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PROPELLANT MANAGEMENT IN BOOSTER AND UPPER STAGE PROPULSION SYSTEMS

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Abstract

A summary review of some of the technical issues which surround the design of the propulsion systems for Booster and Upper Stage systems are presented. The work focuses on Propellant Geyser, Slosh, and Orientation. A brief description of the concern is given with graphics which help the reader to understand the physics of the situation. The most common solutions to these problems are given with there respective advantages and disadvantages.

1.0 Introduction

The design and analysis issues regarding the management and the thermo-fluid dynamics associated with rocket propellants are often underestimated when a rocket vehicle system is conceived. The problems often do not lend themselves to analytical solutions and testing must be done. In addition, these problems are often geometrically or mission specific. This requires full scale or near full scale testing in environments which are difficult to create in the test stand. When added to the very nature of liquid propellants, their flammability, their cryogenic properties and problems with testing can be a severe impediment to the development of a launch vehicle. When these problems are ignored prior to flight, the effects can be spectacularly catastrophic and very expensive. The advent of Computational Fluid Dynamics (CFD) and other methods of advanced computer simulation have provided one method to at least grapple with these issues from an analytical point of view. As the reader will see, CFD solutions can provide a very accurate analysis when compared with experimental data, the question still can be raised prior to flight, whether analysis alone provides enough insight into these problems to proceed without testing.

This paper has as its objective to summarize the major issues regarding propellant management in both booster and upper stage propulsion systems. There are many issues which effect the propellants, such as tank insulation which is beyond the scope of this work. This effort will stay to the traditional areas of vehicle design associated with propellant management. "Management" is defined by Websters Dictionary as " to control the movement or behavior of" [1]. The issues regarding managing propellants will be discussed herein.

2.0 Booster System Issues

Some of the physical issues regarding propellants which we are discussing in this paper often may manifest themselves anywhere during the vehicles mission profile.

However most of the issues have some tendency to happen during particular phases of the operation. These phases include ground-hold, Booster MECO, Booster - Upper Stage separation, Upper Stage MECO and Upper Stage engine restart.

2.1 Geyser Effects

The term "geyser" refers to the phenomenon seen in a long vertical line, such as a booster's feedline when the cryogenic propellant boils off at a rate which exceeds a normal bubble release. This boiloff gradually allows the entire line to go dry. When the line becomes dry it is quickly refilled due to gravity from the propellant tank above in a vertically launched rocket (or storage tank in a ground application). This refilling of the line causes a pressure surge due to the propellant free-falling into the line and is analogous to waterhammer. The pressure surges which are created can be very large and can damage the feedlines, line and valve supports as well as disconnects and the engine. [2] There are three main areas which we need to focus on: 1. What is the physical phenomenon which causes this problem, 2. When is geyser most likely to be a problem, 3. What can be done to prevent it from happening.

2.1.1 The geyser physical phenomenon

The cryogenic propellant in the vertical line is in a sub-cooled condition, as referenced to the local static pressure in the line. Convective heat transfer occurs into the propellant, thereby increasing the temperature. The temperature increases until it reaches the saturation temperature relating to the local static pressure. When this condition is satisfied continued heat transfer will either cause nucleate boiling or the convective heat transfer will continue by placing this heat into superheating of the fluid. The mode of heat transfer will be dependent upon such factors as line surface conditions, the purity of the cryogen and other such factors. [2] Once the boiling begins the resultant bubbles effect the line in two ways. The bubbles provide boiling centers which will encourage further boiling, this will serve to release the heat stored in the case of the superheated fluid. The second result is that the bubbles displace liquid from the line into the propellant tank, thereby causing a decrease in the head pressure any point below the bubbles. The loss of head pressure, in effect superheats the cryogen left in the line resulting in its release of more vapor, which in turn decreases the hydrostatic pressure and results in further superheat. This cycle continues, but does not cause a problem until the resultant bubbles interfere with themselves and their ability to release this pressure form the system. At A_v/A_t ratios of .55-.6 the bubbles will begin to intermingle and will cause the creation of a single large bubble, called a Taylor bubble. The fast moving bubbles below will join this large bubble and this single large bubble will grow at a fast pace, all the while decreasing the static pressure below the bubble causing more vapor to form. Provided that the rate of change of saturation temperature because of the static pressure drop, exceeds the rate of decrease in liquid temperature due to flashing, more and more vapor will be created. At some point the amount of vapor will be great enough to force the remaining cryogen at the top of the line and erupt into the propellant tank, through the liquid and into the ullage region. The resultant reaction occurs with some violence and is termed a geyser.

The vaporization process will serve to decrease the temperature of the leftover fluid in the line, below the saturation point, thereby causing vapor production to cease. As liquid begins refill the line, the saturation temperature increases because of density increase and the vapor is further cooled by the cryogen which is falling through it. The vapor itself then condenses and the liquid enters a free-fall mode which results in a large pressure spike at the bottom of the line.

The phenomenon has two results. The first is when the geyser erupts into the ullage. When a quantity of cryo fluid is dispersed like this into the ullage volume, the result is a rapid decrease in the pressure of the ullage gas as the bulk temperature is lowered. The result is the same whether the pressurant is homogenous or another fluid. The rapid depressurization can cause the tank to structurally collapse. The second result is the damage due to the surge pressure in the feedline and the engine interface.[2]

2.1.2 When geyser Occurs

The geyser phenomenon, as can be seen from above is strongly dependent on the physics of the "bubbles" and their motion through the feedline, specifically vapor release, liquid heating, and bubble formation. Boiling of a liquid at its saturation temperature is enabled by the presence of boiling centers. A critical piece to understanding the boiling phenomenon is that since the curvature of the surface of a newly formed very small bubble is very great and the vapor pressure is thereby reduced significantly. The formation of this bubble will require a warmer temperature than the saturation at the given pressure as is the case of the propellant/ullage interface. [4] The boiling centers are formed by impurities such as dissolved gases, dirt, dust, rough surfaces on the line or another bubble. Under perfect conditions (i.e. a system containing a pure liquid with smooth line surfaces) a great deal of superheat may be stored prior to the onset of boiling. The fluid in this state can be considered unstable and any imbalance or disturbance will result in the release of superheat very rapidly. [Figure 1]

The bubbles, as they develop, move toward the centerline, the region of lowest drag. The bubbles begin to coalesce in this region, albeit this effect is dependent upon the nature of the bubbles. A bubble which is moving in the wake of another will catch up to the bubble in front due to the "drafting" or wake effect. A plot of velocity versus separation distance is shown in Figure 2. This figure points out the decrease in static pressure which occurs in the wake region. This accelerating effect along with an increase in the number of bubbles causes the bubbles to interact and form a large mass of vapor. This vapor mass may manifest itself as a "swarm" of small bubbles or even as a large spherical "hat" bubble or a spherical topped slug of cylindrical shape. This latter is referred to as a Taylor Bubble (see Reference 3). [2]

This accretion of bubbles impedes the normal escape of vapor from the line due to the buoyancy effect. This impedance causes an increase in drag to which the closely formed bubbles are subjected due to the torturous path they must travel. The walls proximity to the vapor mass also causes an increase in drag.

The makeup of the bubble mass and the escape mechanism is shown in Figure 3. The figure highlights 3 flow regions. Region 1 is made up of a low number of bubbles and there is little or no interference. Region 2 sees the beginning of mutual interference . A strong circulation current develops in the buoyant action of the bubbles forcing the mixture towards the centerline and the onset of the wake effect, causing the bubbles in the aft of the mass to increase velocity. The increase in velocity is approximately 2 to 4 ft/sec. Region 3, where A_v = bubble cross-section area and A_t =tube or flow area the bubble mass has a density that the Taylor bubbles are formed. The creation of the Taylor Bubbles sees a corresponding drop in release velocity.

When the spherical bubbles form the Taylor bubbles, the bubbles occupy the majority of the line diameter. This results in the cylindrical sides seeing an increased drag which decreases the Taylor Bubbles velocity much less than a spherical bubble would see (see Figure 4). The formula in Figure 4 indicates a velocity of 1.4 ft/sec which is equivalent to a spherical bubble approximately 0.25 in in diameter.

The presence of bubbles in vertical lines has two effects on the static pressure below. First, the viscous shear causes a reactive force which reduces the static pressure below. This is proportional to bubble shape, size and line diameter. The second effect is liquid displacement. In a typical feedline configuration, the presence of bubbles creating large volumes of vapor will displace large amounts of propellant from the line. The change in static pressure in the line (head) due to the displaced liquid will be great, even though the corresponding change in tank liquid level is slight.

2.1.3 Eliminating the Geyser problem

There are three ways to reduce the possibility of geyser in a propellant feedline which make sense in a booster vehicle. They are:

1. Controlled topping
2. Helium Injection
3. Recirculation

2.1.3.1 Controlled Topping

From the paragraphs above which described the boiling and release process during the geyser cycle, it was shown that until the ratio A_v/A_t approached 0.55 interference with the release mechanism was non-critical. Thus prior to the development of a critical condition, considerable evaporation in the feedline will occur. In the analysis it has been presented[5] it states that topping inlet temperature versus flow rate required to hold the vapor to line exit area ratio less than 0.55. The assumptions utilized in that analysis are that all boiling in the column would occur at saturation, and even though several degrees of superheat could occur under perfect condition, such conditions are unlikely in the agitated nature of the fluid under flow conditions.

Granting this caveat, it was determined that flowrates between 1 and 4 lb/sec would suppress the geyser phenomenon with less than 3 degrees of subcooling required at the inlet of the topping flow. Figure 5 summarizes the results and has as its assumptions that saturation conditions and the associated boiling at various levels in the line from exit to inlet.

This concept appears to be an acceptable method for geyser prevention, but it must be noted that the liquid topping rate required to prevent geyser could be higher than the boiloff rate and could cause tank overfill. The solution to that issue could be to require several degrees of sub-cooling to prevent tank overfill.

