. 8) by a deployment mechanism attached to the Centaur Integrated Support Structure (CISS). Separation of the two vehicles is accomplished by release of several CISS mounted springs which are positioned circumferentially around the aft Centaur structure. These springs impart a separation force to the Centaur vehicle along its central axis yielding a differential velocity between the Orbiter and the Centaur of approximately 0.3 m/sec (1 ft/sec). However, due to pre-deployment Shuttle maneuvers and atmospheric drag, the propellant in the Centaur vehicle is not likely to be positioned symmetrically with respect to the vehicle axis. Consequently, the resulting spring force at separation will probably not act through the center of gravity of the Centaur and pure translational motion, parallel to the applied force vector, may not occur. A safety concern thus arises over whether this Centaur rotation is severe enough to cause impact between the Centaur and the CISS or Shuttle Orbiter.

A NASA committee, composed of low-g fluid management experts, was formed to assess the importance of the Centaur separation dynamics concern and, if necessary, recommend solutions to the problem. The committee accepted the conclusions of the Centaur prime contractor, General Dymnamics Space Systems Division, that: (1) axisymmetric positioning of the liquid propellant prior to separation will be highly unlikely, (2) due to the relative densities of liquid hydrogen and oxygen, the influence of the hydrogen propellant motion on the resulting Centaur vehicle motion will be minimal, and (3) the separation dynamics problem is likely to be more serious for missions which require significantly less than full propellant tanks.

An experimental program, utilizing the Lewis Zero-Gravity Facility, and numerical modeling techniques were employed by the NASA committee to aid in their evaluation. The following sections of this paper will expand on this experimental and analytical effort as an example of how the Lewis fluid management program can be adapted to support the development of systems designed for in-space operation.

The in-house experimental program established: (1) possible zero-g location of the oxygen tank vapor bubble prior to Centaur separation and (2) vapor bubble motion resulting from an impulse similar, but not scaled, to the separation maneuver. Numerical modeling techniques were first verified by simulating the fluid motion observed in the experimental tests conducted in the Zero-G Facility. Then the computer code was used to predict the liquid oxygen motion and resulting pressure field in the Centaur vehicle tank. These computer-generated predictions of the liquid oxygen tank pressure field were then employed in a vehicle dynamics analysis to establish Centaur vehicle motion.

For the first two Centaur in Shuttle missions, the 1986 launches of the Galileo and Ulysses spacecraft, the vehicle propellant tanks will be approximated 90 and 95 percent full, respectively. Based on the experimental and analytical work performed, it has been concluded that no undesirable vehicle motion will result from the separation maneuver. Some future Centaur missions will, however, require significantly less than full propellant tanks (65 to 80 percent liquid fillings). Under these initial conditions axisymmetric positioning of the liquid propellant prior to separation will still be highly unlikely. The liquid oxygen center of gravity may be significantly offset from the thrust axis so that the resulting motion between the two vehicles could be excessive. Consequently, these missions are currently being examined by employing the same analytical techniques to quantify the effect of the Centaur deployment on the resulting vehicle motion. It is anticipated that, for missions which will have large oxygen tank vapor bubbles, specification of the Shuttle/Centaur orientation relative to the orbital plane and/or the use of the Shuttle Reaction Control System may be required prior to the Centaur separation to provide positioning of the vapor bubble so that the resulting liquid motion is minimized.

Experimental Program

The major goal of the experimental program was to verify the capability of a numerical analysis to predict the behavior of a liquid subjected to an impulsive acceleration. Because this computer code would be extremely helpful in analyzing Centaur liquid oxygen motion during the separation of the Centaur from the Shuttle, verification of the code was required as quickly as possible. Thus, the experimental program used existing hardware in order that the drop apparatus could become operational within a limited time.

The Lewis Zero Gravity Facility was used to obtain the experimental data for this investigation. In addition to the drop area, which was discussed previously, this facility has a control room, a clean room and a shop area. Assembly, servicing, and balancing of the experiment vehicle were accomplished in the shop area.

Apparatus. - The experiment vehicle consisted of a cylindrical section which housed the experimental apparatus and the electrical systems. The experiment was mounted on a test tray as shown in figure. 9. Located below the test tray were 28 V battery packs which supplied and regulated direct current to the experiment.

The hardware mounted on the test tray included a high speed motion picture camera, digital clock, lighting system and test container. The test container was mounted on a cradle which was fastened to a linear bearing slide assembly. During the drop, a lateral acceleration was applied to the test container by an air cylinder system. The air cylinder consisted of a piston head (inside the cylinder walls), and a piston shaft, which extended beyond the end of the cylinder. The shaft of the piston was designed to push against the test container frame, which was held in place with a retaining pin. A known pressure of gas had previously been loaded into the air cylinder. During the drop, the retaining pin was retracted by a solenoid. This allowed the air cylinder to impart an acceleration to the test container. The time the force was applied to the container was controlled by adjusting the length of the piston stroke. Once the piston reached the end of its stroke, and no longer was in contact with the container, the container slid on the linear bearing at a constant velocity. Figure 10 shows a schematic of the experimental apparatus just described.

Jerking of the container was avoided by having the retracting pin rotate away from the base of the container, instead of pulling it away perpendicular to the container base. Also, the force applied to the container was assumed constant, since the change in volume of the air cylinder (7.3 cm^3) as the piston completed its stroke was much smaller than the volume of the bottle supplying the air pressure (3000 cm^3). This meant that a nearly constant pressure, and consequently a constant force, was maintained on the piston head throughout the experiment.

The length of the linear bearing, and therefore, the distance the container could travel after being accelerated, was dictated by the experimental package dimensions and the need to view the entire carriage displacement. Although it would have been desirable, the slide assembly did not have sufficient space to mount the camera. Consequently, through the use of a wide angle lens, it was possible to view approximately 27 centimeters of container motion with the rigidly attached camera. The displacement of the tank was measured by tracking the motion of pointers attached to the test container, against a scale accurate to 1 mm. The scale was mounted above the container in the same plane as the container's centerline, and in the field of view of the camera.

Test container and liquids. - The test container was an oblate spheroid formed from clear acrylic plastic, with a semimajor and semiminor axis of 2.00 and 1.47 cm, respectively (fig. 11). The eccentricity of the tank is 0.68, where eccentricity is defined as $e = \sqrt{1 - (z^2/x^2)}$ (here, x is the semimajor axis and z is the semiminor axis). This tank geometry was chosen for the test program because of its similarity with the liquid oxygen tank used on the Centaur vehicle.

The liquids which were used in the zero gravity tests were ethanol and FC-43. Both liquids exhibited a zero-degree contract angle on the spheroidal tank walls. The zero-degree contact angle characteristic is identical with that of liquid oxygen on the Centaur oxidizer tank surface. Other properties of these liquids, such as surface tension, density and viscosity are presented in table I.

Test set-up and procedure. - Before each series of tests, the experimental container was cleaned ultrasonically so that contamination of the spheroid surface was avoided. Immediately prior to each test, the ellipsoidal tank was rinsed with a solution of distilled water, dried in a warm air dryer and then rinsed with the test liquid. After rinsing, the test container was filled to the required volume with a syringe. Once the container was filled to the proper level, it was hermetically sealed and mounted on the test vehicle.

The entire test vehicle was then balanced. During this balancing procedure the cradle on which the test container was mounted was leveled in order to ensure that the ellipsoidal tank was oriented properly prior to and during the drop. Once the test container was mounted and the package was balanced, the vehicle was suspended at the top of the tower and released as described previously.

Data analysis. - The data obtained in this investigation were collected during the free-fall period by a high speed motion picture camera. Information on the zero-gravity liquid-vapor interface configuration was taken from the film by use of a film analyzer. From the analyzer the observed interface shape could be directly plotted at various times throughout the drop. In the test films, the general outline of the interface was defined by a dark band as shown in figure 12. Specifically, the points used for plotting the interface shape followed the outer perimeter of this dark band. Because of symmetry of the interface about the ellipsoid centerline prior to, and during the drop, this outer perimeter corresponds to the part of the interface located in the plane defined by the ellipsoid centerline and the tank minor axis.

This observed interface, however, became distorted due to refraction effects and, at times, due to the angle at which the camera viewed the test container. The constantly present refraction of the observed interface was caused by the walls of the ellipsoidal tank and a layer of test liquid. Another form of distortion was created when the container was laterally accelerated during a drop. When this occurred, the tank started at one end of the linear bearing track and traveled to the other end. The camera did not move with the tank (due to hardware limitations discussed previously), but instead was mounted approximately halfway along the distance the test container traveled. This caused a parallax effect when the tank was not at the center of the track. It was possible to correct for the refraction error alone by using a calibration grid from which actual interface coordinates could be determined (see ref. 62 for a detailed explanation). Correcting for parallax effects, in combination with refraction, however, was not possible. Therefore, when the test container was near the ends of the track, an approximate, or qualitative, interface location and configuration was determined by studying the test film and using the calibration grid. When the ellipsoidal tank was near the middle of the track and was positioned along the optical axis of the camera lens, the calibration grid could be employed to obtain an actual interface configuration.

In addition to the liquid-vapor interface plots, the lateral acceleration characteristics of the ellipsoidal tank were also obtained from the test film. This was accomplished by recording lateral displacement versus time data from the film. Two pointers were attached to the container and used for reading displacement measurements. One pointer was aligned with the camera centerline when the container was at the far end of the track prior to the application of the impulsive acceleration. The other pointer became centered in the field of view of the camera as the container traveled across the linear bearing track. This allowed for accurate displacement readings regardless of the location of the test container.

Accurate knowledge of the time the test container first started to accelerate was critical in determining the correlation of the initial displacement characteristics with time. In this investigation, the starting time was indicated by illumination of a light emitting diode. This light emitting diode was activated when the retaining pin was rotated away from the container base, allowing the air piston to accelerate the ellipsoidal tank. Since the stroke of the piston was usually adjusted to only 1.27 cm, the time of the lateral acceleration which the container experienced was 0.1 to

0.2 sec. This acceleration was determined by plotting displacement time points on log-log graph paper. A curve was fitted to these points by using a slope of 2; the acceleration was then obtained from the appropriate intercept of the curve. Figure 13 shows a typical plot and illustrates the intercept concept for determining the acceleration.

After the piston reached the end of its stroke, the acceleration value went to zero and the velocity of the test container became constant. This velocity was determined by plotting displacement versus time, and taking the slope of the plot. Such a plot is shown in figure 14. As can be seen, once the force is no longer applied, the displacement versus time plot becomes linear. Although some deceleration occurred as the container slid on the bearing (due to friction), it was not significant and was calculated to be no more than two-thousandths of a g.

RESULTS AND DISCUSSION

The dimensionless parameter that is useful in determining the low-gravity liquid-vapor interface configuration is the Bond number. The Bond number is the ratio of acceleration forces to capillary forces acting in a system. For the ellipsoidal container used in this investigation, the Bond number was defined as:

$$Bo = a\, x^2/\beta$$

where x is the tank semimajor axis, a is the equivalent gravitational acceleration and β is the specific surface tension (surface tension/density) of the liquid. From this equation, it can be seen that acceleration, fluid properties and tank geometry are all necessary to characterize a low gravity liquid-vapor system.

