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Propellant Management in Booster and Upper-Stage Propulsion Systems

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A summary review of some of the technical issues that surround the design of the propulsion systems for booster and upper stage systems is presented. The work focuses on propellant geyser, slosh, and orientation. A brief description is given with graphics that help the reader to understand the physics of the situation. The most common solutions to these problems are given with their respective advantages and disadvantages.

I. Introduction

THE design and analysis issues regarding the management and the thermofluid dynamics associated with rocket propellants are often underestimated when a rocket vehicle system is conceived. The issues often do not lend themselves to analytical solutions, and testing must be done. In addition, these problems are often geometry or mission specific. This requires full-scale or near full-scale testing in environments that are difficult to create in the test stand. When added to these issues, 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) has provided one method to at least approach 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 as to whether analysis alone provides enough insight into these problems to proceed without testing. Before testing, analysis, or detailed computer modeling can be undertaken, however, the potential problems must be recognized and addressed.

The objective of this paper is to summarize the major issues regarding propellant management in booster- and upper-stage propulsion systems. There are many issues that affect the propellants, such as tank insulation, which are beyond the scope of this work. This effort will concentrate on the traditional areas of vehicle design associated with propellant management. "Management" is defined as "the act of controlling the movement or behavior of."[1] The issues regarding managing propellants will be discussed herein.

II. Booster System Issues

Some of the physical issues regarding propellants that are being discussed in this paper manifest themselves at various times during the vehicle's mission profile. However, most of the issues tend to happen during particular phases of the operation. These phases include ground-hold, booster main engine cut off (MECO), booster–upper-stage separation, upper-stage MECO, and upper-stage engine restart.

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A. Geysering

The term "geyser" refers to the phenomenon occurring in a long vertical line, such as a booster's feedline, when the cryogenic propellant boils off at a rate exceeding a normal bubble release. This boiloff gradually allows the entire line to go dry. When the line becomes dry it is quickly refilled by 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 as a result of the propellant free-falling into the line and is analogous to water-hammer. The pressure surges that are created can be very large and can damage the feedlines and the line and valve supports, as well as the disconnects and engine.[2] There are three main areas on which we need to focus: 1) what is the physical phenomenon that causes this problem, 2) when is a geyser most likely to be a problem, and 3) what can be done to prevent it from happening?

1. *Geyser Physical Phenomenon*

The cryogenic propellant in the vertical line is in a subcooled condition, as referenced to the local static pressure in the line. Convective heat transfer occurs, transferring energy into the propellant, thereby increasing the temperature. The temperature increases until it reaches the saturation temperature corresponding to the local static pressure. When this condition is satisfied, either continued heat transfer will 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 and the purity of the cryogen.[2] Once the boiling begins, the resultant bubbles affect the line in two ways. The bubbles provide boiling centers, which will encourage further boiling. This will 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 at any point below the bubbles. The loss of head pressure, in effect, superheats the cryogen left in the line, resulting in the release of more vapor. This vapor in turn decreases the hydrostatic pressure and results in further superheat. This cycle continues, but does not cause a serious problem until the resultant bubbles interfere with themselves and their ability to release this pressure from the system. If we define A_V to be the bubble cross-sectional area and A_T to be tube or flow area, an important ratio (A_V/A_T) can be developed.

At A_V/A_T ratios of 0.55–0.6, the bubbles will begin to intermingle and will coalesce into 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, as the static pressure below the bubble decreases, causing more vapor to form. More and more vapor will be created,

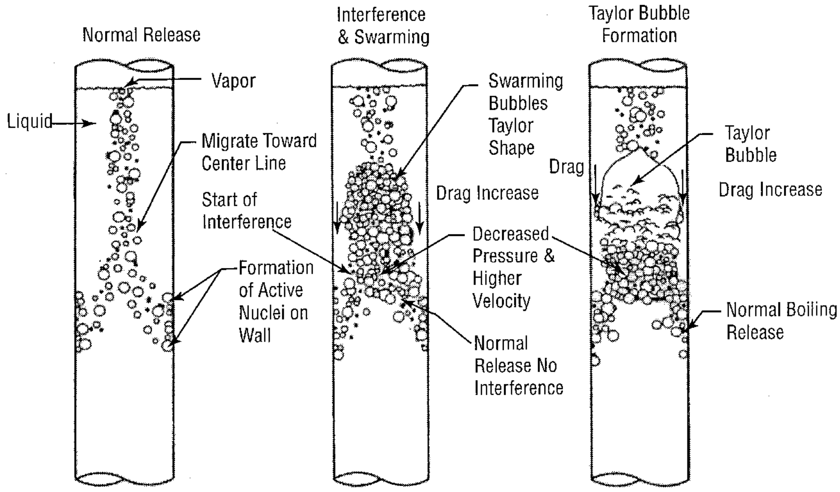


Fig. 1 Modes of vapor release in the Geyser phenomenon.[2]