2.1.3.2 Helium Injection

The second method to prevent geyser involves the injection of helium (or another non-condensible gas) low in the feedline. This method has been utilized in a variety of vehicle applications (including the current STS ET) and has even been used for the densification of the LOX in addition to its capability for geyser suppression.

The injected helium, being pure, has in the bubbles, a partial pressure of zero for oxygen. The difference in the partial pressure of GOX in the injected helium bubble and the vapor pressure of LOX causes a mass transfer of oxygen, via diffusion, into the helium gas. This mass transfer results in the localized cooling due to the absorption of heat of vaporization from the surrounding fluid. The cooling which occurs is equivalent to the heat of vaporization multiplied by the mass of LOX vaporized. This cooling tends to lower the bulk liquid temperature. This sub-cooling of the propellant, if great enough, prevents the boiling bubbles forming at the wall from lowering the static pressure and thereby prevents the flashing effect. Thus the geyser phenomenon is prevented. If enough helium is injected, the prevention of any heat accumulation is possible. This refrigeration can be made equal to or even greater than the pipe wall heat leak, thus sub-cooling the bulk propellant.

This method, although providing an adequate method for geyser suppression has several drawbacks. To ensure sufficient cooling, a tremendous quantity of helium could be required. The resulting agitation of the fluid in the line and the displacement of liquid in the line and tank could cause problems in the accuracy of the propellant load. Additionally, such a system is an active one, requiring more complicated ground operations which can cause more expense for launch.

2.1.3.3 Recirculation

The next method for geyser suppression is recirculation. This method lends itself towards the vehicle configuration involving two or more LOX lines. It is apparent that the key to eliminate the accretion of superheat in the feedline by eliminating the heat as it enters. The LOX system of a vehicles tank and run duct can provide a somewhat efficient refrigeration system.

As the heat is transferred through the tank wall, natural convection currents transport the warmer LOX forward toward the liquid surface, where after boil off occurs, the remaining LOX is cooled by the release of heat of vaporization. The resultant colder, denser LOX circulates toward the bottom of the tanks.

If we use a dual feedline system as an example (see Figure 6), the lines would need to be connected at the bottom of the system, and the heat leak into the lines would need to be unequal (i.e. insulation removed from one line). The LOX in the uninsulated line will warm quicker, the density will decrease and the propellant, moving from a region of higher density to lower, will displace the warm LOX out of the line into the tank. The convection process described above will occur and the resultant boiloff will cool the local propellant where it will descend into the tank bottom region, thereby allowing the cycle to begin again. Testing on such a system has shown that it behaves in a cyclic or periodic behavior, gradually flushing the line and then pausing while the system builds energy and it occurs again. This method brings with it the attractive proposition, that in the event of a geyser, the rapid loss of liquid in the line due to bubbling, would result in the line filling from below, thereby preventing the geyser. The system has as another advantage that it is passive, i.e. requiring no active control from the facility after loading.

A method evolved from the above was part of the STS in early ET's, although extensively tested it nevr flew. A small uninsulated line was attached to the feedline both above and below. [6] The line, being uninsulated and of higher L/D than the main feedline would empty and refill from the bottom. This line was referred to as the Ant-geyser line (see Figure 7).

One of the reasons the geyser phenomenon exists in launch vehicles is that the vehicles flight dynamics requires that the heaviest propellant is stored forward. The use of LOX so extensively in the U.S. as the oxidizer of choice, its cryogenic and other properties lend itself to geyser. If the vehicle dynamics allow, and LOX can be stored aft, the geyser problem may thus be eliminated (see Figure 8).[7]

2.2 Slosh Concerns During Ascent

The physics associated with slosh in the propellant tanks of a launch vehicle during ascent are evident to anyone who has tried to drink a glass of water while riding in a car. The water and the propellant both have a tendency, while in a variable velocity/acceleration field to "slosh" about. Even under the acceleration of a launch vehicle, typically near 3.5 "g"s, the slightest disturbance may result in slosh which in turn can have a serious effect upon the stability of the vehicle. In the worst cases, where the launch vehicles guidance system cannot control the changes due to the dynamic excitation, the result can be catastrophic. The severity of the result can be explained by the fact that for most launch vehicles at launch, the mass of the propellants is greater than 90% of the Gross Lift Off Weight (GLOW). If the natural frequencies of the propellant in the tanks reside near the control frequency, or close to the lower modes of elastic vibration, for example the fundamental body-bending mode or to the natural frequency of a control sensor, than the problems difficulty to predict and resolve can be great. Therefore in the case of an ascending launch vehicle the dynamic stability and control analysis and there effect on the oscillatory nature of the propellant must be understood. [2]

2.2.1 Fundamental Theory

The fundamental theory behind understanding the slosh can be shown with a simple mathematical model based on a linearized potential theory modeling the propellant as incompressible, irrotational and non-viscous. The analysis (developed in Reference 2) shows the Eigen values from the free oscillation to be:

$$\omega_n^2 = (g/a)\,\varepsilon_n \tanh(\varepsilon_n h/a) \quad n = 0,1,2,\ldots$$

Where ε_n is a root of $J'_1(\varepsilon) = 0$ and has the values;

$$\varepsilon_0 \approx 1.84$$

$$\varepsilon_1 \approx 5.33$$

$$\varepsilon_3 \approx 8.53$$

The natural frequency of the propellant is therefore

$$f_n = 1/2\Pi \sqrt{g/a \quad \varepsilon_n \tanh(\varepsilon_n h/a)}$$

It is apparent from this equation that the natural frequency of the propellant is proportional to the square root of the longitudinal acceleration, g, and goes down with the square root of the tank diameter. In the case of constant tank dimensions and acceleration, the change in frequency will occur mostly when the propellant is shallow i.e. for a fluid height of less than one tank diameter for the first mode and even less for higher modes. During ascent the longitudinal accelerations will be increasing. Only shortly before MECO does the influence of fluid height overcome the influence of the acceleration, g, and decrease the frequency. [2] Further discussions of the analytical techniques are beyond the scope of this work. However, these mode shapes, frequencies and damping are required to determine the magnitude of response of the booster to any dynamic excitation i.e. wind-induced oscillations in the vertical, transonic buffeting, gusts in flight etc. These natural frequencies also play an important part in the design of the guidance system.

2.2.2 Damping

In order to minimize the amplitude of the slosh due to these in flight excitations any damping a way to increase the damping of the system must be employed. The most common method for damping is by using ring baffles (see Figures 9, 10) attached to the interior of the tank walls. Tests have shown [Reference 8] that the damping provided by the baffles decreases with the depth at which the baffle is located under the surface of the liquid.

3.0 Upper Stage System Issues (Low-g Propellant Issues)

The problems associated with upper stage systems are slightly different than boosters primarily during two time intervals. The first is at Upper Stage MECO when the vehicle is in a low gravity field. The second is when the Upper Stage engine must restart in that same low gravity field.

3.1 Liquid Slosh at MECO

The first issue to be dealt with is slosh. The only difference between the booster phenomenon and this case is that this is not while under the longitudinal acceleration vector, but at MECO when the acceleration of the vehicle transitions to zero, often rather abruptly. Liquid sloshing amplitudes which remain damped during powered flight may obtain very large amplitudes at engine termination. At MECO propellant potential energy is converted into kinetic energy with removal of imposed constraining accelerations. This problem was of critical importance during the development of the Saturn V/S-IVB stage propellant control system.

To alleviate these concerns an experimental study was initiated to investigate propellant dynamics of the S-IVB stage. The program included ground tests using scale models in a drop tower facility and a full scale flight experiment on board a Saturn launch vehicle. The ground experiments utilized the 4.3 sec drop tower facility at NASA

Marshall Space Flight Center (see Figure 11). The main goal was to understand the behavior of a sloshing liquid subjected to a sudden reduction in acceleration. These tests were accomplished primarily with scale models and provided valuable data on fundamental laws and scaling parameters applicable to individual phenomena. The fluid behavior which occurs at MECO is shown in Figure 12. The solution is again the use of ring baffles. The use of CFD has been shown to accurately predict the resultant fluid motion in low gravity. A commercially available software package was used, as is, to generate the plots shown in figure 12. The accuracy which results is evident. [9]

3.2 Propellant Orientation

Once the vehicle has been in orbit the propellant has become oriented in some fashion, often with the ullage bubble in the center of the tank. The ullage bubble may also be oriented directly over the tank outlet. The ability to restart the engine is dependent upon the liquid in the inlet as opposed to gas. The other concern over the knowledge of where the ullage bubble is concerns venting. In upper stage vehicles the tank vents are closed during the powered portion of flight. During the orbital hold period as the pressure in the cryogenic vessel rises the pressure must be vented off. It is undesirable to vent useable liquid and therefore the position of the ullage bubble over the vent is required.

3.2.1 Liquid Acquisition

It is critical to ensure that liquid is available at the outlet of the tank at the time of engine restart. This ability to have propellant at the engine inlet is referred to as liquid acquisition. The two most common methods for liquid acquisition are propellant settling and capillary liquid acquisition devices (LADs).