In order to understand the problems associated with the dynamics of low-gravity liquid-vapor systems in oblate spheroidal tanks, it is essential that a complete description of the initial liquid-vapor interface - prior to any disturbance - be known. Although this equilibrium interface has been studied previously (refs. 62 to 64), only interface configurations symmetric about the ellipsoid minor axis were considered. Initial drops in this investigation were performed with the objective of determining if equilibrium interface configurations could exist at other locations in an oblate spheroid. Thus, in the first phase of this study, the test container was not given an acceleration, but instead was clamped to the linear bearing in a fixed position such that the tank aligned with the optical axis of the camera. Since the test container experienced no effective acceleration during a drop, the system Bond number was zero. This zero Bond number, coupled with solid liquid-vapor combinations which produced zero-degree static contact angles, resulted in a spherical zero-g liquid-vapor interface shape inside the ellipsoid. By varying test conditions it was possible to examine whether this equilibrium low gravity vapor bubble could exist at more than one location in an oblate spheroid. A detailed explanation of the experimental work concerning the equilibrium interface configuration, and its possible locations in the ellipsoidal tank, can be found in reference 65.

The results described in reference 65 indicated that, depending on the size of the vapor bubble, the liquid-vapor interface could exist at several locations in the tank. This was true as long as the interface was able to meet the minimum energy requirement by forming a sphere within the walls of the ellipsoidal container. Liquid fill levels of 80 percent or more resulted in vapor bubbles with small diameters (2.12 cm) that could be accommodated anywhere within the container boundaries. This included the area of the test container where the radius of curvature of the wall is smallest (fig. 15). As the interface radius of curvature increased with decreasing fill level, the vapor bubble exhibited a tendency to exist towards the area of the ellipsoidal tank where the radius of curvature of the wall is greatest, since this was the only area of the tank where the spherical interface could fit within the container boundaries. For fill levels between 80 and 70 percent, the resulting vapor bubble was still small enough so that only a slight tendency existed for the vapor bubbled to be located away from the area of the tank where the wall curvature is greatest. Consequently, the liquid-vapor interface could essentially exist at any location in the container. As the fill level approached 60 percent, the tendency of the interface to only exist near the center of the tank became more evident (fig. 16). Finally, when the fill level was decreased to 50 percent or less the interface could not form a single sphere within, or tangent to, the walls of the ellipsoidal tank. Instead the interface satisfied the minimum energy condition for a stable low gravity interface with a shape which is a segment of a sphere. This, consequently, results in an annular interface with the liquid positioned against the tank walls (fig. 17). At these lower fill levels, this appears to be the only zero g interface configuration and position possible. Figure 18 shows a qualitative plot of interface locations versus liquid fill level for the ellipsoidal tank tested.

After acquiring a better understanding of the equilibrium interface configuration, the experimental investigation continued by applying a lateral acceleration to the ellipsoidal tank. The objective of this part of the investigation was to obtain quantitative and qualitative information on the interface motion during and after the impulse.

As described earlier, an air piston was used to apply the acceleration. From the first phase of this experiment, the amount of time needed to form a equilibrium zero gravity interface for different liquids, fill levels and initial liquid orientations was known. For drops when the test container was laterally accelerated, liquids and fill levels were chosen such that the time to form a nearly queiscent interface was as short as possible - usually about 2 sec. The application of the lateral acceleration was preceeded during the drop by a time delay to allow the liquid-vapor interface to form its zero Bond number configuration. This formation period was sufficiently short to allow adequate time to view the lateral acceleration and resulting motion of the test container.

Figures 19 and 20 show a sequence of pictures from one of the zero gravity tests (number 5, table II) in which the ellipsoidal tank was accelerated. In figure 19, the first portion of the drop can be seen. This part of the drop involves the formation of a stable liquid vapor interface. The initial condition of the experimental system is such that the liquid is bottomed in the tank and symmetric about the container major axis (fig. 19(a)). Upon entry into the low gravity environment, the liquid-vapor interface underwent an oscillatory motion, but remained symmetric about the ellipsoid major axis (fig. 19(b)). This transient motion displaced the bubble along the major axis (fig. 19(c)) to the other side of the tank, where the liquid motion dampened and the vapor bubble became stable (fig. 19(d)). The process just described took approximately 2 sec, and was well understood from the first phase of the experimental work.

Once the interface became nearly quiescent, the lateral acceleration was applied to the test container. Just after the acceleration was applied, the vapor bubble started to move from the center of the tank towards the left wall (fig. 20(a)) since the acceleration was applied to the right side of the tank (as viewed from the camera). After the acceleration had been applied for approximately 0.1 sec, a geyser appeared to form and the vapor bubble became highly deformed (fig. 20(b)). When the piston reached the end of its stroke and the applied acceleration was no longer present, the geyser collapsed - leaving an interface which appeared to have no distinct shape (fig. 20(c)). However, in a very short time (approximately 0.4 sec) after the acceleration became zero, the interface again appeared to be dominated by capillary forces and started to take on a spherical shape (fig. 20(d)). As the ellipsoidal tank continued to move across the track, the interface traveled from the left side to the right side of the container (fig. 20(e)). Towards the end of the drop period the liquid motion dampened, and the liquid-vapor interface appeared to be forming its equilibrium zero-g configuration (fig. 20(f)).

In figure 21, plots of the liquid-vapor interface corresponding to some of the pictures just described are shown. Figure 21(a) illustrates the initial condition of the low gravity interface prior to any impulse. This plot was derived from the first phase of the experimental program. Figures 21(b) and (d) correspond to times when the interface is distorted due to refraction and parallax, and therefore, are qualitative interpretations of the observed interface (determined as described in the Data Analysis section of this report). A more accurate interface shape was plotted when the container was near the middle of the track (fig. 21(c)). It should be noted that this plot is not complete, however, because of refraction which was particularly high near the edge of the ellipsoidal tank.

Four other lateral acceleration runs were performed and each run had similar results. In every run but one, a geyser formed, and in all tests, the vapor bubble remained intact and was becoming stable near the end of the drop period. Table II summarizes the test conditions and the results from all the tests made for this phase of the experimental program.

This part of the program was performed to provide data for the verification of a computer code and did not actually scale Centaur flight conditions. Time constraints permitted only a limited number of tests to be made. Consequently, no attempt was made to develop a correlation of the lateral Bond number (or other parameter describing the influence of the lateral acceleration) with the observed behavior of the liquid and vapor within the model tank.

Numerical Modeling

A commercially available three-dimensional fluid dynamics computer code, HYDR-3D, was employed to analyze the Centaur liquid oxygen motion resulting from the deployment of the vehicle from the Shuttle cargo bay. Three-dimensional computational capability is essential since the liquid and vapor motion are not axisymmetric.

The HYDR-3D computer code is an exclusive product of Flow Science, Inc. of Los Alamos, New Mexico. The code solves the three-dimensional, time dependent equations for incompressible fluid flows with free surfaces. HYDR-3D incorporates user definable geometry and translational acceleration features making this code uniquely qualified for the analysis of the fluid dynamics associated with the separation of the Centaur from the Shuttle.

Three of the Zero-Gravity Facility tests, numbers 3, 4, and 5 (table II), were numerically modeled. Inputs to the HYDR-3D computer code included fluid properties (table I), tank geometry, vapor bubble size and location prior to initiation of the tank motion, and the duration and magnitude of the applied acceleration (table II). The results of the numerical modeling activity for experimental test number five are shown in figure 22. The two-dimensional views of the vapor bubble and the liquid velocity vectors shown are a graphical output feature of the HYDR-3D computer code. The sequence in time of the first four cross-sectional views of the vapor bubble shown in figure 22 were selected to correspond approximately in time with the photographic experimental data presented in figures 19(d) and 20(a) to (c). The numerical modeling was terminated at approximately 0.3 sec (fig. 22(f)) when significant vapor bubble motion was no longer observed.

Comparison of the experimental data generated in the Lewis Zero-Gravity Facility with the HYDR-3D numerical modeling output leads to the conclusion that the computer code was generating valid results and could be used to predict liquid oxygen motion in the Centaur vehicle. Excellent agreement exists between the experimental and numerical results during the application of the accelerating force when the majority of the fluid motion takes place and the highest fluid velocities were calculated. However, after approximately 0.3 sec, the computer code defines a liquid-vapor interface which reattaches to the tank wall (fig. 22(f)). This phenomena was not observed experimentally and is thought to be a result of the nonprecise treatment of surface tension forces by the HYDR-3D computer code. The NASA-SOLA family of computer codes provide much better treatment of surface tension dominated fluid dynamic phenomena, but only two-dimensional numerical modeling capability currently exists. The liquid motion has significantly subsided, as observed experimentally and determined numerically, prior to the time when the vapor bubble reattachment is observed in the computer generated results. Since the liquid momentum is proportional to the square of the liquid velocity, this numerical discrepancy should not adversely affect the ultimate objective, the prediction of the Centaur vehicle motion in response to the liquid oxygen motion for the Ulysses and Galileo missions.

Currently the HYDR-3D computer code is continuing to be used to predict the liquid oxygen motion in the Centaur vehicle during the deployment maneuver. Similar to the modeling of the experimental data from the Zero-G Facility, inputs to the code include liquid oxygen properties, the initial vapor bubble geometry and location, and the acceleration applied during the separation of the Centaur from the Shuttle. Numerical modeling of the liquid oxygen motion has been completed for the assumed worst case initial conditions consisting of zero-gravity with the vapor bubble located on the side of the propellant tank. Subsequent analysis of the vehicle motion has indicated that adequate clearance between the Centaur and its CISS or the Shuttle Orbiter exists.

For the Galileo and Ulysses spacecraft missions the Centaur deployment will occur at an altitude of approximately 204 km (110 nmi). At this altitude atmospheric drag is sufficient to positively position the oxygen tank vapor bubble so that the attitude of the combined Shuttle/Centaur relative to their velocity vector becomes important. Consequently, the further use of the HYDR-3D code will include running cases with input which defines the initial vapor bubble conditions for this low-g environment. The vapor bubble location and geometry will be established by an analysis which includes Shuttle/Centaur altitude and attitude in the determination of the acceleration environment prior to the Centaur separation.

CONCLUDING REMARKS

Lewis, during the past two decades, has been a leading developer of low-gravity fluid management technology. This technology base, primarily associated with liquid storage and supply, has provided direction for the design of fluid systems which must operate in space. However, the continuing need for advanced on-orbit fluid management technology to support future NASA and DOD missions has been established, with the current emphasis on the orbital transfer of liquids.

Recent analytical and experimental efforts have addressed the potential fluid dynamic problem associated with the separation of the Centaur vehicle from the Shuttle Orbiter. These activities serve to illustrate Lewis' capability to provide timely fluid management technology information to developers of advanced space systems. The current Lewis low gravity fluid management program includes the further development of numerical modeling capability, analytical and experimental studies of advanced heat exchanger/radiator concepts and the development of the CFMF for the study of on-orbit cryogenic liquid transfer.

In terms of resources committed, the Lewis CFMF development activity is clearly the current focal point for the NASA Office of Aeronautics and Space Technology's low-gravity fluid management program. The fluid dynamic and thermodynamic processes associated with the in-space transfer of cryogenic liquids are expected to be highly complex and gravitationally dependent. Consequently, it is essential that experimentally verified analytical tools and design criteria be made available before initiating development of advanced space systems requiring resupply of cryogenic liquids in space. This goal is being pursued, as part of the NASA Lewis low-gravity fluid management technology program, through the development of both analytical models, which will describe fluid transfer system performance, and the CFMF experimental hardware which will be used to obtain the data necessary to verify or modify, as required, the analytical models. The mission planning and preliminary hardware design for three CFMF missions has been completed. The phase 1 safety analysis and studies to define Shuttle integration hardware for the first CFMF mission are nearing completion.