provided that the rate of saturation temperature change because of the static pressure drop exceeds the rate of decrease in liquid temperature because of flashing. At some point the amount of vapor will be great enough to force the remaining cryogen out the top of the line and into the propellant tank, where it erupts through the liquid and into the ullage region. The resultant reaction occurs with some violence and is called a geyser.

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

The geyser phenomenon has two results. The first is that the geyser erupts into the ullage. When a quantity of cryogenic fluid is dispersed like this into the ullage volume, the ullage pressure decreases rapidly while the bulk temperature also decreases. The result is the same whether the pressurant is homogenous or heterogeneous. The rapid depressurization can cause the tank to collapse structurally. The second result is the damage resulting from the surge pressure in the feedline and the engine interface.[2]

2. When Geyser Occurs

The geyser phenomenon has been well documented[2] and a summary is provided here. The geyser phenomenon, as can be seen from the previous text, is strongly dependent on the physics of the bubbles and their movement 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 nucleation points. It should be noted that for a given pressure, a liquid must be warmer to evaporate into a small vapor bubble than it must be to evaporate into the ullage. This is because the surface curvature of a very small, newly formed bubble is great, so that the vapor pressure is substantially reduced. This, in turn, causes a temperature higher than saturation to be required.[3]

The nucleation points 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 before the onset of boiling. The fluid in this state can be considered unstable and any imbalance or disturbance will result in the rapid release of superheat (refer to Fig. 1).

The bubbles, as they develop, move toward the centerline, the region of lowest drag. The bubbles begin to coalesce in this region, although this effect is dependent upon the nature

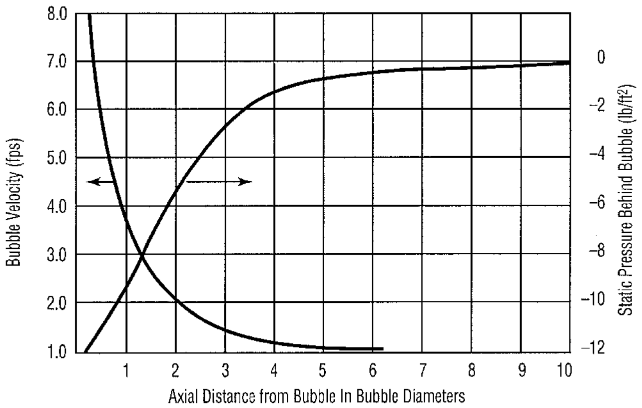


Fig. 2 Bubble separation distance vs velocity and pressure in the Geyser phenomenon.[2]

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 Fig. 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 cylindrical bubble with a spherical top. This last type is referred to as a Taylor bubble.[4]

This accretion of bubbles impedes the normal escape of vapor from the line because of the buoyancy effect. This impedance increases the drag forces to which the closely formed bubbles are subjected. The walls' proximity to the vapor mass also causes an increase in drag.

The makeup of the bubble mass and the escape mechanism are described in detail in Ref. 2.

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 that decreases the Taylor bubbles' velocity much less than a spherical bubble would encounter.

The presence of bubbles in vertical lines has two effects on the static pressure below. First, the viscous shear causes a reactive force that 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 head in the line as a result of the displaced liquid will be great, even though the corresponding change in tank liquid level is slight.

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, and 3) recirculation.

a. Controlled topping. In the preceding text, 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 noncritical. Thus, prior to the development of a critical condition, considerable evaporation in the feedline will occur. The analysis that has been presented states that topping inlet temperature versus flow rate required to hold the vapor-to-line-exit-area ratio must be less than 0.55.[2] 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 conditions, such conditions are unlikely given the agitated nature of the fluid under flow conditions.

Granting this caveat, it was determined that flow rates between 1 and 4 lb/s would suppress the geyser phenomenon with less than 3 deg of subcooling required at the inlet of the topping flow.