The use of propellant settling has been the primary method for flight vehicles in the past. The S-IVB/Saturn V utilized settling via a continuous thrust produced by routing liquid oxygen boiloff through small thrusters pointing down the longitudinal axis of the vehicle. The Saturn V/S-IVB design, referred to as LUTs (LOX Ullage Thrusters) was based on its ability to create an acceleration which would cause a Bond number (B_0) greater than 70 in the Liquid Hydrogen tank. The ability for this system to perform was proven in the flight of AS-203. Bond number is the ratio of inertia forces to surface tension forces and is expressed by the following relation:

$$Bo = (\text{Acceleration} * \text{Tank Radius}^2)/(\text{Kinematic Surface Tension})$$

To determine the level of thrust required to resettle the propellants to the orientation desired, the required Bond number must be calculated for the configuration and the appropriate thrust level must then be employed. A slightly different form of settling is referred to as Tank Head Idle (THI). An engine with the capability for THI can accept either liquid or vapor at the inlets, allowing the engine to provide the settling thrust at a high initial specific impulse (Isp). For a hydrogen engine the Isp would be in the range of 360 - 460 sec during the start transient, this results in extremely high Bond numbers (~ 2000 - 5000), and a resultant force which may result in problems with the liquid dynamics or the vehicle control. Such a method has not been proven in flight, and still requires development. [10]

The other method which uses the capillary motion effect, offers the advantage of providing vapor-free liquid without propellant settling. A partial LAD (known as a start basket) collects enough propellant to allow the engine to start and resettle the propellants. It is essentially a screen box which allows the propellant to wick in to the engine inlet. Refer to Figure 13. One of the disadvantages is the extra weight of such a system.

Another capillary device which is utilized in the storable propellant regime are vanes. A vane is a device which is a structure adjacent to the tank wall which creates an open passage, through which propellant can flow. Since all propellants "wet" due to there surface tension properties, the fluid forms along the structure (see Figure 14). The devices advantages are the light weight, high reliability (no moving components) and they are compatible with most propellants (100% Titanium designs are possible). The use of vanes however are limited by acceleration and flow rate, they can be used in any attitude. The traditional uses of vanes are in flexible demand storeable propellant systems or in bipropellant systems where they are used in conjunction with sponges. [11]

A similar device known as a sponge is often utilized in conjunction with vanes. A sponge is an open structure of tightly spaced radial panes of metal which holds the propellant by the surface tension effect (see Figure 15). Again these devices are reliable and can be used in a multitude of propellants but are limited by being able to deliver only limited quantities at certain accelerations. These devices are traditionally used in 1. Settling thrust systems requiring propellant access during engine start. 2. Propulsion systems required to perform station-keeping maneuvers (repeated use of certain propellant amount), 3. Vehicle systems requiring control of the center of gravity of the propellant while in low g. Sponges have been used in both mono- and bi propellant systems. [12]

3.2.2 Propellant Venting

In the case of a cryogenic propellant on orbit, the heat leak into the tanks eventually requires a way to control the tank pressure. Venting the vapor to relieve tank pressure is an easy task in an acceleration field, however when in low gravity conditions the liquid vapor interface is not known. As has been mentioned for liquid acquisition, settling can be used to orient the vapor over the vent. Once the vapor is in place the vent can be open and the pressure can be relieved. However this requires the use of propellant and makes the boiloff penalty even higher. A very innovative alternative to settled venting was developed in the early 1960's. The device , known as a Thermodynamic Vent System, (TVS) can be utilized in an active or a passive mode (see Figure 16). The active configuration uses a Joule-Thompson valve, a two-phase heat exchanger and a mixing pump to condense tank ullage, cool the bulk fluid, reduce thermal gradients and minimize vented mass. A passive TVS also utilizes a joule-thompson valve with a wall mounted heat exchanger or a vapor cooled shield around the tank to intercept incoming heat, with the same result. The active mixing system is designed to assure adequate homogeneity of the propellant, which can reduce the amount of uncertainty which accompanies the passive system. The heat dissipation due to the pump may, however, offset the advantages of the active system. This very elegant solution has never been tried on-orbit, although a certain amount of development testing has been accomplished.

(Reference 13 and 14). The TVS also has applications for the long-term storage of cryogenic propellants on-orbit.[10]

4.0 Conclusions

The technical issues which have been previewed in this paper have caused consternation amongst launch vehicle designers since the early rockets , such as the V-2 and Redstone Missile. The problems are difficult to understand analytically and may require on-orbit testing. Two such examples are the flight of the modified Saturn 1B, AS-203 and its dedicated fluid management flight in 1966 [13] (see Figure 17), as well as the Shuttle flight experiment called FARE for Fluid Acquisition and Resupply Experiment (see Figure 18) which flew in 1992 using a reference fluid to examine on - orbit fluid behavior. [14] It has been over 40 years since the design of the Redstone and over 20 years since the Space Shuttle and many of these issues and there resolution have been relegated to the back corner. As new launch vehicle systems are designed and tested, the physics will once again bring these issues to spotlight. One of the purposes of this paper is to add a firm reminder of some of these technical challenges so that the would be designer can perform the research and testing required to avoid the sometimes catastrophic results. As has been said " Those who do not learn from the past are doomed to repeat its failures". [15]

5.0 References

1. Webster's New World Dictionary, Warner Books, 1987.

2. Ring, Elliot, " Rocket Propellant and Pressurization Systems", Prentice-Hall, Inc, Englewood Cliffs, N.J., 1964.

3. Davies, R.M., and Sir Geoffrey Taylor, " The Mechanics of Large Bubbles Rising Through Extended Liquids and Through Liquids in Tubes," Proceedings of the Royal Society, Vol. 200, 1950.

4. McAdams, William H., "Heat Transmission", McGraw Hill Book Company, New York, 1954.

5. Morgan, S.K., and H.F. Brady, "Geysering and methods of Elimination," Martin Propulsion Symposium April, 1961.

6. Martin Marietta, " Space Shuttle External Tank: System Definition Handbook Volume1", MMC-ET-SE07, November 1975.

7. Fisher, Mark F., "Propulsion Test Article Design Binder", Book 2 PTA1 Systems, Critical Design Review Package, December 16, 1996.

8. Roberts, James F., and Basurto, Eduardo R. and Chen, Pei-Ying, " Slosh Design Handbook Vol.1", Technical Report No. 27, NAS8-11111, Sept. 1964.

9. Fisher, Mark F., Schmidt, George R., and Martin, James, J., " Analysis of Cryogenic Propellant Behavior in Microgravity and Low Thrust Environments", AIAA/SAE/ASME/ASEE, 27th Joint Propulsion Conference and Exhibit, June 24-26, 1991, Sacramento, California, AIAA-91-2173.

10. Hastings, Leon J., Tucker, Stephen P., and Huffaker, C. Fred, " CFM Technology Needs for Future Space Transportation Systems", AIAA/NASA/OAI Conference on Advanced SEI Technologies, Cleveland Ohio September 4-6, 1991, AIAA-91-3474.

11. Jaekle, D.E. Jr, " Propellant Management Device Conceptual Design and Analysis: Vanes", AIAA/SAE/ASME/ASEE, 27th Joint Propulsion Conference and Exhibit, June 24-26, 1991, Sacramento, California, AIAA-91-2172.

12. Jaekle, D.E. Jr, " Propellant Management Device Conceptual Design and Analysis: Sponges", AIAA/SAE/ASME/ASEE, 29th Joint Propulsion Conference and Exhibit, June 28-30, 1993, Monterey, California, AIAA-93-1970.

13. Chrysler Corp., "Evaluation of AS-203 Low Gravity Orbital Experiment", Contract NAS8-4016, Technical Report HSM-R421-67, January 13, 1967.

14. Dominick, Sam, and Driscoll, Susan, "Fluid Acquisition and Resupply Experiment (FARE I) Flight Results", AIAA/SAE/ASME/ASEE, 29th Joint Propulsion Conference and Exhibit, June 28-30, 1993, Monterey, California, AIAA-93-2424.

15. Clark, John D., "Ignition", Naval Institute Press, 1968.

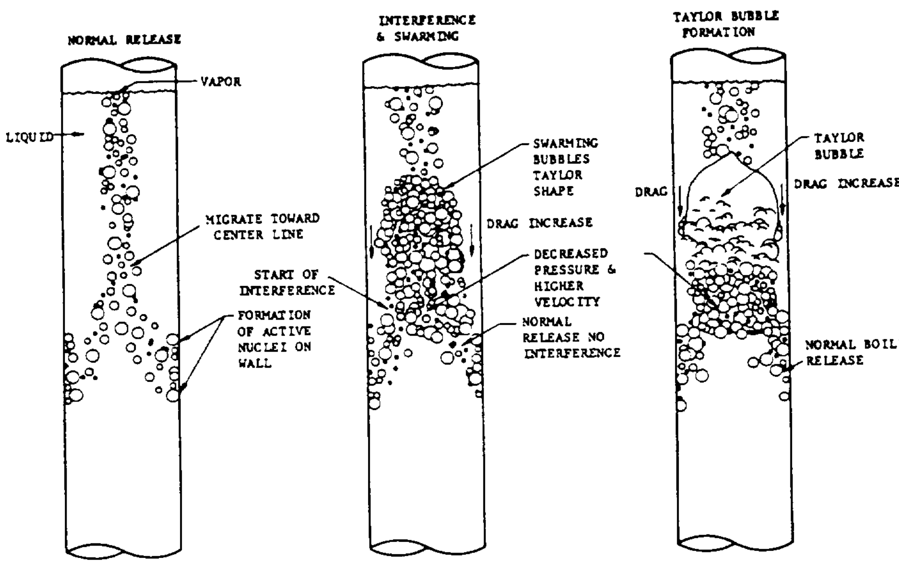


Figure 1 The modes of vapor release in the Geyser phenomenon. [2]