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TABLE I. - PROPERTIES OF TEST LIQUIDS

Liquid	Surface tension, dyn/cm	Density, g/cm^3	Dynamic viscosity, cP	Contact angle with acrylic plastic, deg
Ethanol (at 20 °C)	22.3	0.79	1.20	0
FC-43 (at 20.5 °C)	16.8	1.90	6.41	0

TABLE II. - SUMMARY OF LOW-GRAVITY DATA

Run	Test fluid	Percent ullage	Measured acceleration, cm/sec^2	Measured time acc. applied, sec	Measured average velocity after acc. → 0, cm/sec	Time tank moved, sec	Geyser forms	Ullage remains intact
1	Ethanol	10	217 cm/s^2 = 0.22 g (Bond number = 30)	0.108	22.86	1.31	Yes	Yes
2	Ethanol	10	99 cm/s^2 = 0.10 g (Bond number = 14)	0.160	16.46	1.80	No	Yes
3	Ethanol	25	213 cm/s^2 = 0.22 g (Bond number = 30)	0.109	22.86	1.27	Yes	Yes
4	FC-43	10	142 cm/s^2 = 0.14 g (Bond number = 64)	0.132	17.50	1.66	Yes	Yes
5	Ethanol	10	248 cm/s^2 = 0.25 g (Bond number = 35)	0.101	26.56	1.14	Yes	Yes

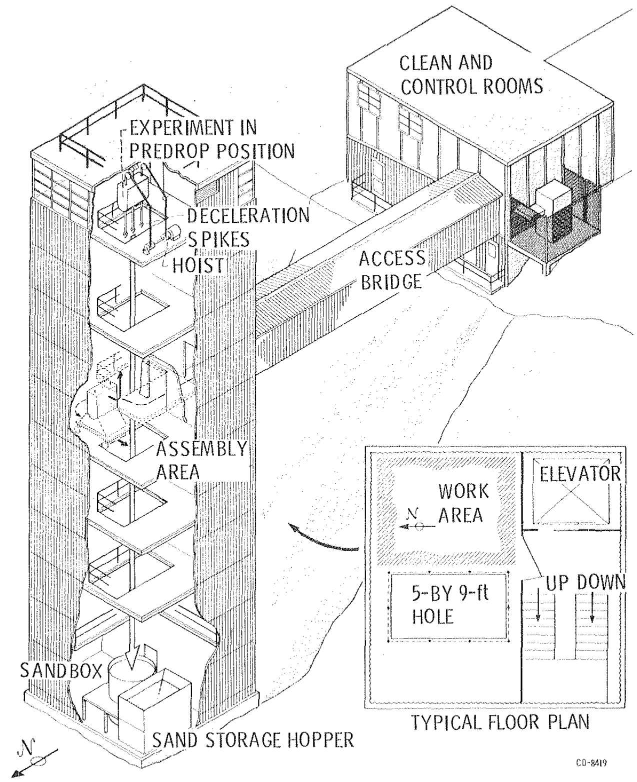
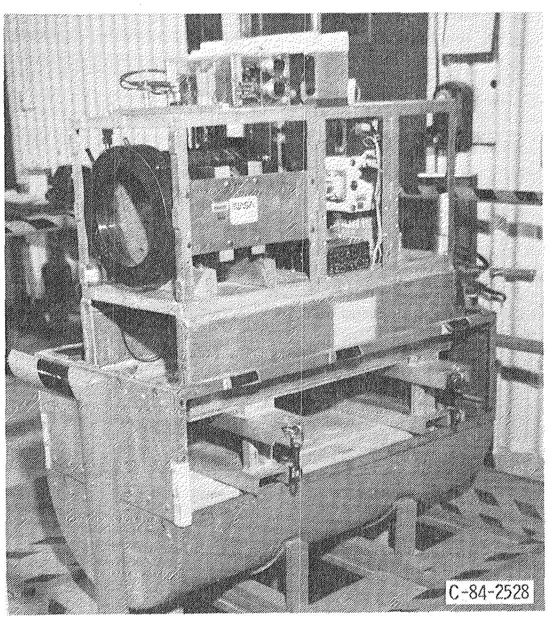
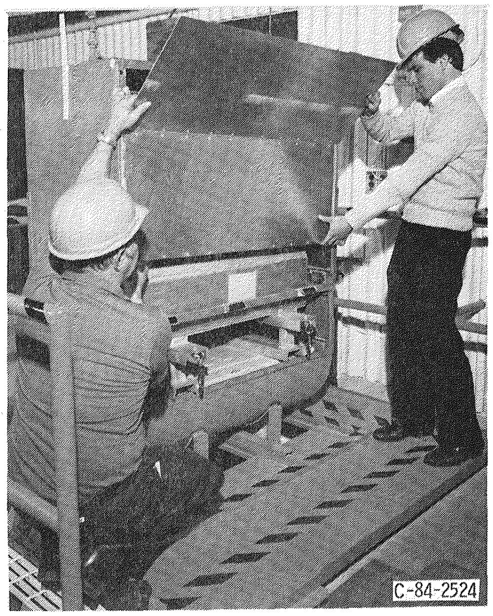


Figure 1. - 100 ft drop tower.



(a) Typical experiment package.

Figure 2. - 2.2 second Drop Tower experiment vehicle used for low gravity tests.



(b) Drag shield assembly.

Figure 2. - Concluded.

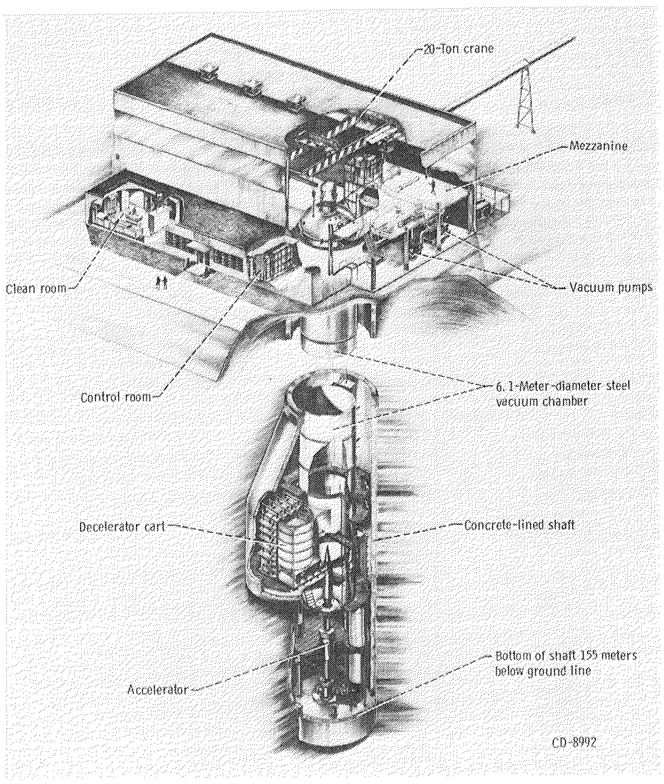


Figure 3. - Zero gravity facility.

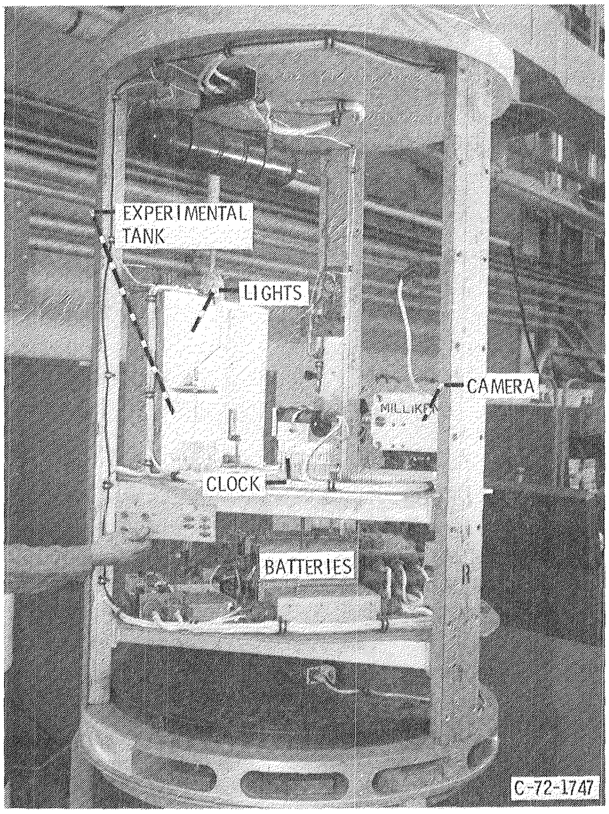


Figure 4. - Typical zero gravity facility experimental package.

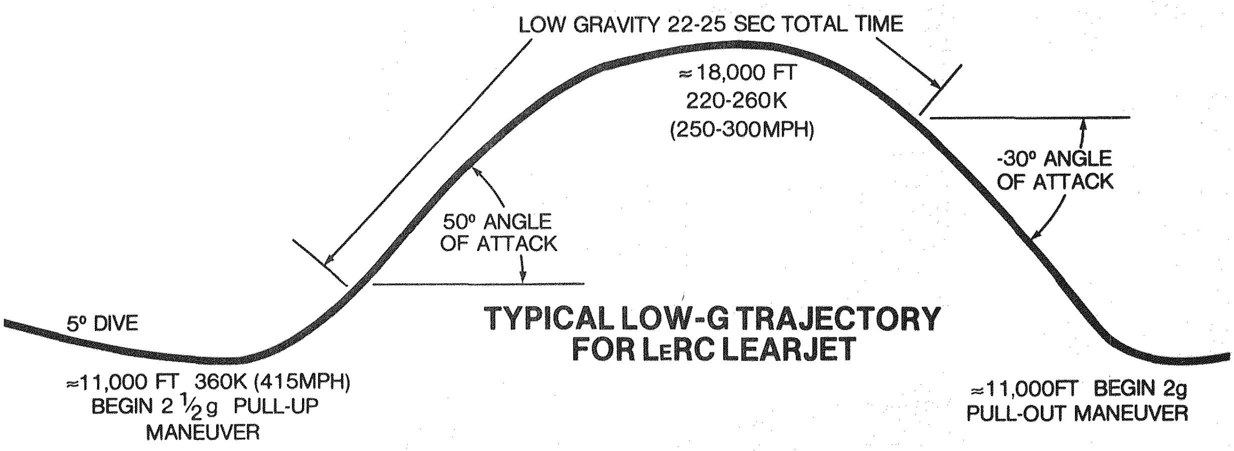


Figure 5. - Model 25 Learjet airborne reduced gravity laboratory.

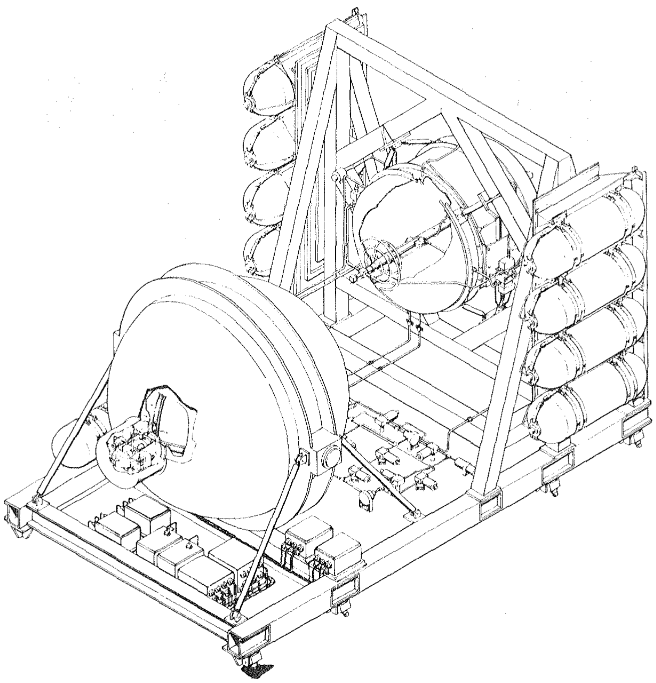


Figure 6. - Cryogenic fluid management facility.