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 problem could be to require several degrees of subcooling. Topping is also not compatible with cryogenic loading-facility operations such as stop flow, revert/reinitiate, and engine-firing aborts. In these cases the topping flow to the vehicle must be stopped for uncertain periods of time, leaving the vehicle in a potential geyser situation.

b. Helium injection. The second method for preventing geyser involves the injection of helium (or another noncondensible gas) low in the feedline. This method has been utilized in a variety of vehicle applications [including the current space transportation system (STS) external tank (ET)], and has even been used for the densification of the liquid oxygen (LOX) as well as for geyser suppression.

The injected helium, being pure, has a partial pressure of zero for oxygen in the bubbles. The difference in the partial pressure of gaseous oxygen (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 localized cooling because of the absorption of heat of vaporization from the surrounding fluid. The cooling that occurs is equivalent to the heat of vaporization multiplied by the mass of LOX vaporized. This cooling lowers the bulk liquid temperature. This subcooling 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, preventing the geyser phenomenon. 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 subcooling the bulk propellant. The injection of a small amount of the noncondensible helium gas also has the benefit of significantly reducing the acoustic velocity by reducing the bulk modulus of the mixed noncondensible gas and cryogen. This reduction in acoustic velocity should reduce pressure surges during refill.

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 measuring the accuracy of the propellant load. Additionally, such a system is an active one, requiring more complicated ground operations that could create more expense per launch.

c. Recirculation. The next method for geyser suppression is recirculation. This method lends itself to use in the vehicle configuration involving two or more LOX lines. It is apparent that the key to stopping the accretion of superheat in the feedline is to eliminate the heat as it enters. The LOX system of a vehicle's tank and run duct can provide a somewhat efficient refrigeration system that uses the passive thermal siphon principle.

As the heat is transferred through the tank wall, natural convection currents transport the warmer LOX forward toward the liquid surface where, after boiloff 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 (Fig. 3), 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 more quickly, the density will decrease, and the propellant, moving from a region of higher to lower density, will displace the warm LOX from the line into the tank. The convection process just described 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 continue. Testing on such a system has shown that it behaves in a cyclic or periodic manner, 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 because of 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 similar method for geyser prevention was part of the Space Shuttle in early ETs; such a configuration flew on STS-1 through STS-6. A small line was attached to the feedline both above and below.[5] Helium gas was injected in the small line to create the density difference, thereby producing recirculation flow. This line was referred to as the antigeyser line (see Fig. 4) and was later removed to simplify the configuration and reduce the hardware cost.

One of the reasons the geyser phenomenon exists in launch vehicles is that the vehicles' flight dynamics require that the heaviest propellant be stored forward (in some vehicles an aft

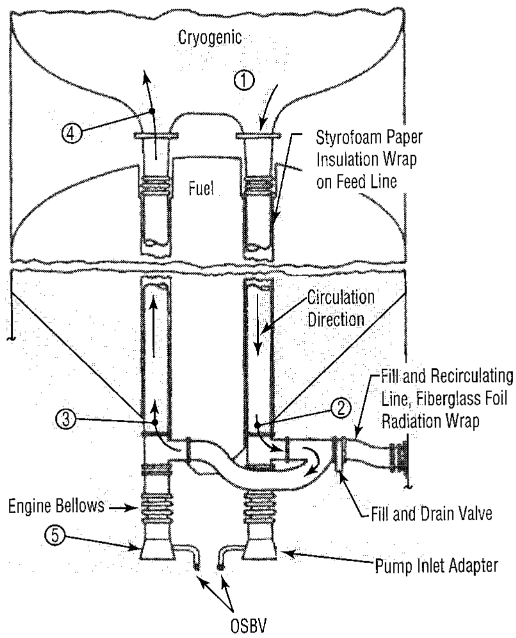


Fig. 3 Cryogenic recirculation system in a two-run duct configuration.[2] Representative temperatures for liquid oxygen (°F): 1, −295; 2, −293; 3, −291; 4, −288; and 5, −290.