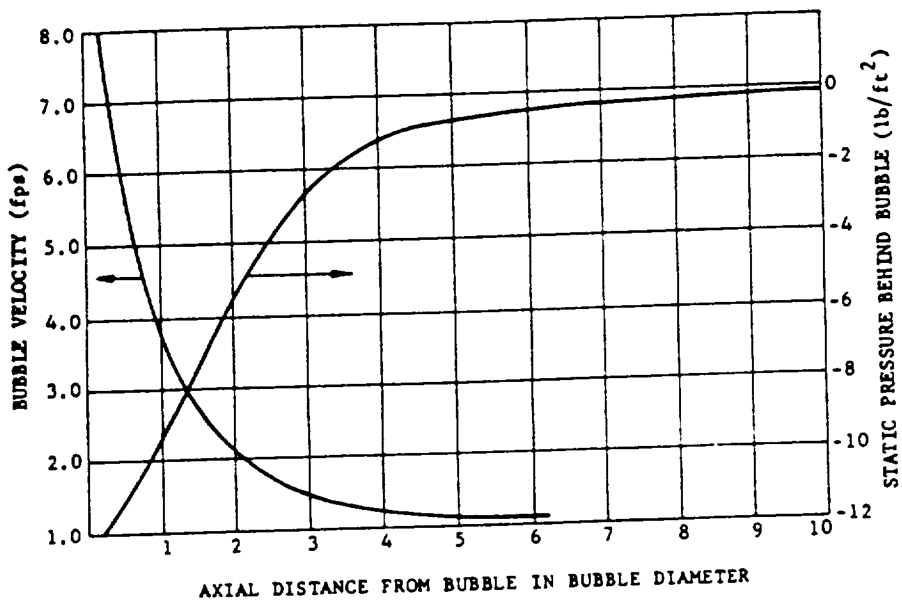


Figure 2 Bubble separation distance versus velocity and pressure in the Geyser Phenomenon. [2]

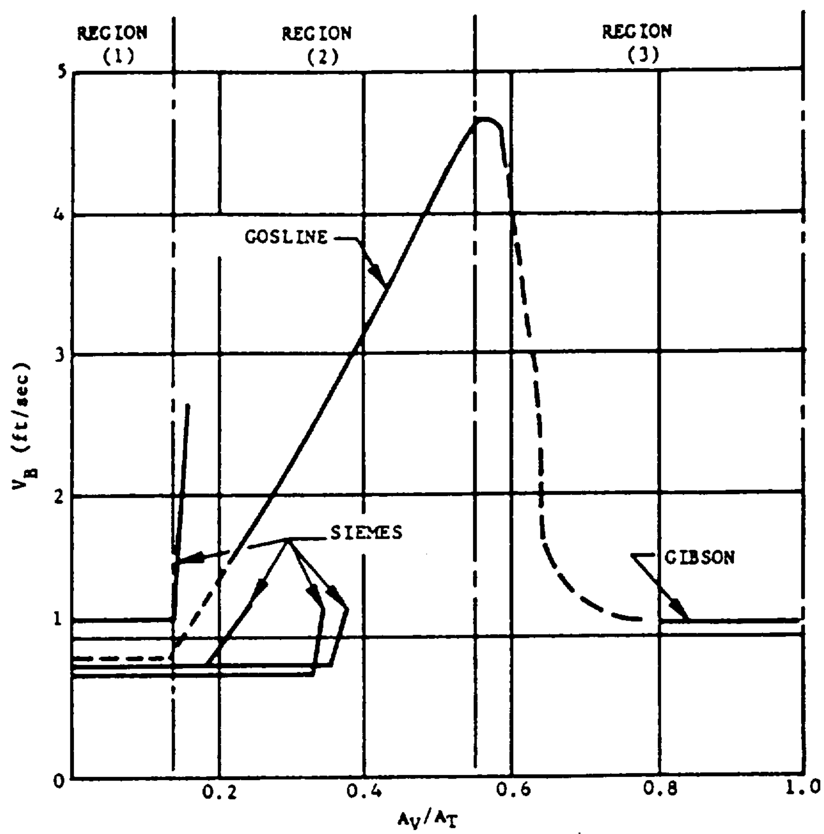


Figure 3 Velocity of gas bubbles in liquid column with closed bottom.[2]

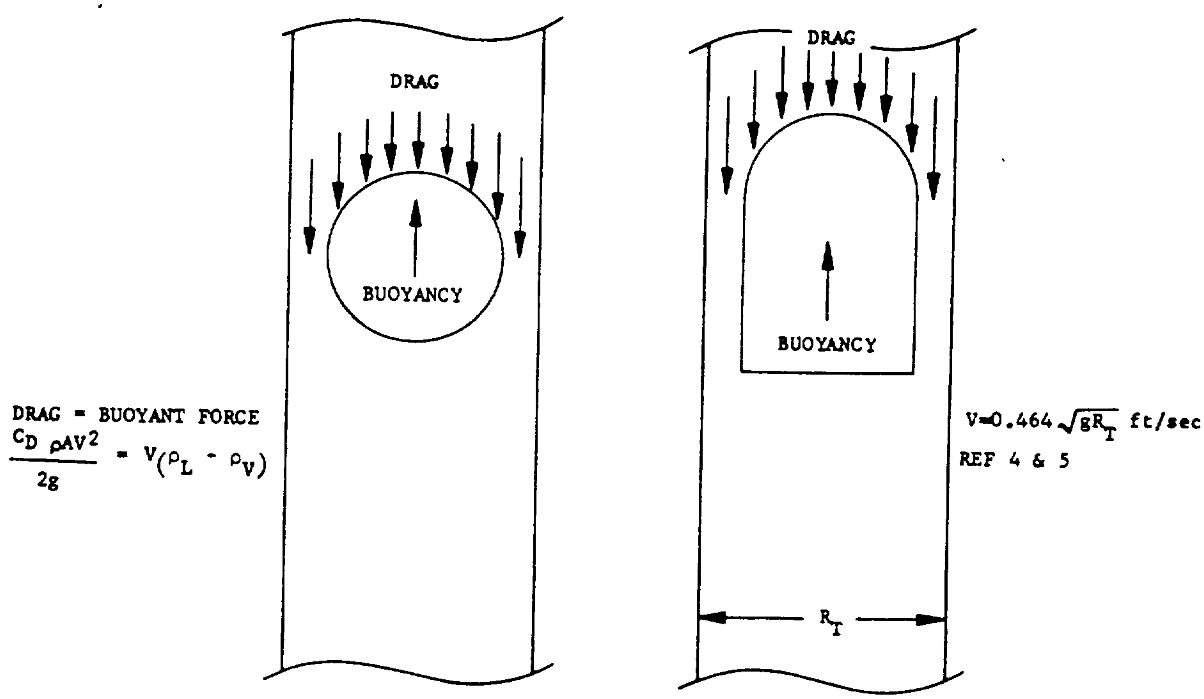


Figure 4 Terminal velocity, where l_d = liquid density, l_v = vapor density, v = velocity and V = Volume.[2]

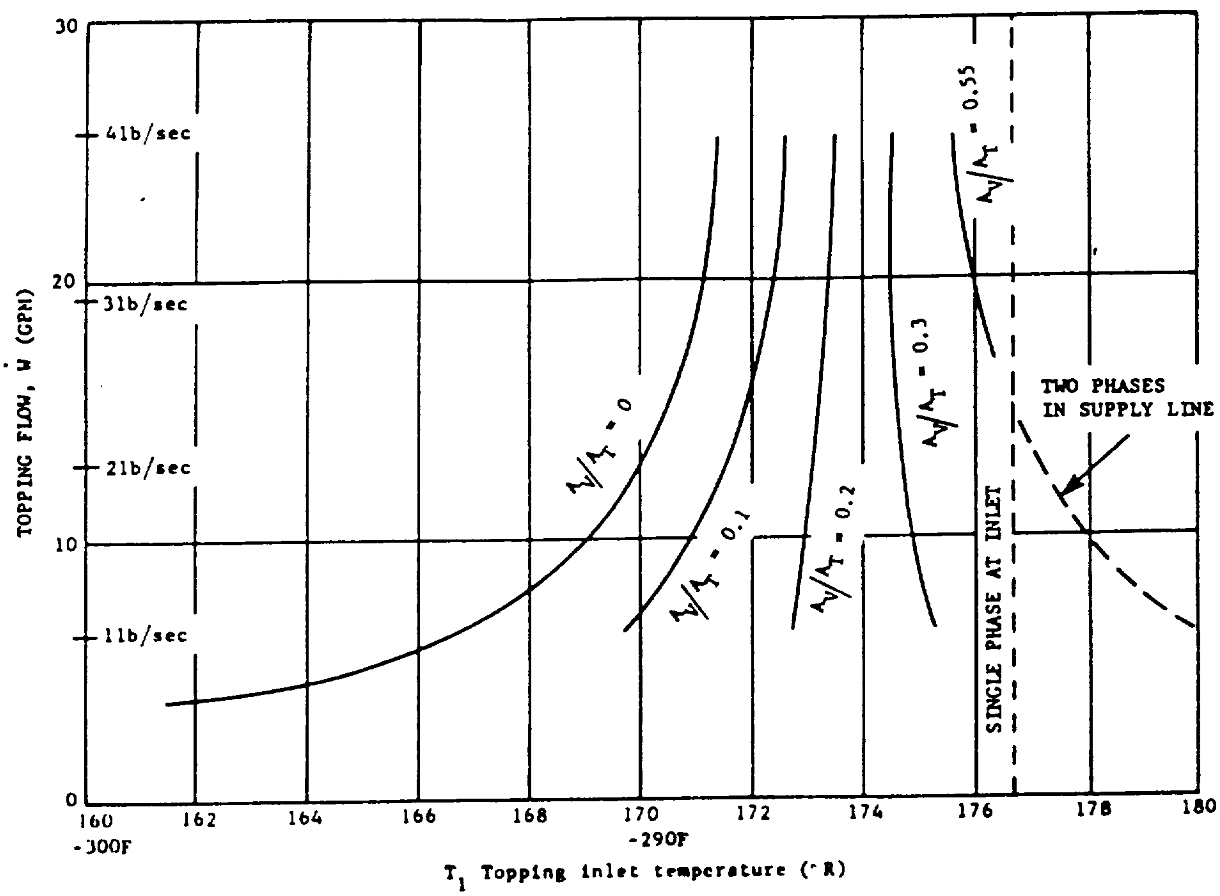


Figure 5 Geyser-suppression topping flow rate versus topping inlet temperature. [2]