RADIATIVE "FINS" AND "HEAT PIPES" OF CONVENTIONAL RADIATORS
REPLACED BY MULTIPLE STREAMS OF UNIFORM LIQUID DROPLETS

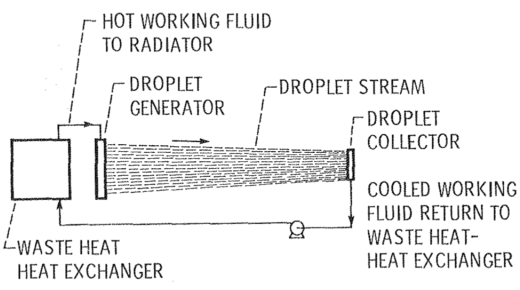


Figure 7. - Liquid droplet radiator concept.

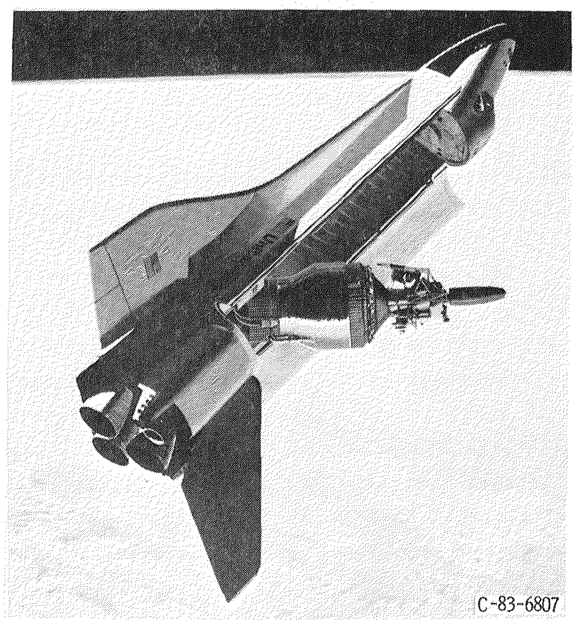


Figure 8. - Centaur in shuttle prior to separation.

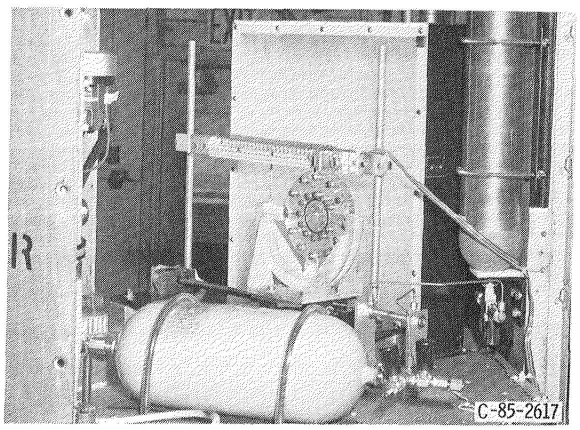


Figure 9. - Experimental apparatus mounted on test tray.

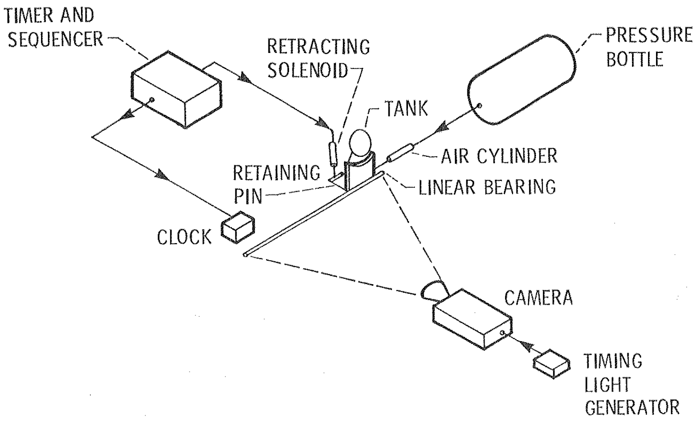


Figure 10. - Experimental apparatus schematic.

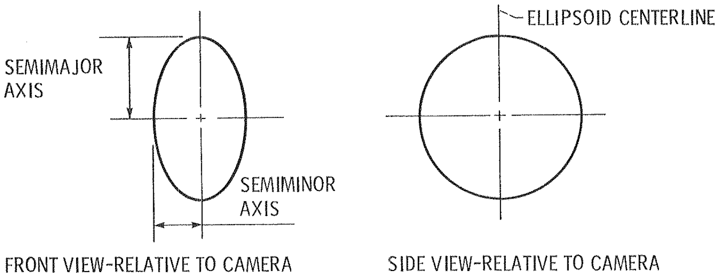


Figure 11. - Centaur model tank ellipsoidal configuration.

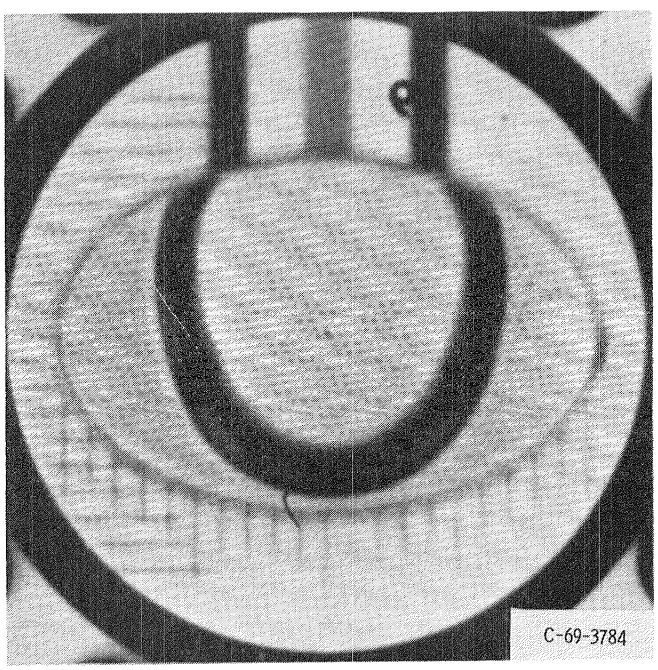


Figure 12. - Photographic observation of liquid vapor interface configuration.

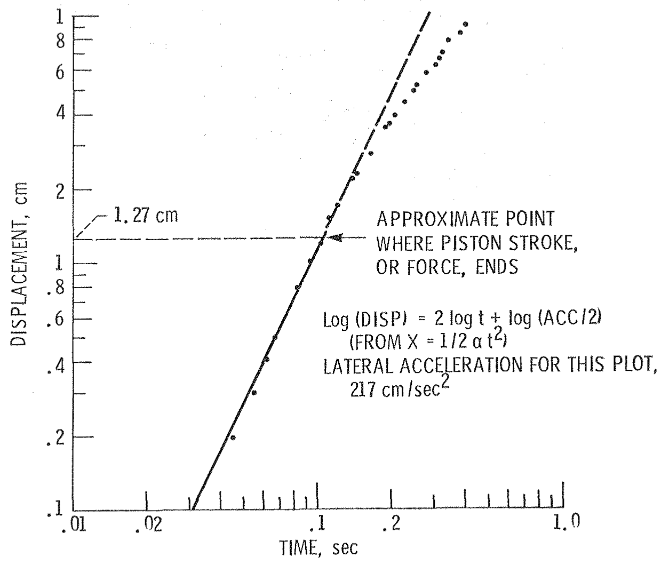


Figure 13. - Representative lateral acceleration characteristics using assumed slope of two.

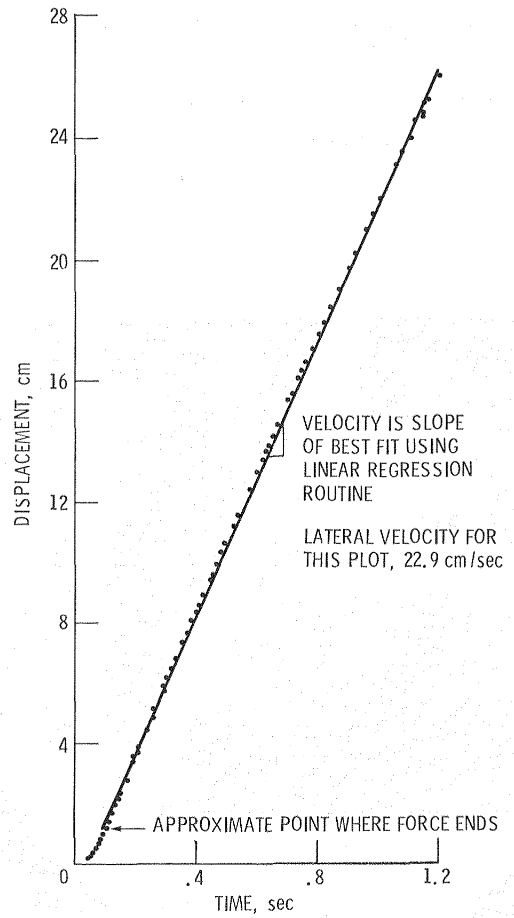


Figure 14. - Representative lateral velocity characteristic.

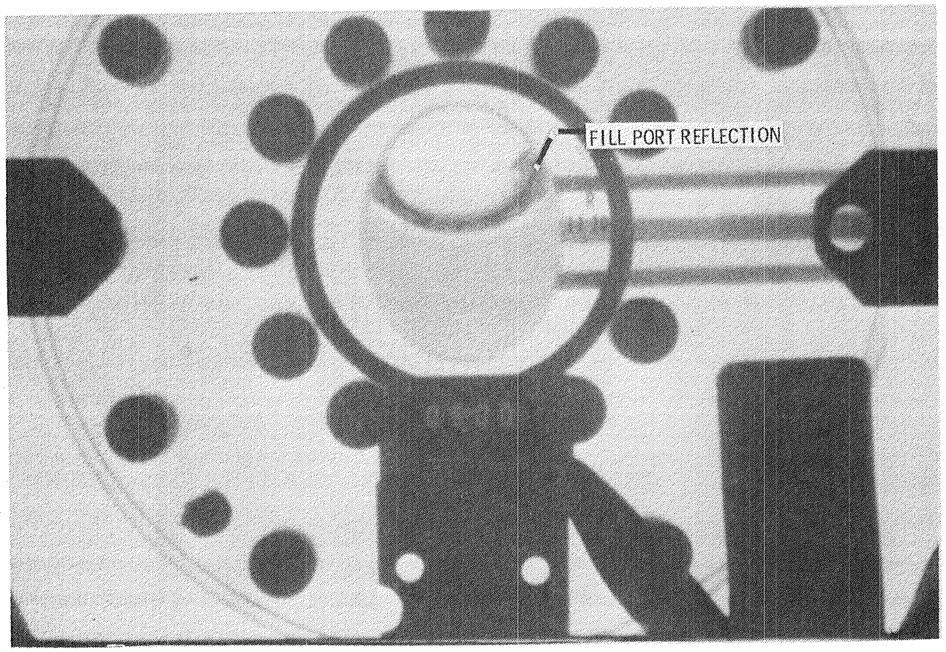


Figure 15. - Equilibrium liquid vapor interface configuration in spheroidal tank. Bond number, 0; 80% filling.