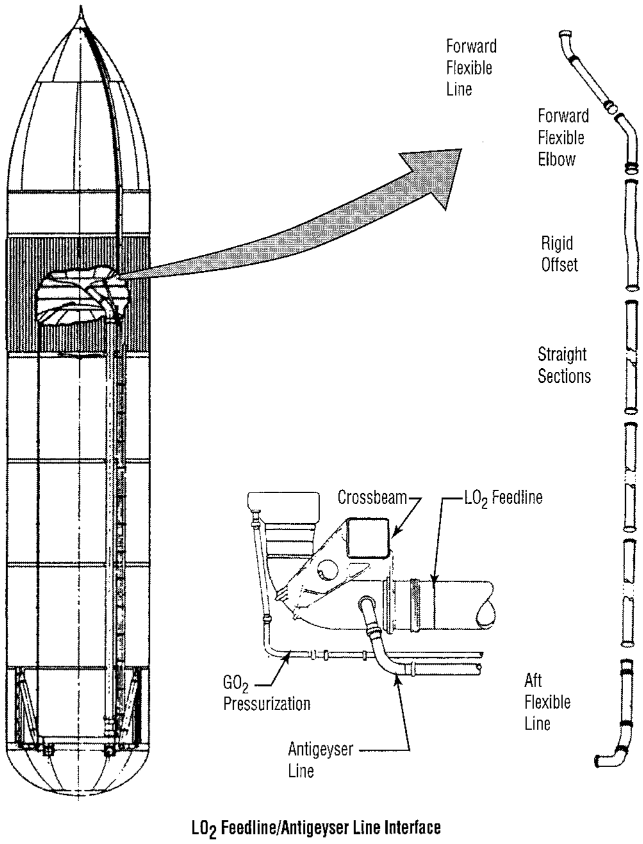


Fig. 4 Antigeyser line configuration on the Space Shuttle ET.[5]

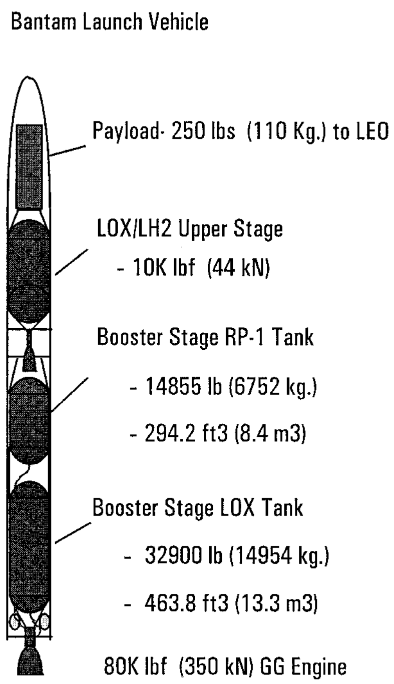


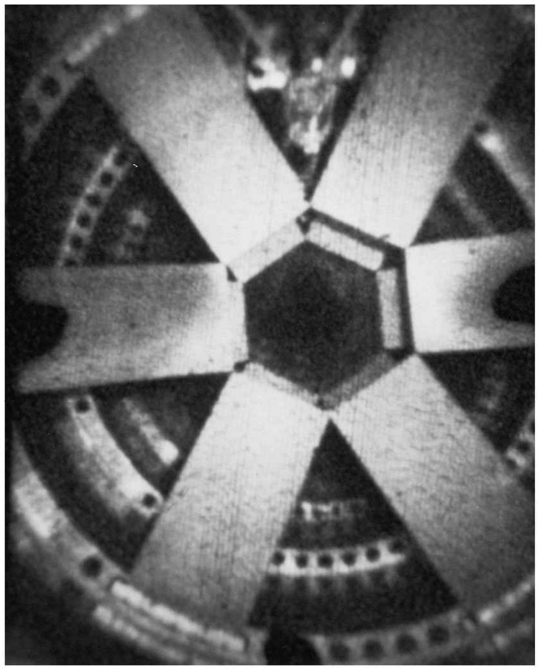
Fig. 5 Prototype booster configuration with LOX tank aft, aiding the elimination of the geyser phenomenon.

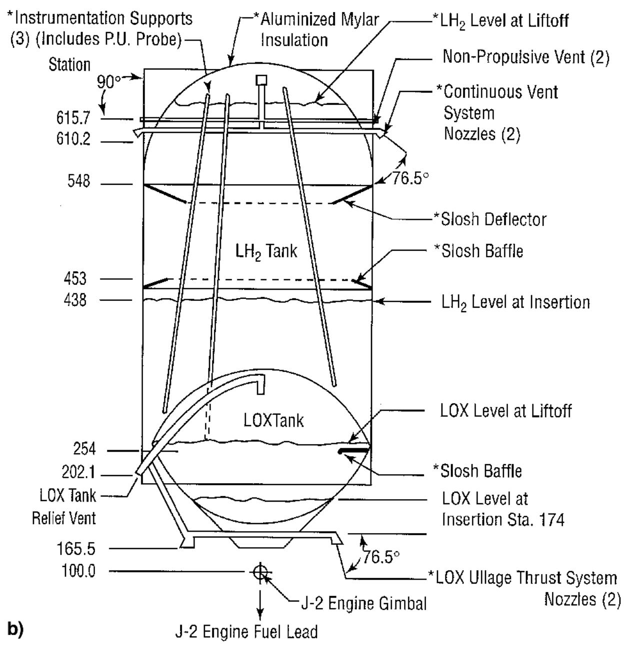
LOX tank requires unacceptably large gimbal angles). In the U.S. LOX is widely used for the vehicles' oxidizer. LOX, with its cryogenic properties and high density, is highly susceptible to the geyser phenomenon. If the vehicle dynamics allow, and LOX can be stored aft, the geyser problem may thus be eliminated (Fig. 5).