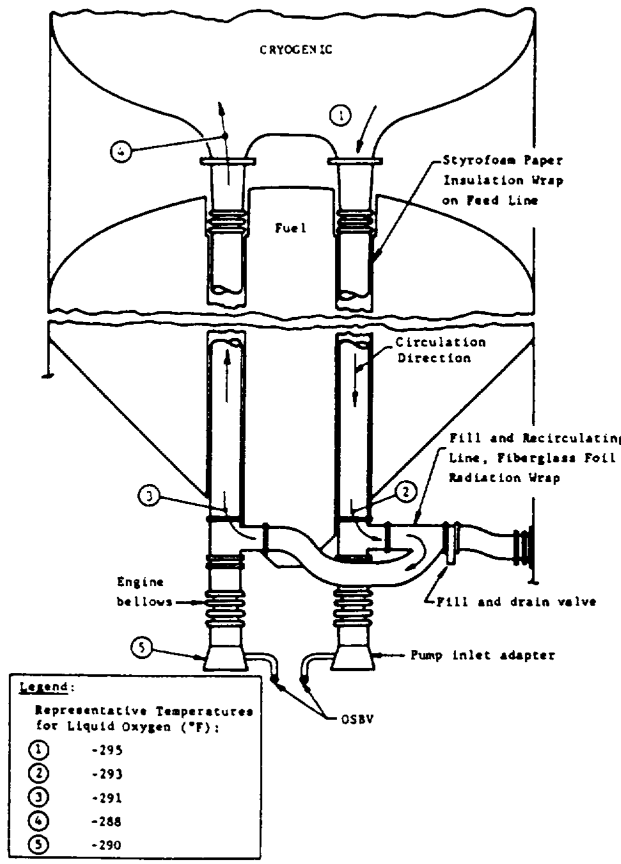


Figure 6 Cryogenic recirculation system in a two run duct configuration. [2]

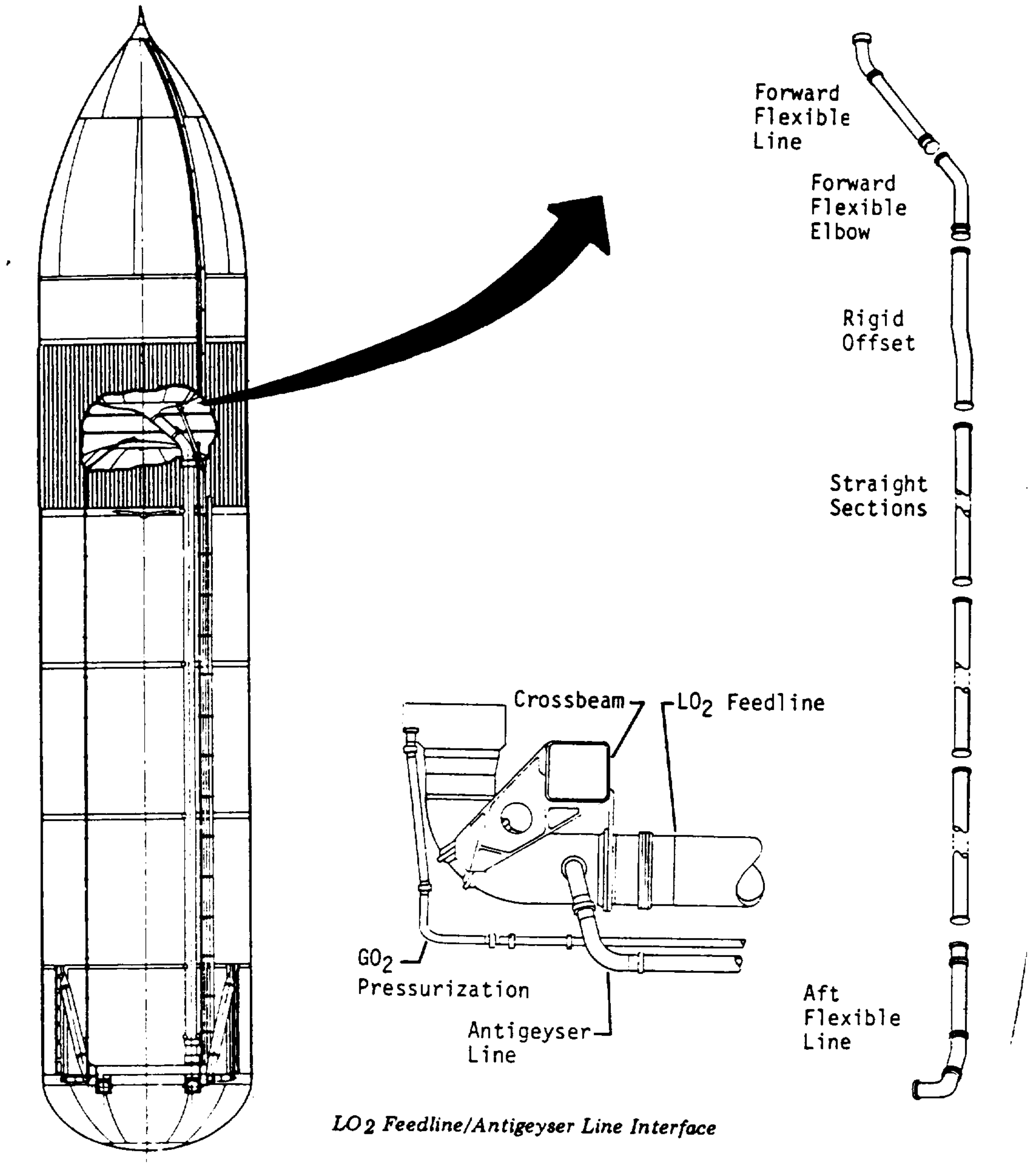


Figure 7 Anti-geyser line configuration on the Space Shuttle External Tank. [6]