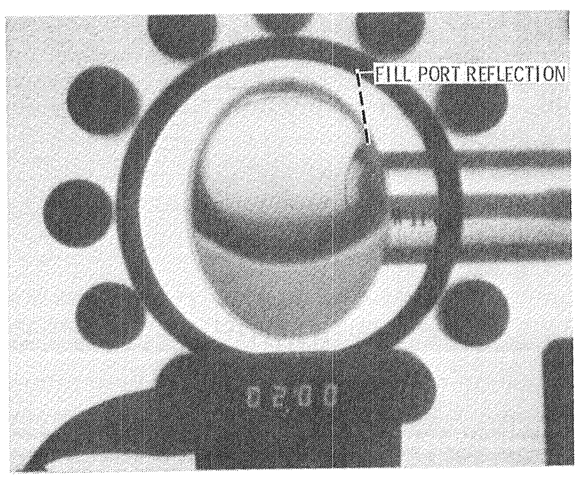


Figure 16. - Equilibrium liquid vapor interface configuration in spheroidal tank. Bond number, 0; 60% filling.

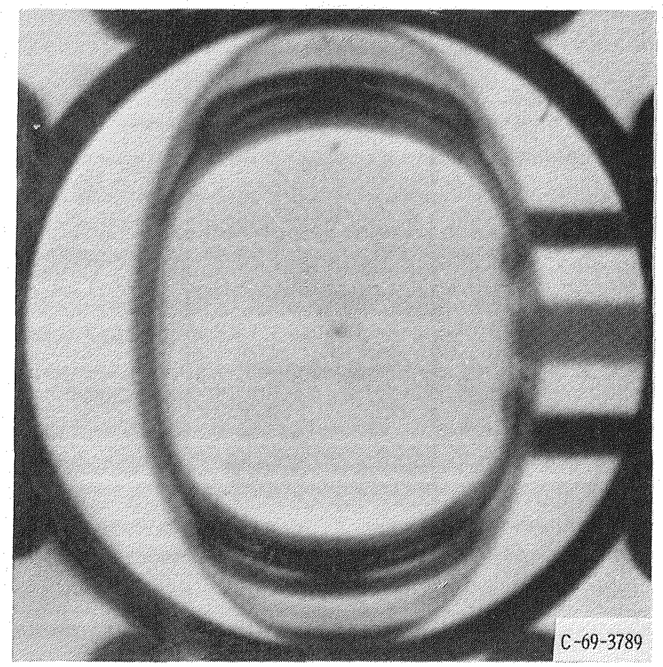


Figure 17. - Equilibrium liquid vapor interface configuration in spheroidal tank. Bond number, 0; 37.5% filling.

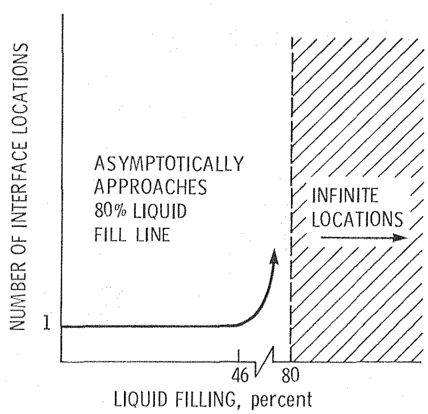
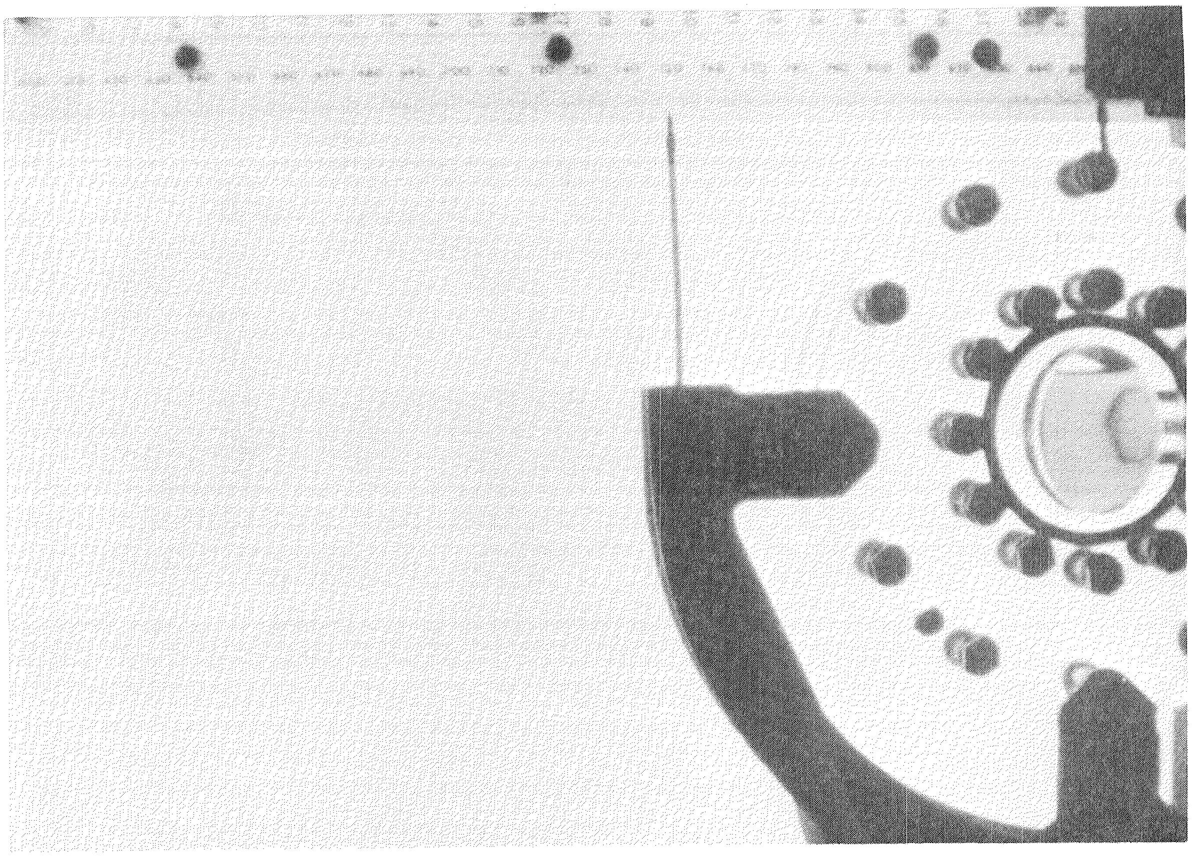
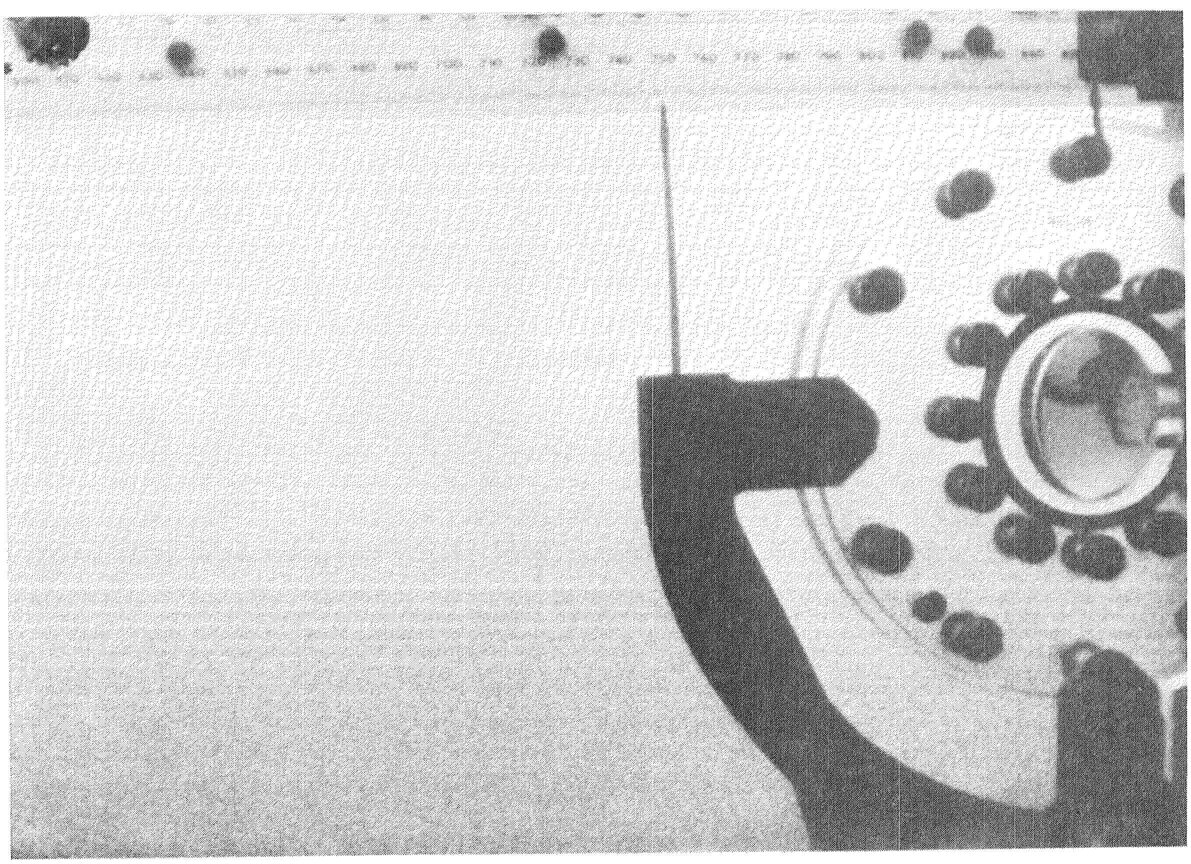


Figure 18. - Qualitative summary of interface locations as function of fill level. Tank eccentricity, 0.68; tank semimajor axis, 2 cm.

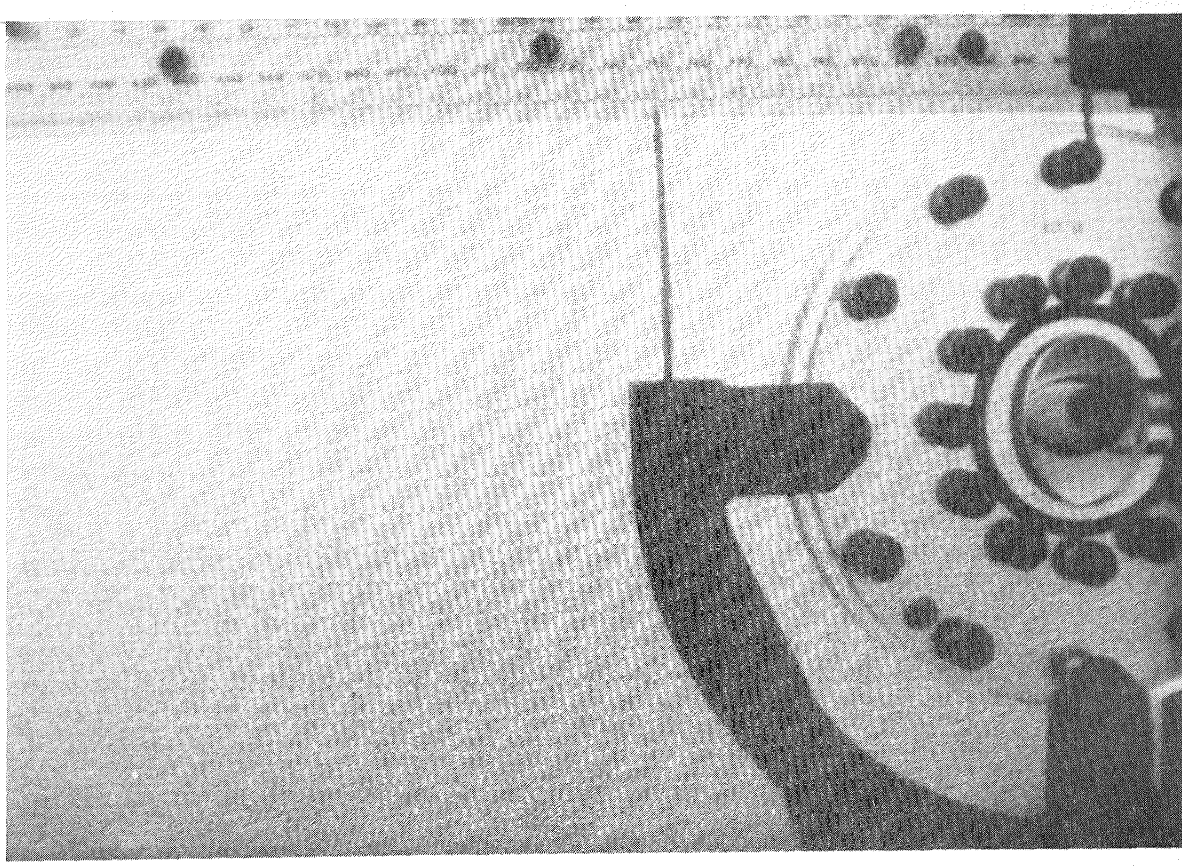


(a) Intial liquid-vapor interface configuration; time, 0 second.