B. 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 gs, the slightest disturbance may result in slosh that in turn can have a serious effect upon the stability of the vehicle. In the worst cases, where the launch vehicle's guidance system cannot control the changes caused by 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, e.g., the fundamental body-

a)





b)

Fig. 6 Depiction of the use of ring baffles to prevent slosh dynamics on the a) Saturn 1B and b) Saturn V/S-IVB vehicles.[12]

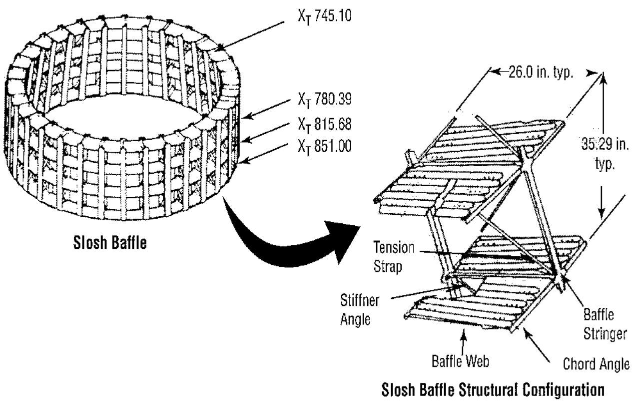


Fig. 7 Depiction of the use of ring baffles to prevent slosh dynamics on the Space Shuttle ET.[5]

bending mode or to the natural frequency of a control sensor, then it can be very difficult to predict and resolve the problem. Therefore, in the case of an ascending launch vehicle, the analysis of dynamic stability and control and their effect on the oscillatory nature of the propellant must be understood.[2]

1. Fundamental Theory

The fundamental theory behind the slosh can be shown with a simple mathematical model based on a linearized potential theory, modeling the propellant as incompressible, irrotational, and nonviscous. The analysis (developed in Ref. 2) shows that the natural frequency of the propellant is therefore

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

where the variables are f_n = natural frequency of the propellant, g = longitudinal acceleration, a = tank radius, ε_n = zero's of Bessel function, and h = liquid height. 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 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, such as 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. Damping

To minimize the amplitude of the slosh caused by these inflight excitations, a method to increase the damping of the system must be employed. The most common method for damping is the use of ring baffles (Figs. 6 and 7) attached to the interior of the tank walls. Tests have shown that the damping provided by the baffles decreases with the depth at which the baffle is located under the surface of the liquid.[6]

III. Upper-Stage System Issues (Low-*g* Propellant Issues)

The problems associated with upper-stage systems are slightly different from those associated with 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.

A. Liquid Slosh at MECO

The first issue to be dealt with is slosh. The only difference between slosh in the booster and this case is that slosh in the upper stage does not occur while under the longitudinal acceleration vector, but at MECO, when the acceleration of the vehicle transitions to zero, often rather abruptly. Liquid sloshing amplitudes that remain damped during powered flight may attain 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 difficulties, 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 onboard a Saturn launch vehicle. The ground experiments utilized the 4.3-s drop-tower facility at NASA Marshall Space Flight Center. 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 that occurs at MECO is shown in Fig. 8. The solution is again the use of ring baffles. The use of CFD has been shown to predict accurately the resultant fluid motion in low gravity. A commercially available software package was used to generate the plots shown in Fig. 8; the resulting accuracy was evident.[7]