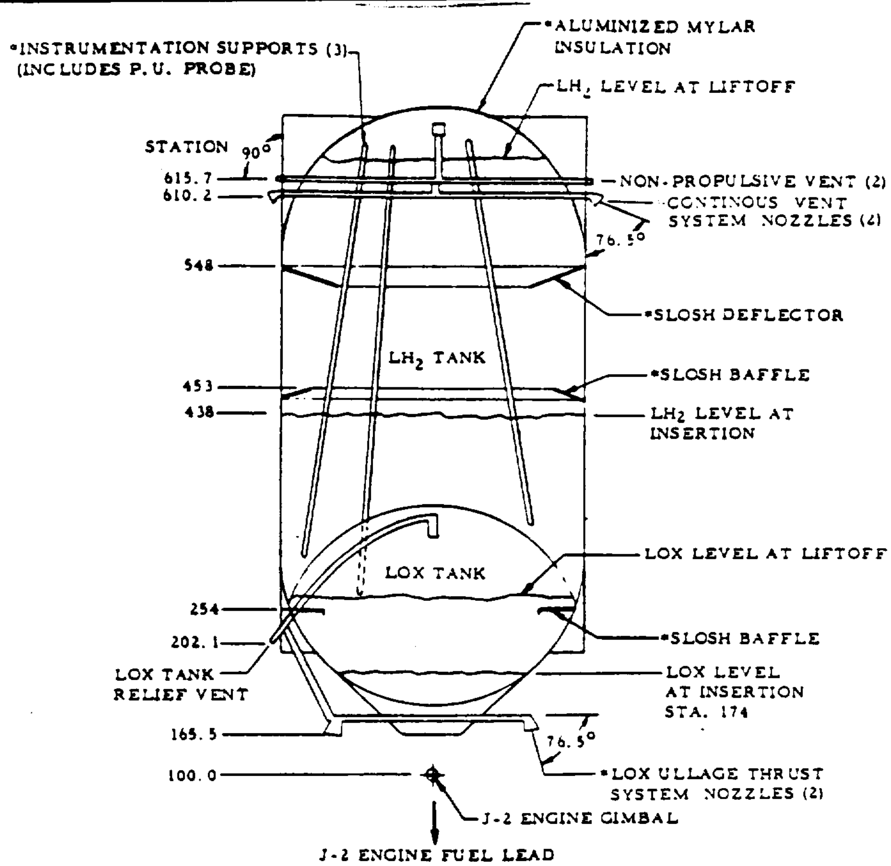
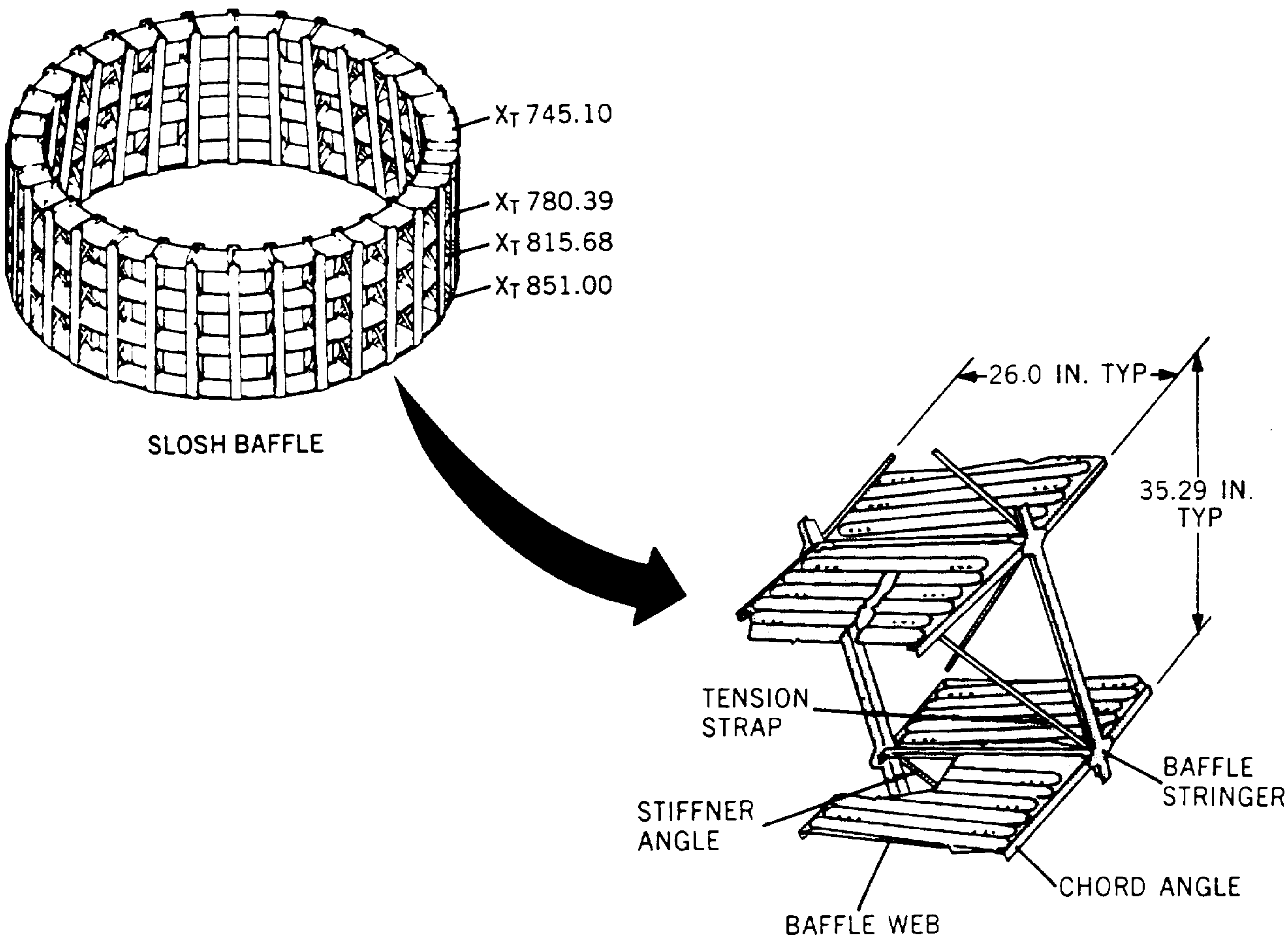
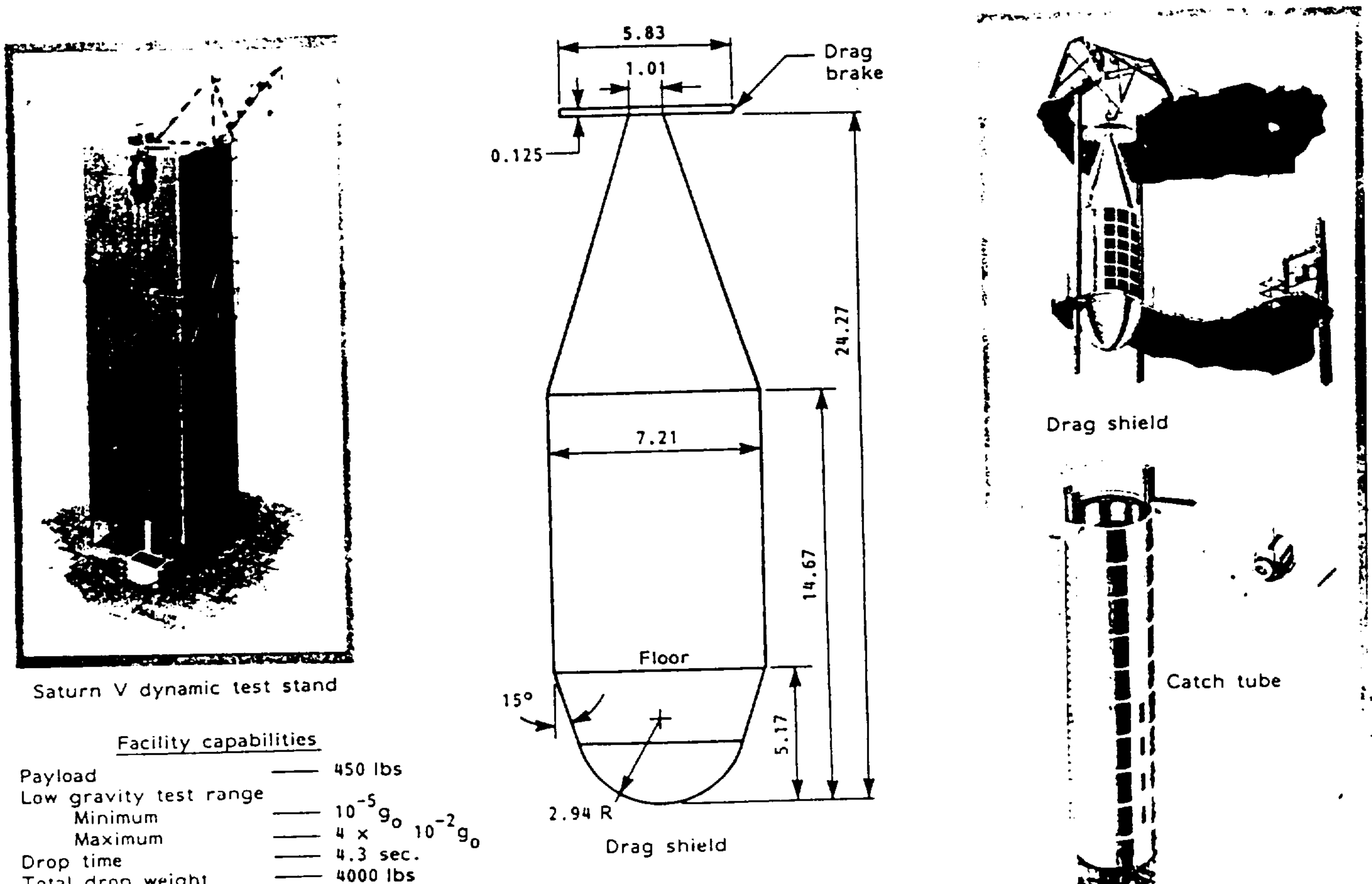


Figure 9 Depiction of the use of ring baffles to prevent slosh dynamics on the Saturn 1B (above) and the Saturn V/S-IVB vehicle. [13]



SLOSH BAFFLE STRUCTURAL CONFIGURATION

Figure 10 A depiction of the use of ring baffles to prevent slosh dynamics on the Space Shuttle External Tank. [6]



Facility capabilities

Payload	450 lbs
Low gravity test range	
Minimum	$10^{-5} g_o$
Maximum	$4 \times 10^{-2} g_o$
Drop time	4.3 sec.
Total drop weight	4000 lbs
Maximum test package	3' dia. x 3' high
Deceleration	less than 25 g's

Figure 11 Marshal Space Flight Center's Low Gravity Test facility. [9]

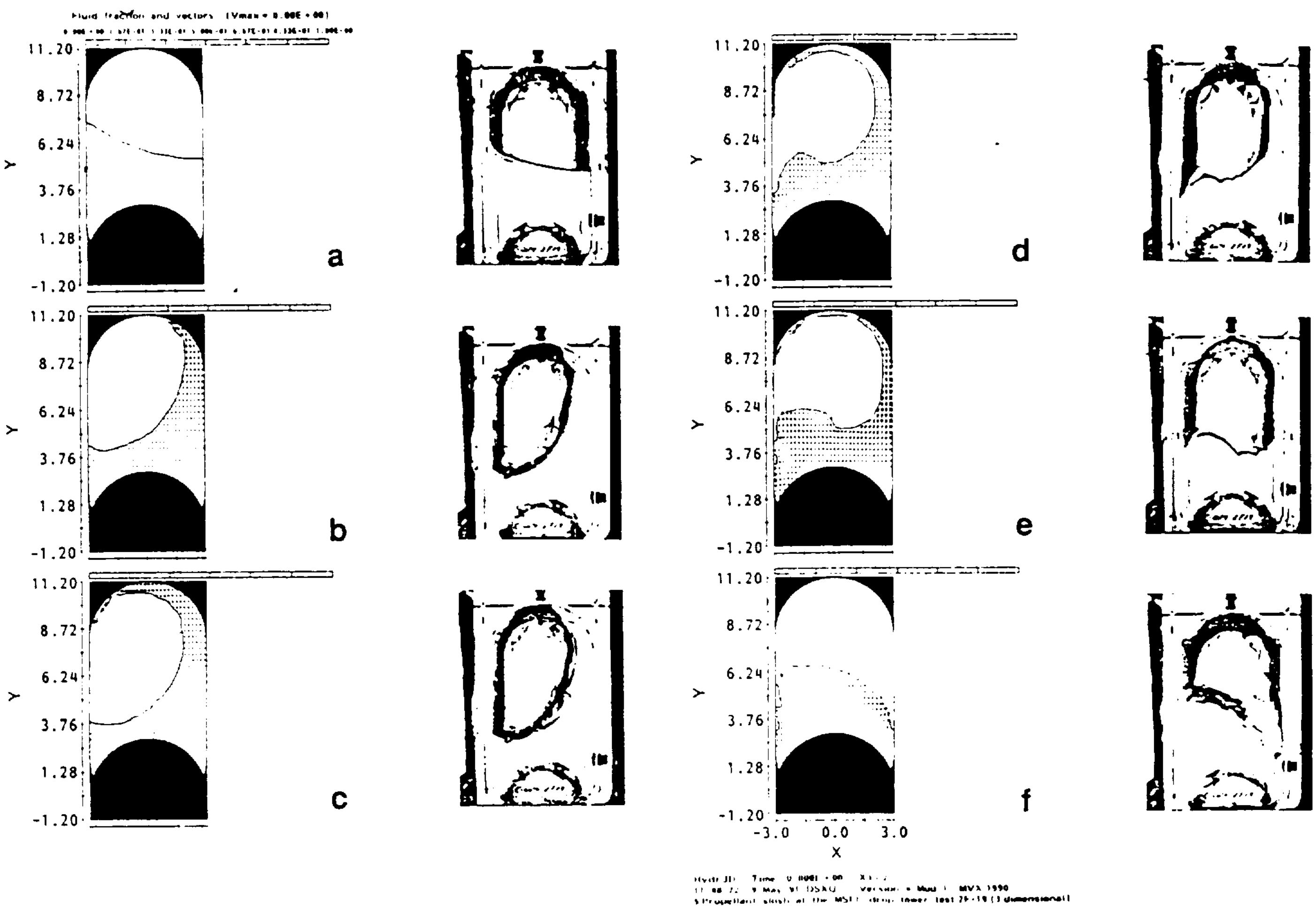


Figure 12 Drop tower results of the S-IVB model showing fluid behavior . [9]