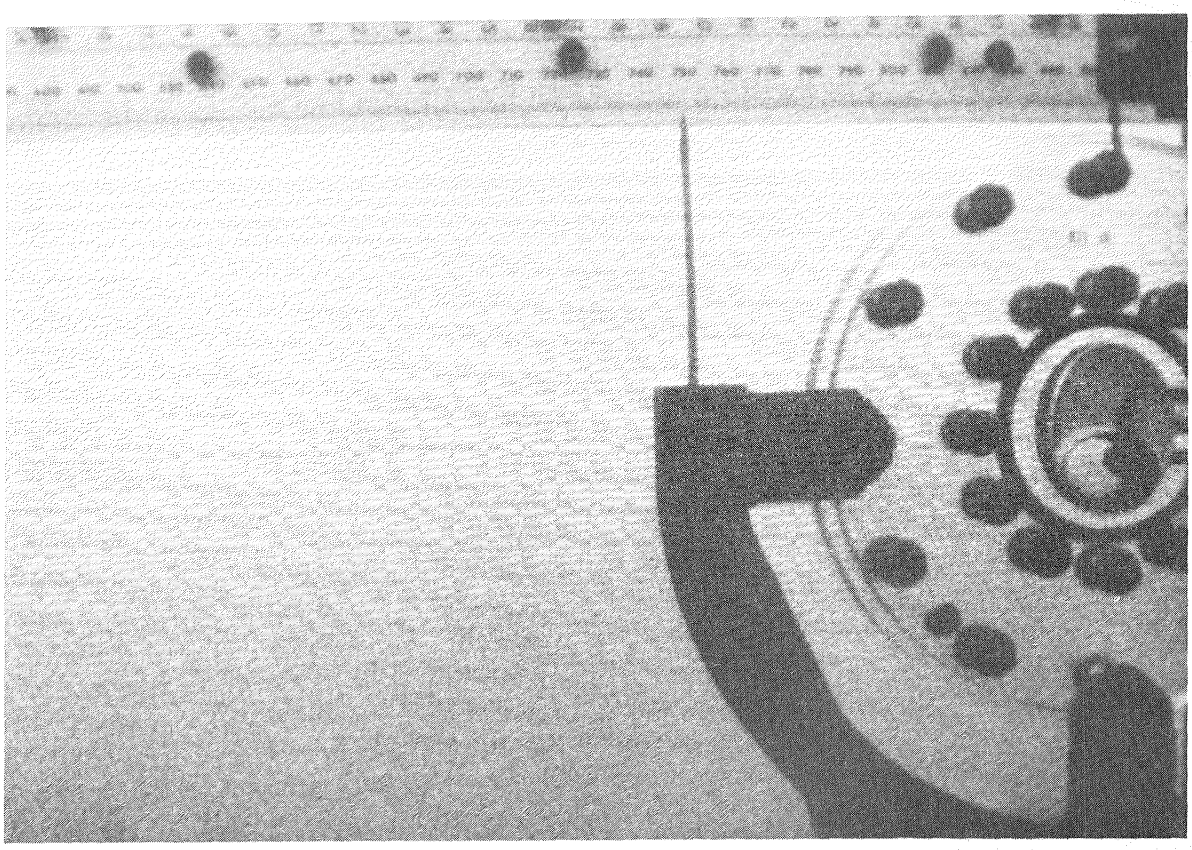


(b) Transient interface shape; time, 0.09 second into drop.

Figure 19. - Transient motion of interface upon entering low gravity. 90% filling.

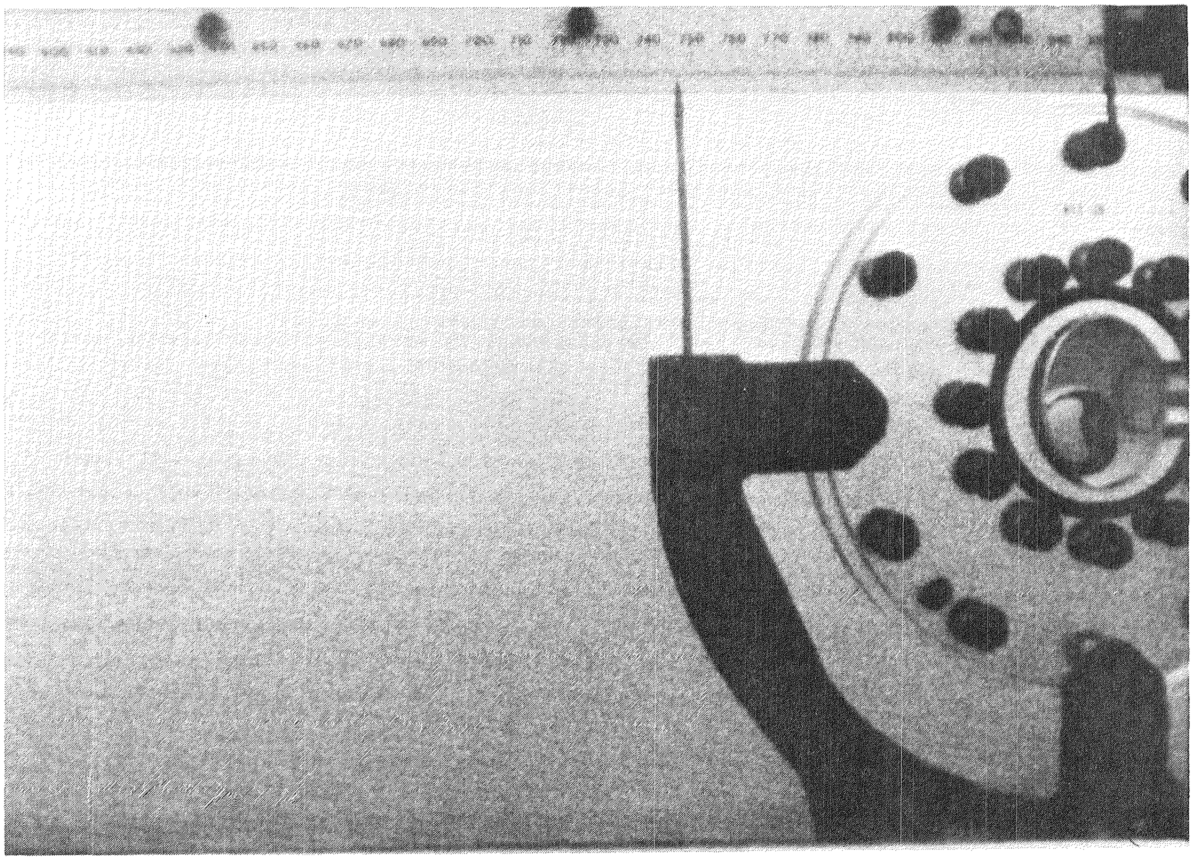


(c) Displacement of interface along tank major axis; time, 0.39 second into drop.

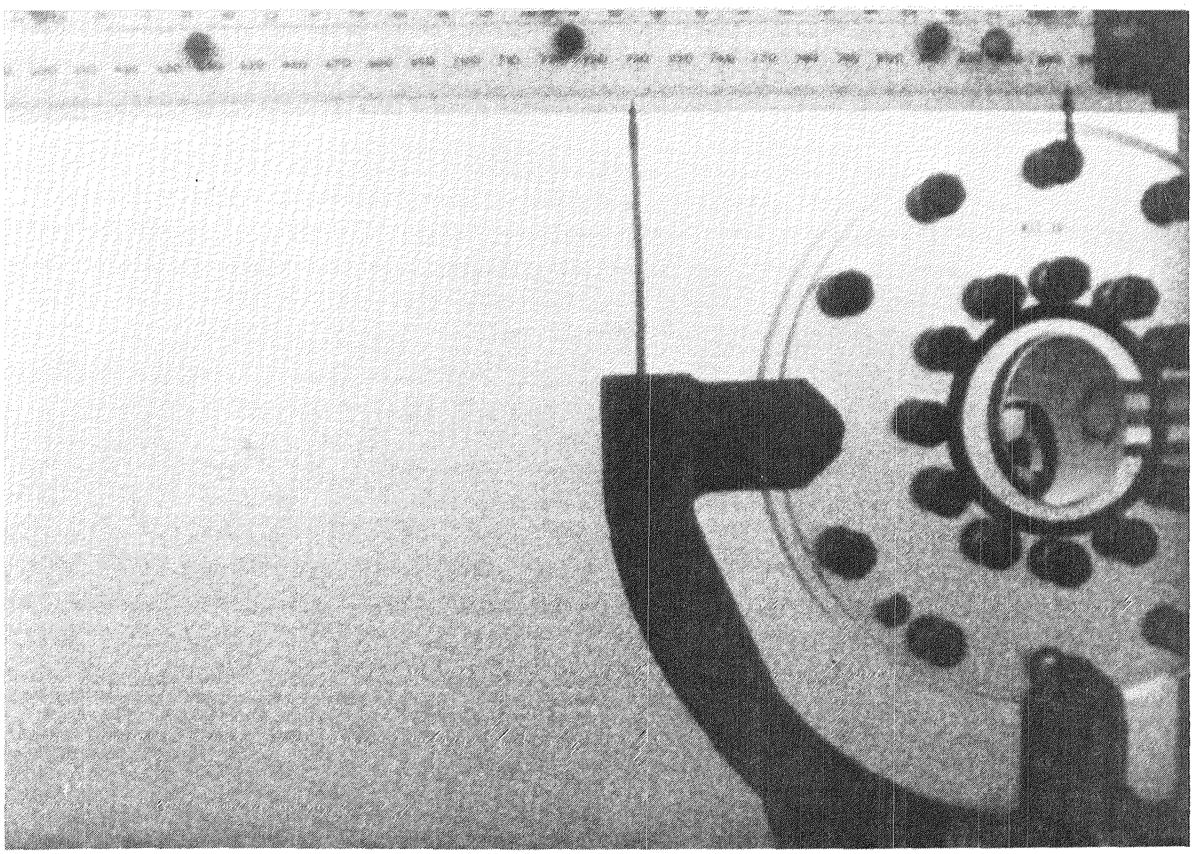


(d) Equilibrium zero gravity interface configuration; time, 2.50 seconds into drop.