In addition to this work, an excellent study of low-gravity fluid behavior involving comparisons between drop-tower, KC-135 flight tests and several analytical models was performed by Yeh and Orton.[8] The work centered around analytical models to predict stable equilibrium liquid-free surface shape, transient liquid reorientation characteristics, and liquid settling and slosh dynamics. These codes, including FREES, REORTN and the well-known SOLA-VOF are verified by low-*g* testing. The drop-tower experiments were performed at the University of Santa Clara. The tower had the capability for 2 s of low-*g* data with test articles up to 3.6 in. in diameter. The test fluid was colored distilled water with a wetting agent. In addition, a series of zero-*g* fluid experiments were performed on the NASA Johnson Space Center KC-135 aircraft. These tests allowed for larger-scale test models and longer-duration, low-gravity data. The test articles were up to 8 in. in diameter and utilized Solvent 160 dyed blue. As in Ref. 9, the results of the analytical models correlated well with the experimental data. These analytical tools are useful for predicting fluid behavior under zero/low-*g* conditions and for assisting in fluid management systems design.[8]

B. 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 having 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 usable liquid and, therefore, the positioning of the ullage bubble over the vent is required.

1. Liquid Acquisition

It is critical to ensure that liquid be 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).

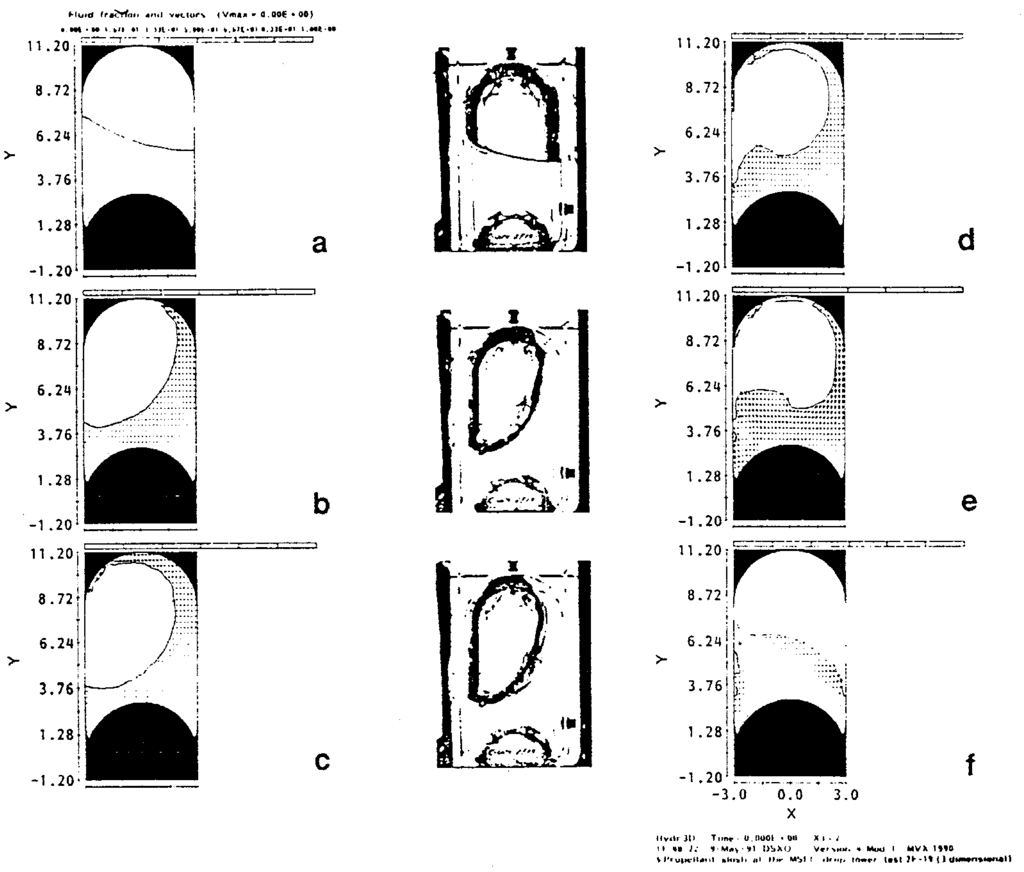


Fig. 8 Drop-tower results of the S-IVB model showing fluid behavior.[7]

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 that would cause a bond number (B_O) greater than 70 in the liquid hydrogen tank. Bond number is the ratio of inertia forces to surface tension forces and is expressed by the following relation:

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

This system's ability to perform was proven in the flight of AS-203. 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 (I_{sp}). For a hydrogen engine the I_{sp} would be in the range of 360–460 s during the start transient, which results in extremely high bond numbers (~2000–5000), and a resultant force that may result in problems with the liquid dynamics or the vehicle control. The engine that would be utilized for the THI system would have to be capable of utilizing propellants ranging anywhere from 0–100% gas to 0–100% liquid or any combination as the propellants became settled. Such a method has not been proven in flight, and still requires development.[9]

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 that allows the propellant to wick in to the engine inlet (Fig. 9). One of the disadvantages is the extra weight of such a system.