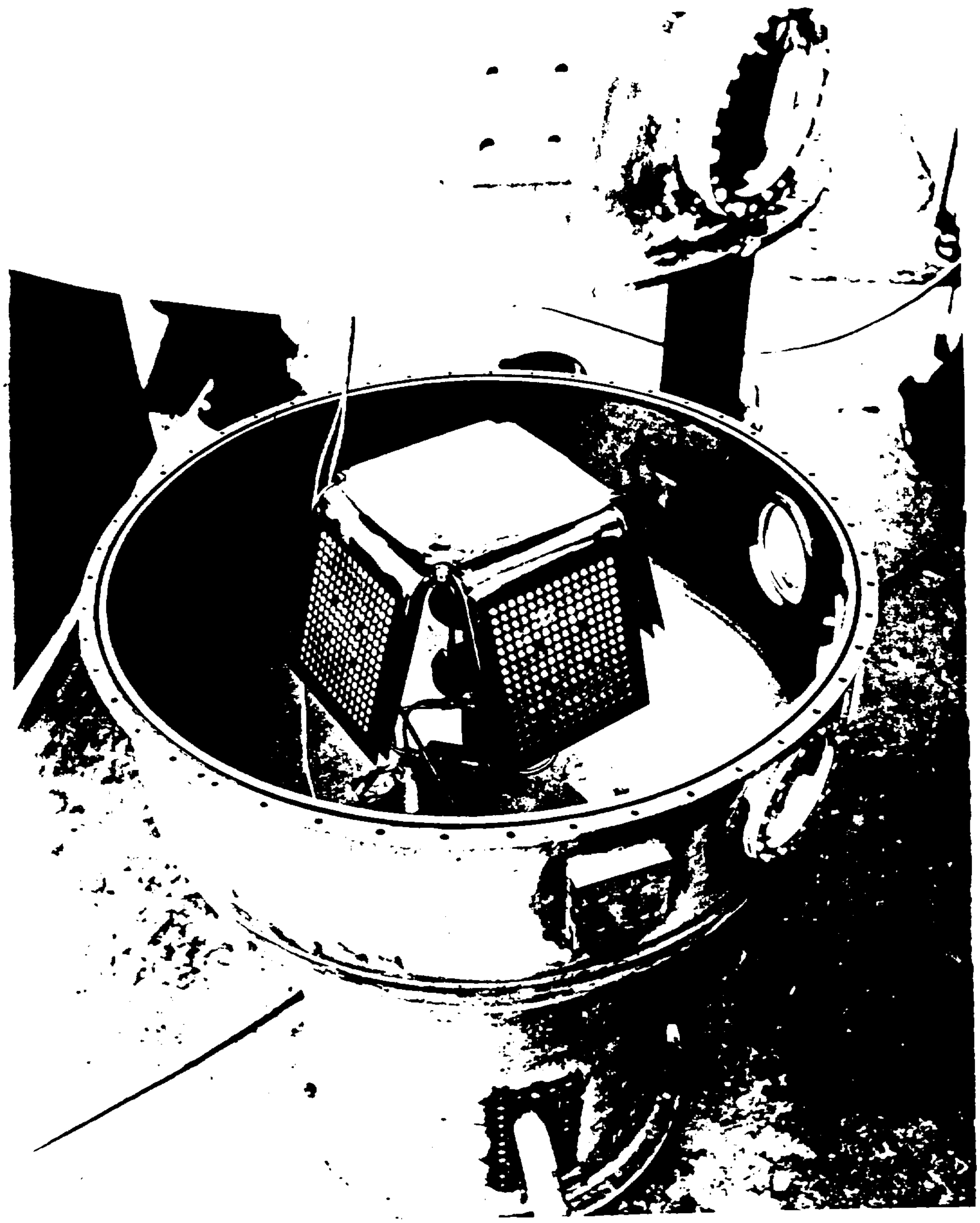


Figure 13 Cryogenic Liquid Acquisition Device known as a Start Basket.

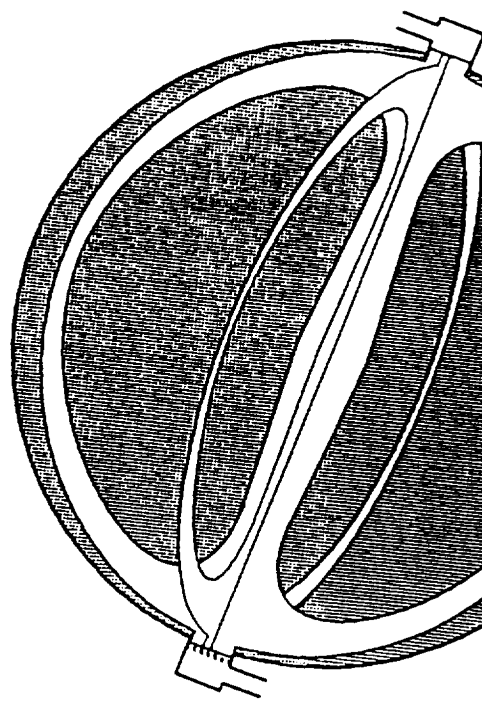


Figure 14 Vane concept for a Flexible Demand System. [11]

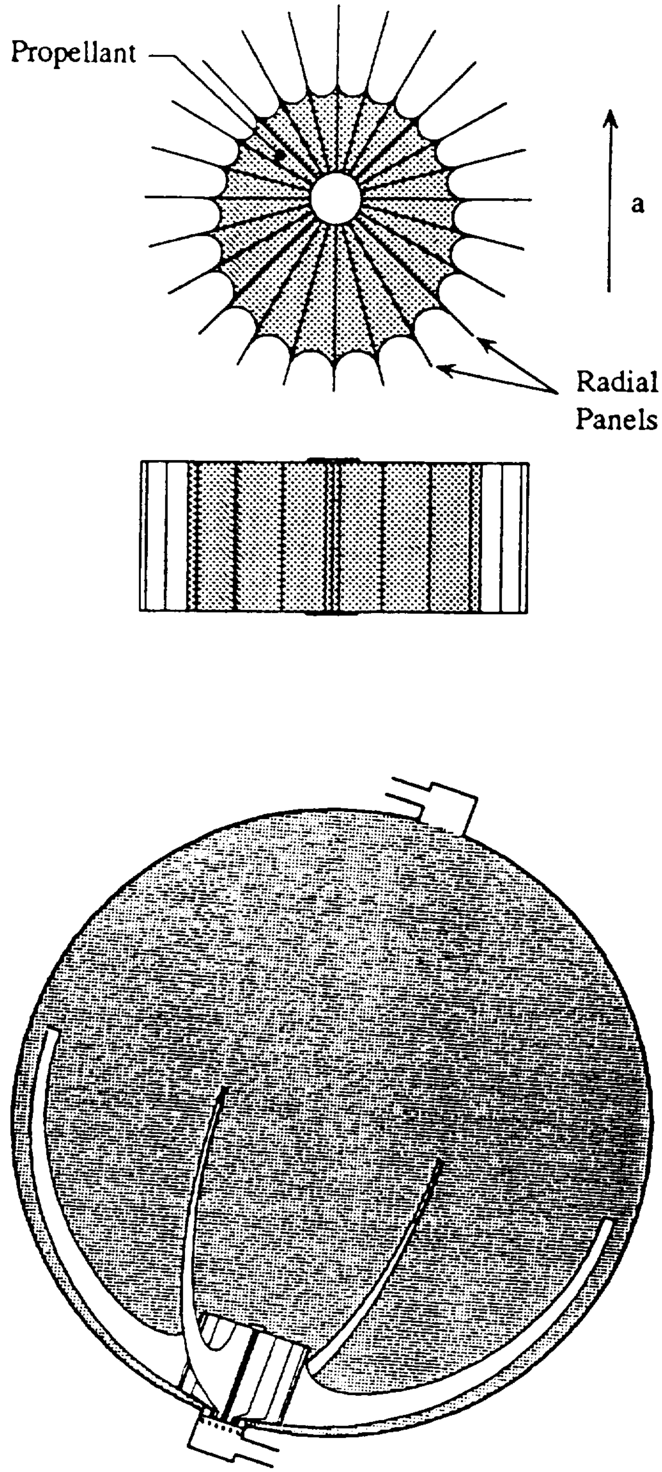


Figure 15 Vane concept for a Refillable Sponge System, and the Sponge system itself. [12]