Figure 19. - Concluded.

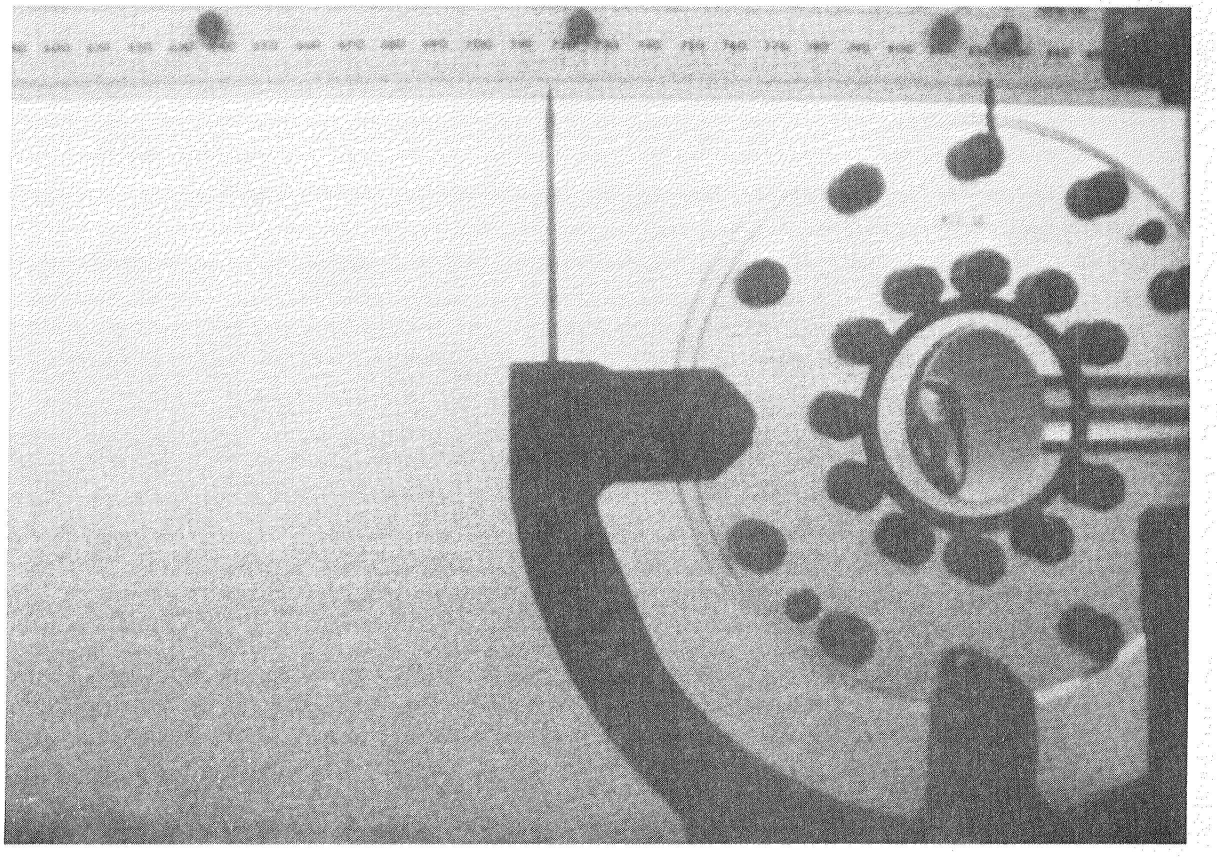


(a) Initial motion of interface just after acceleration is applied; time, 0.06 second after impulse is initiated.

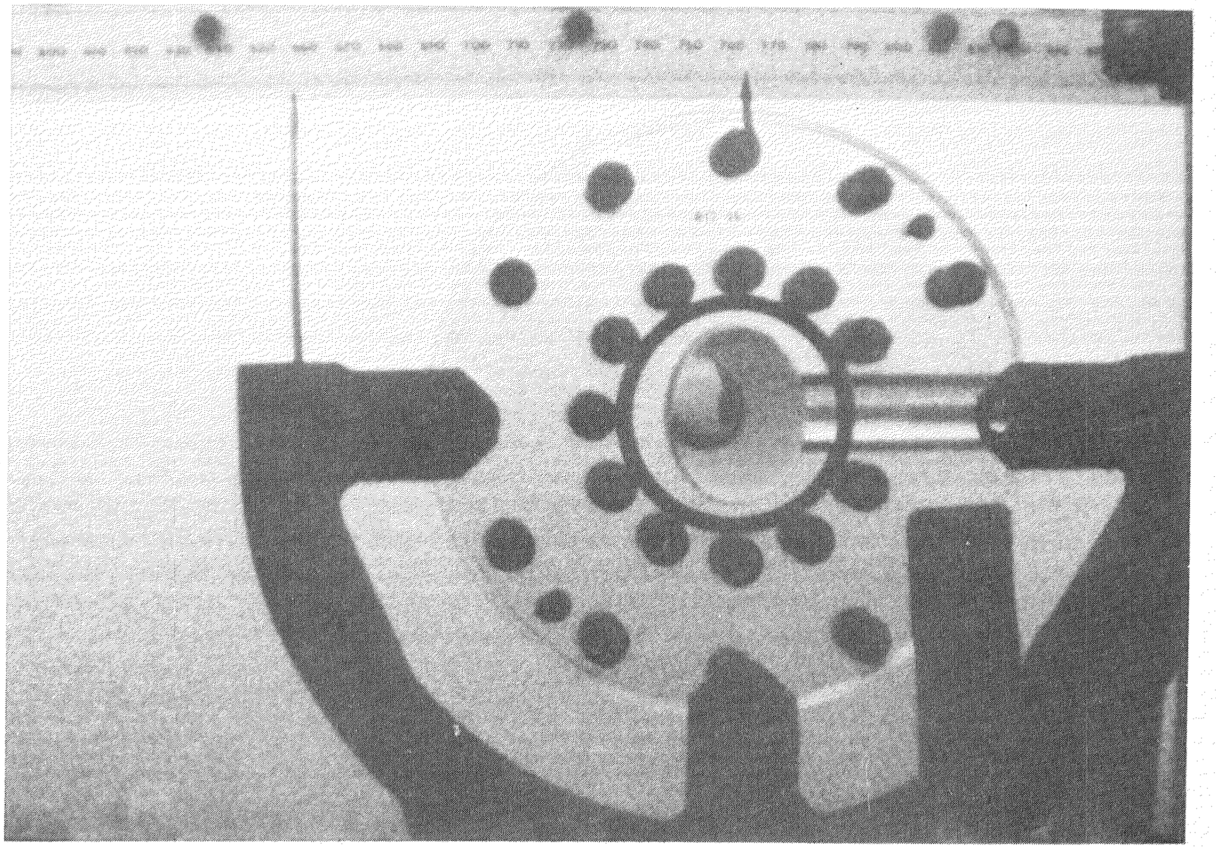


(b) Geyser formation during impulse; time, 0.10 second after impulse is initiated.

Figure 20. - Liquid-vapor interface configuration during and after impulse is applied. 90% filling; 0.25 g impulse.

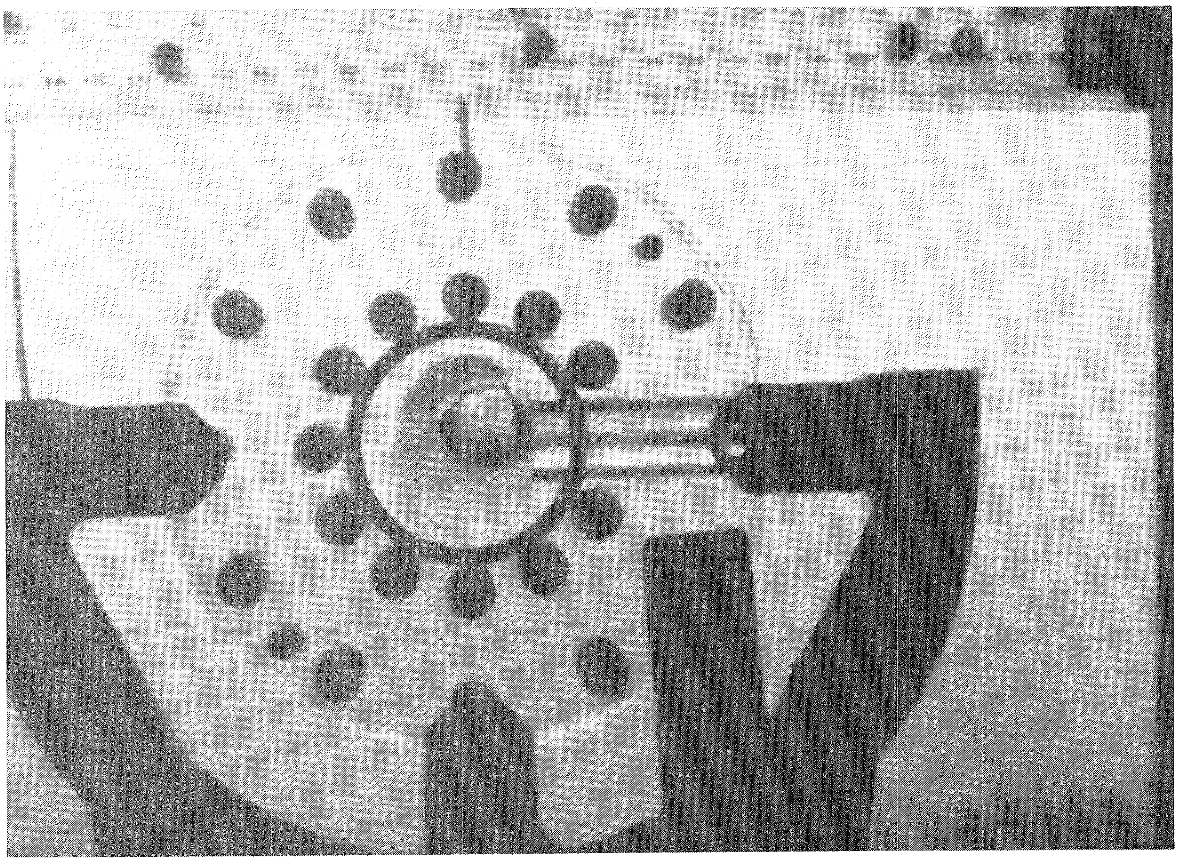


(c) Maximum interface distortion; time, 0.18 second after impulse is initiated.