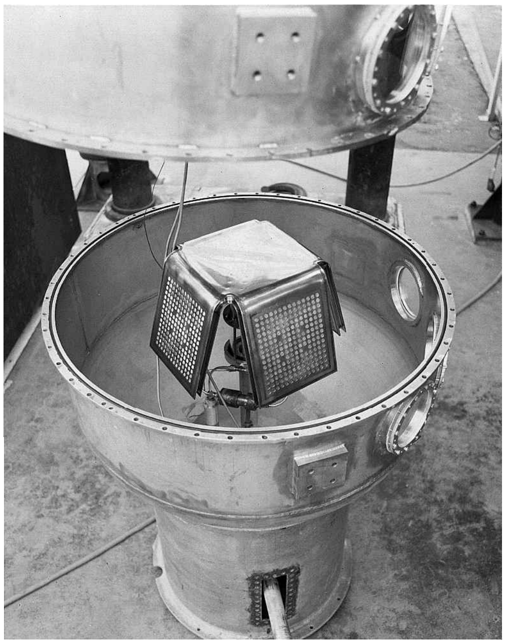


Fig. 9 Cryogenic liquid acquisition device known as a start basket.

Another capillary device that is utilized in the storable propellant arena is a vane. A vane is a structure adjacent to the tank wall that creates an open passage, through which propellant can flow. Because all propellants "wet" due to their surface tension properties, the fluid forms along the structure (Fig. 10). The device's advantages are light weight, high reliability

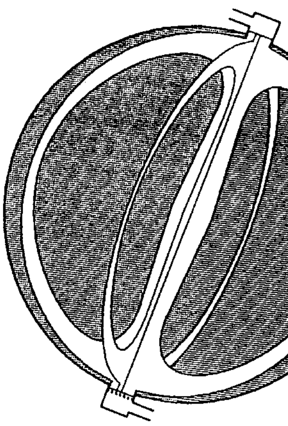


Fig. 10 Vane concept for a flexible-demand system.[10]

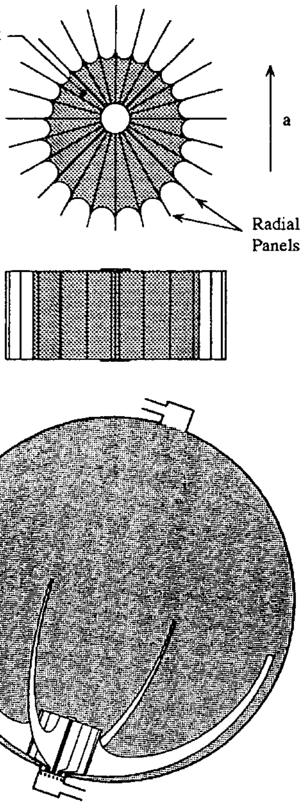


Fig. 11 Vane concept for a refillable sponge system, and the sponge system itself.[11]

(no moving components), and material compatibility with most propellants (100% titanium designs are possible). The use of vanes, however, is 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.[10]

A sponge is an open structure of tightly spaced radial panes of metal that holds the propellant by the surface tension effect (Fig. 11). Again, these devices are reliable and can be used in a multitude of propellants, but they 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 stationkeeping maneuvers (repeated use of a certain propellant amount), and 3) vehicle systems requiring control of the propellant's c.g. while in low *g*. Sponges have been used in monopropellant and bipropellant systems.[11]

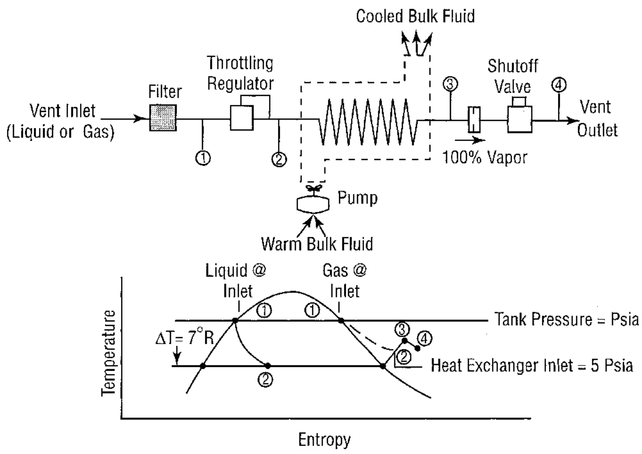


Fig. 12 Depiction of a typical TVS.