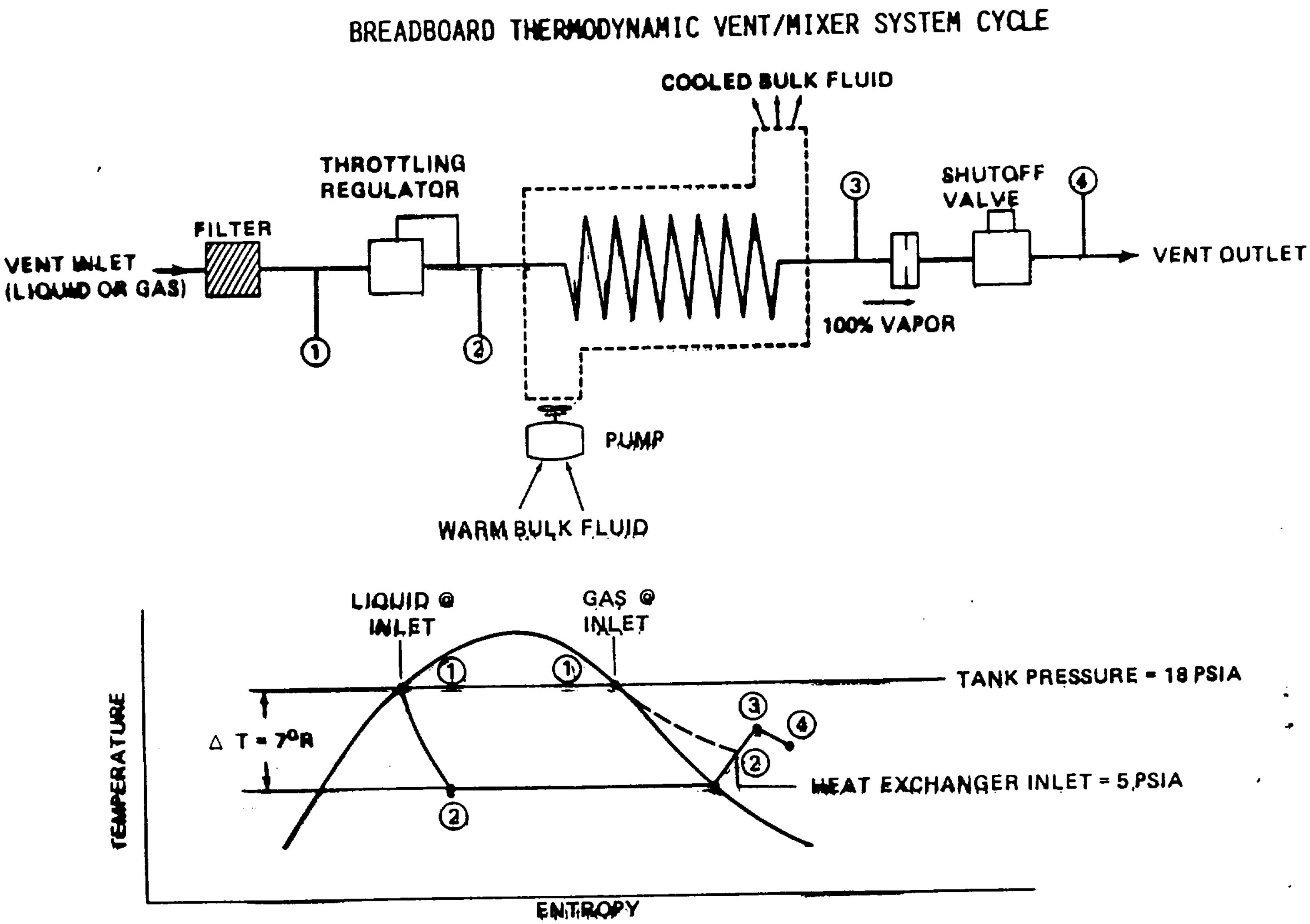


Figure 16 Depiction of a typical Thermodynamic Vent System (TVS).

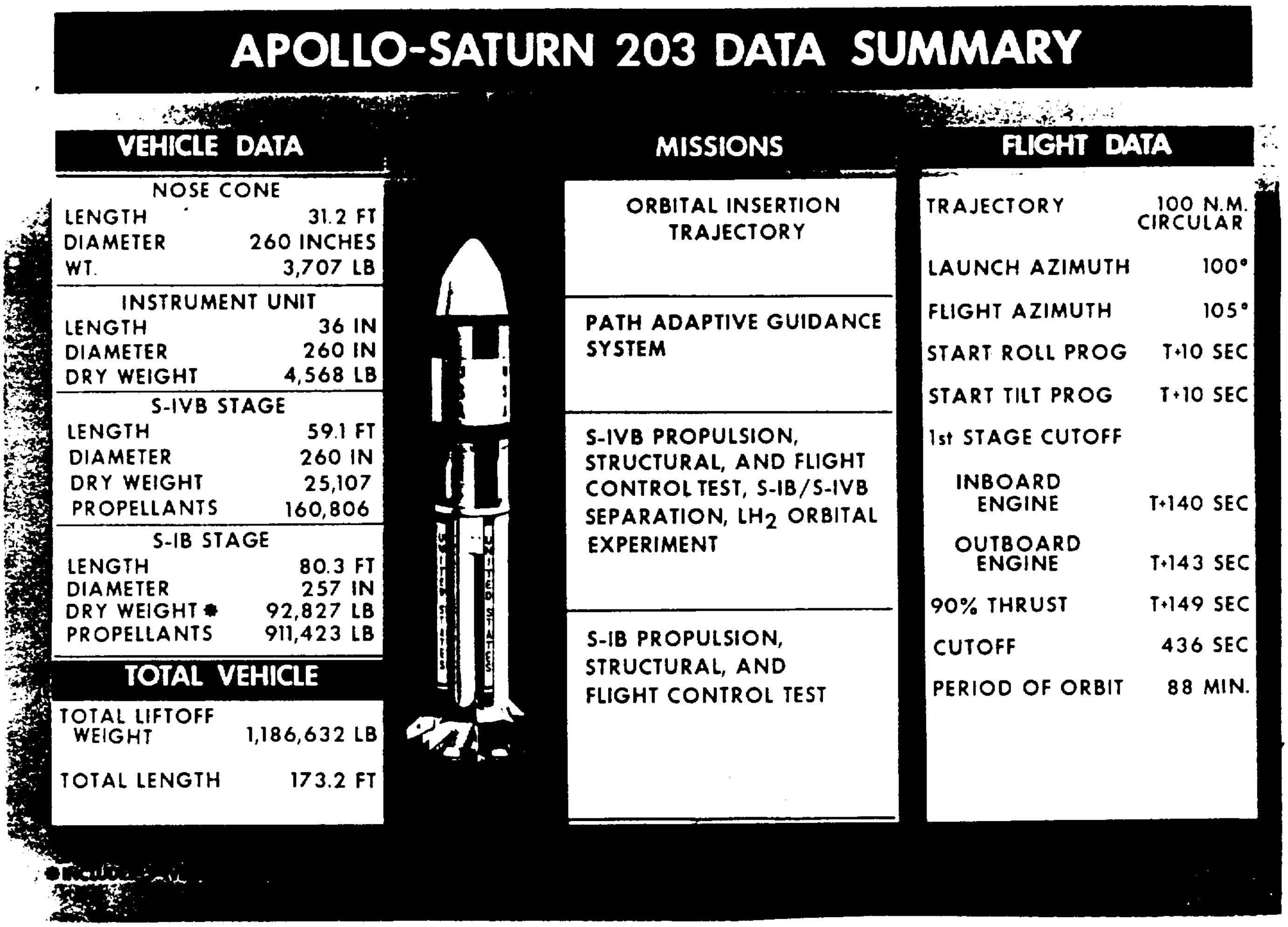


Figure 17 The modified S-1B for the dedicated Fluid Management Flight Experiment flight of AS-203. [13]

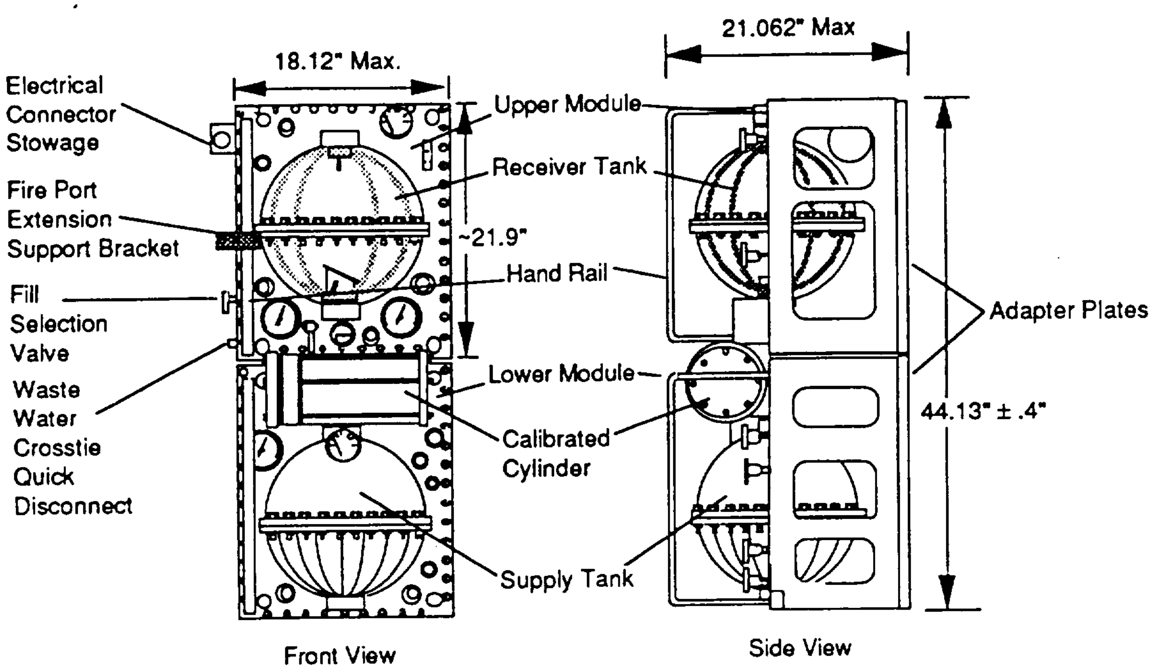


Figure 18 The Fluid Acquisition and Resupply Experiment (FARE I). [14]