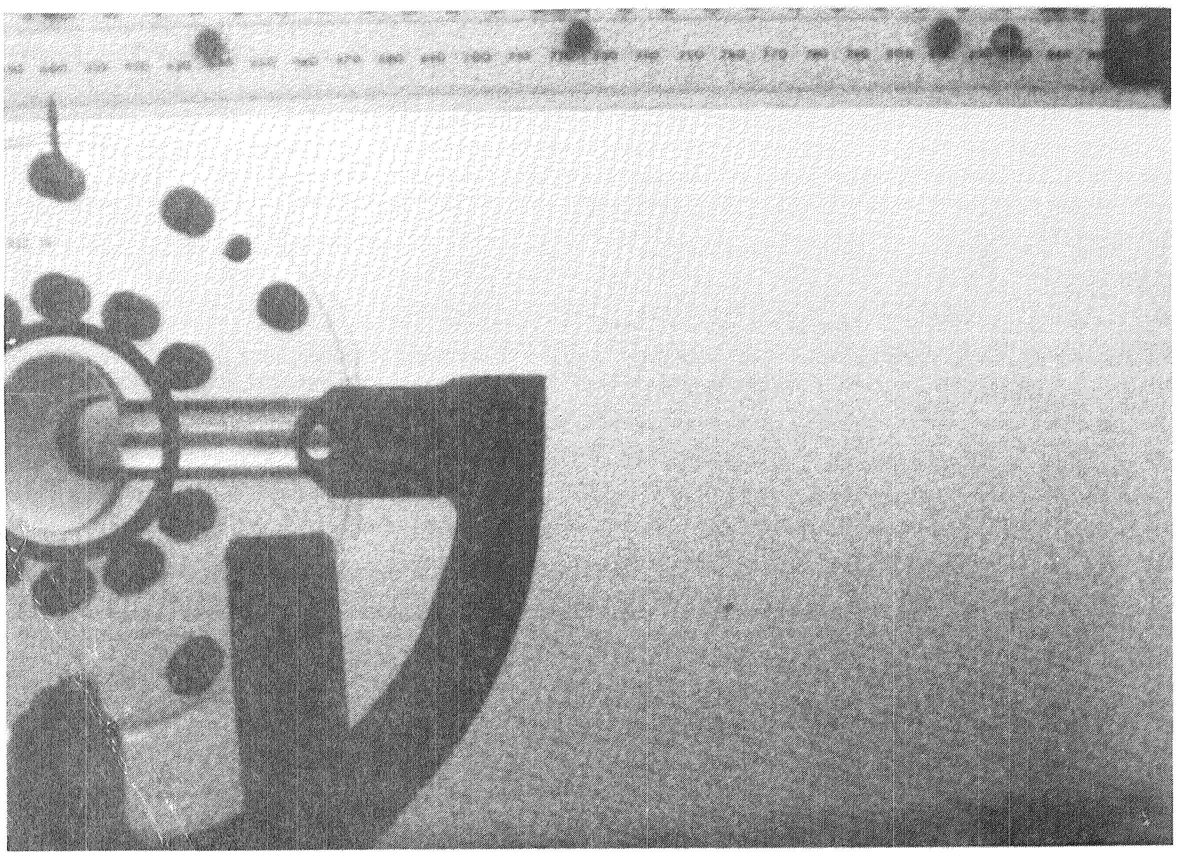


(d) Transient interface shape after acceleration ends; time, 0.40 second after inpulse is initiated.

Figure 20. - Continued.

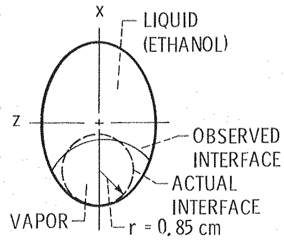


(e) Movement of interface along tank minor axis during constant velocity period of container motion; time, 0.62 second after impulse is initiated.

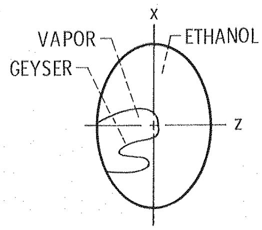


(f) Interface again dominated by capillary forces; time, 1.02 seconds after inpulse is initiated.

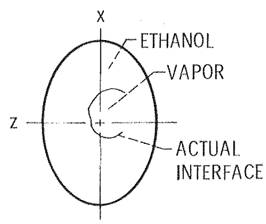
Figure 20. - Concluded.



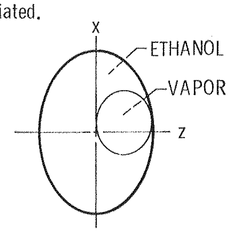
(a) Equilibrium zero-g configuration.



(b) Qualitative view of liquid-vapor interface; time, 0.1 second after impulse is initiated.

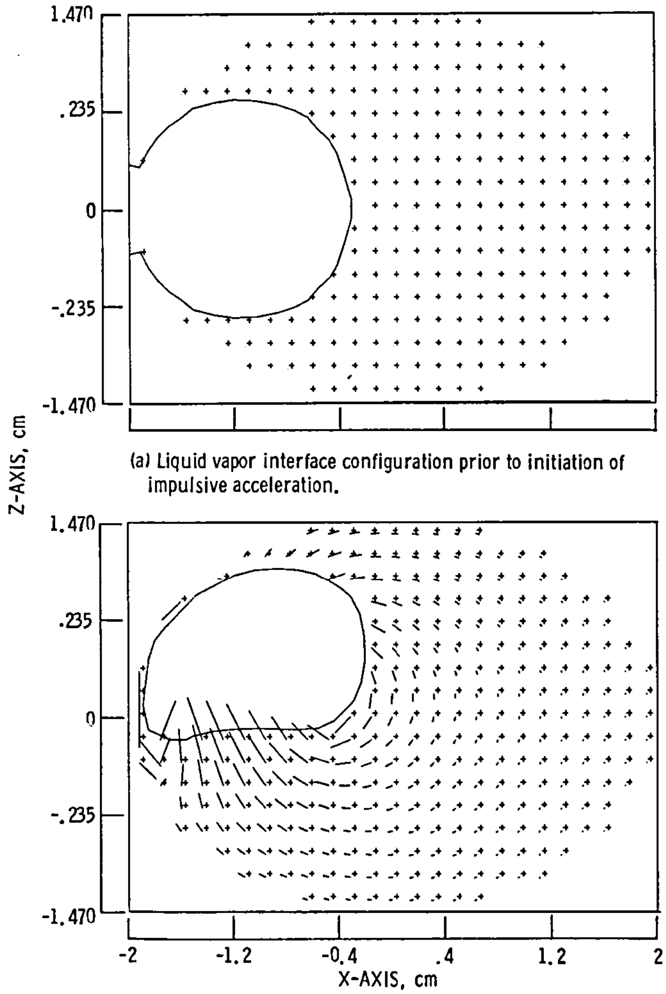


(c) Quantitative view of liquid-vapor interface; time, 0.6 second after impulse is initiated.



(d) Qualitative view of liquid-vapor interface; time, 1.1 seconds after impulse is initiated.

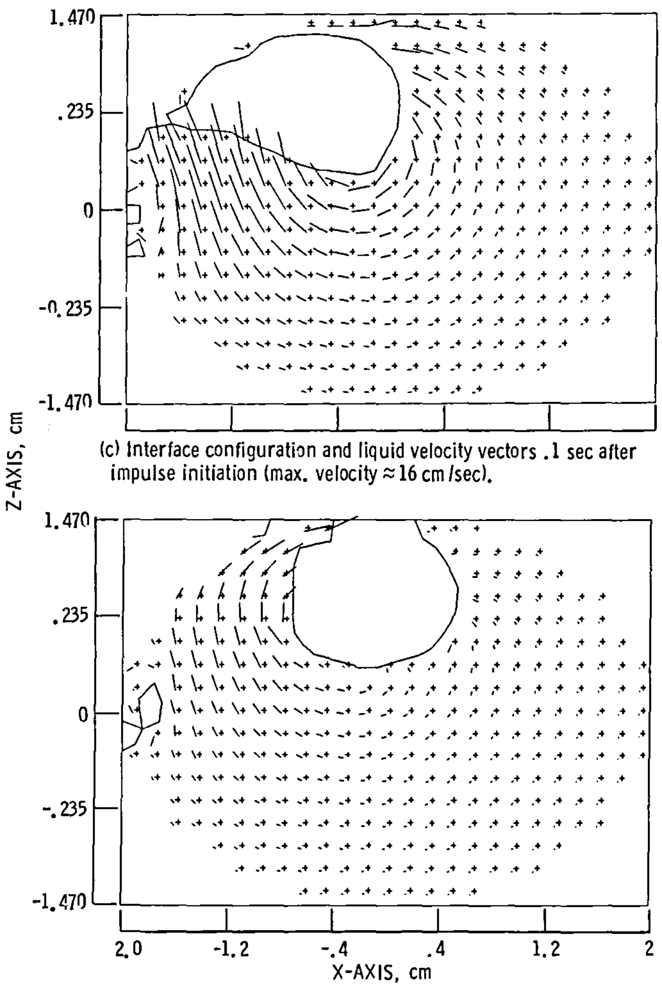
Figure 21. - Plots of liquid-vapor interface configuration prior to, during, and after impulse is applied. 90 percent filling; .25 g impulse.



(a) Liquid vapor interface configuration prior to initiation of impulsive acceleration.

(b) Interface configuration and liquid velocity vectors .06 sec after impulse initiation (max. velocity ≈ 22 cm/sec).

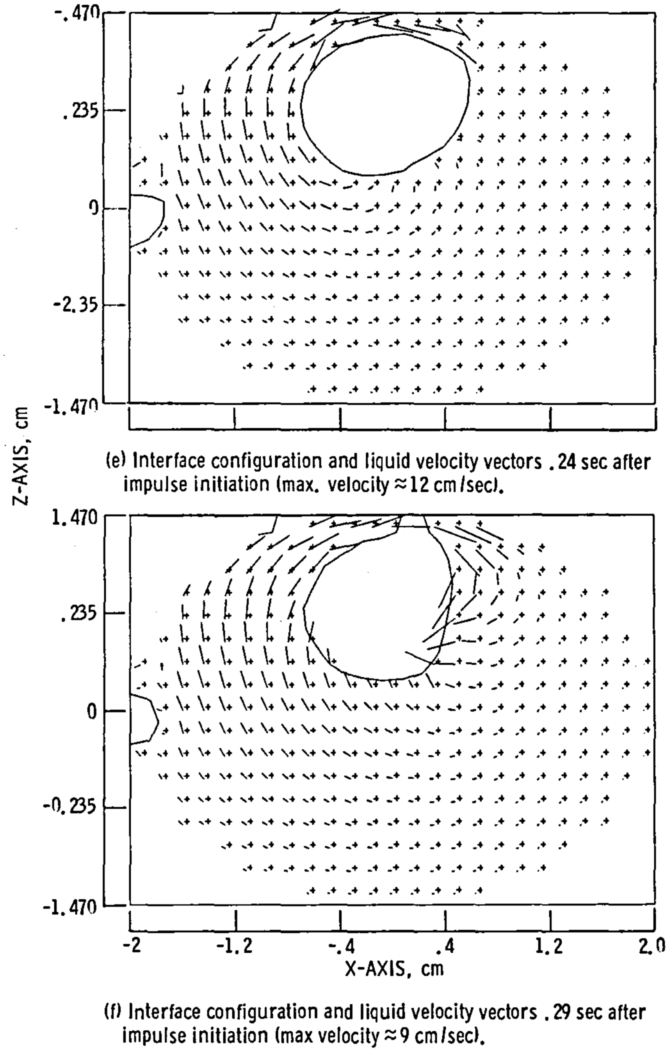
Figure 22. - Numerical modeling of liquid and vapor motion in response to impulsive acceleration (90 percent liquid filling; .25 g's impulse for .1 sec).



(c) Interface configuration and liquid velocity vectors .1 sec after impulse initiation (max. velocity ≈ 16 cm/sec).

(d) Interface configuration and liquid velocity vectors .2 sec after impulse initiation (max. velocity ≈ 16 cm/sec).

Figure 22. - Continued.



(e) Interface configuration and liquid velocity vectors .24 sec after impulse initiation (max. velocity ≈ 12 cm/sec).

(f) Interface configuration and liquid velocity vectors .29 sec after impulse initiation (max velocity ≈ 9 cm/sec).

Figure 22. - Concluded.

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15. Supplementary Notes

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16. Abstract

A history of the Lewis Research Center in-space fluid management technology program is presented. Current programs which include numerical modeling of fluid systems, heat exchanger/radiator concept studies, and the design of the Cryogenic Fluid Management Facility are discussed. Recent analytical and experimental activities performed to support the Shuttle/Centaur development activity are highlighted.

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