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; for low-gravity conditions however, 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 1960s. The device, known as a thermodynamic vent system (TVS), can be utilized in an active or a passive mode (Fig. 12). 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 that accompanies the passive system. The heat dissipation because of 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. The TVS also has applications for the long-term storage of cryogenic propellants on-orbit.[9]

IV. Perspective

The technical issues that have been reviewed in this paper have caused concern among launch vehicle designers since 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[12] (Fig. 13). Another example is the Shuttle flight experiment called FARE, Fluid Acquisition and Re-supply Experiment (see Fig. 14), which flew in 1992 using a reference fluid to examine on-orbit fluid behavior.[13] Although it has been over 40 years since the design of the Redstone and over 20 years since that of the Space Shuttle, many of these issues and their resolution have received little attention. As new launch vehicle systems are designed and tested, the physics will once again bring these issues to the forefront. One of the purposes of this paper is to present a 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 George Santayana said "Those who cannot learn to remember the past are condemned to repeat it."[14]

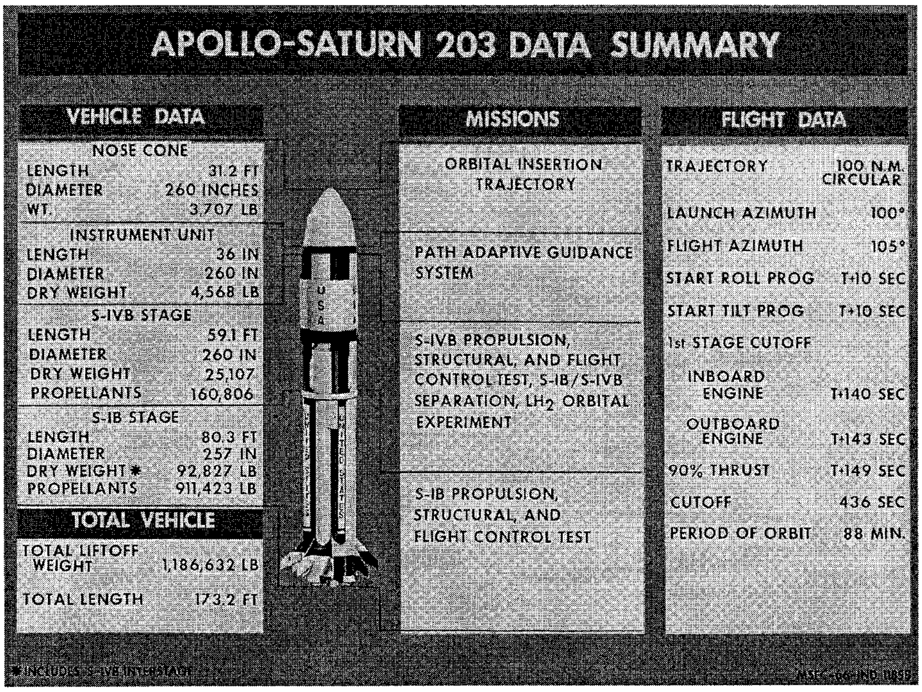


Fig. 13 Modified Saturn 1B for the dedicated fluid management flight experiment, AS-203.[12]

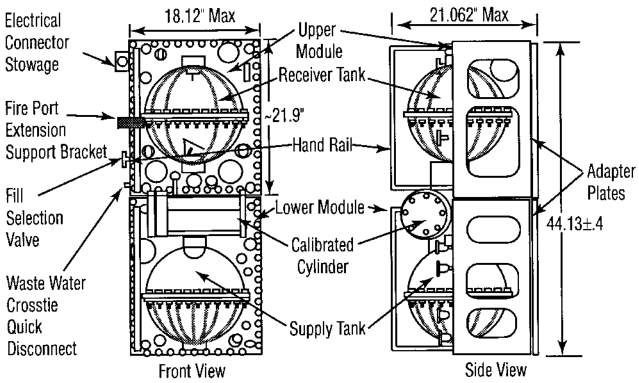


Fig. 14 FARE I.[13]

V. Conclusions

The technology associated with the design of propulsion systems must not be underestimated at the inception of a project. The proper attention in terms of manpower, schedule, and budget should be made available for analysis, and systems testing of the propulsion system as a whole, for the problems that the vehicle will encounter will be of one component or subsystem and its effect upon another. Recent advances in fluid and structural analysis techniques help the situation but are not a substitute for systems testing.

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