Terminal Drainage for the Space Shuttle External Tank

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Maximization of the Space Shuttle external tank mass fraction dictates that nonusable propellant in the tanks and propellant feedlines, at propellant depletion, be minimized. To achieve accuracy and confidence in predictions, an experimental program was conducted to evaluate the influence of the tank outlet-feedline configurations on nonusable propellant at propellant depletion. Test results, when correlated to flight conditions, show that: 1) a contoured outlet minimized nonusable propellants in the LO_2 tank; 2) a contoured siphon outlet minimized nonusable propellants in the LH_2 tank; and 3) the configuration of the feedline and outlet influence the nonusable propellants in the feedline.

Nomenclature

a	= acceleration
a_1	= empirical constant
b	= empirical constant
c, c_1	= empirical constant
d	= length variable
d_1	= empirical constant
ET	= external tank
h	= dropout height
h_L	= length of liquid-gas interface
K	= empirical constant
L_{eff}	= effective length
LO_2	= liquid oxygen
LH_2	= liquid hydrogen
n	= empirical constant
N_{FR}	= Froude number
N_{RE}	= Reynolds number
SRB	= solid rocket booster
SSME	= space shuttle main engine
V	= velocity
$\dot{w}$	= flowrate
ρ	= density

Subscripts

ET	= external tank
M	= test configuration

Introduction

A REUSABLE space launch vehicle that will become operational in the late 1970's is being developed by NASA. The primary advantages of this vehicle are the reduction in transportation costs to and from orbit inherent in a reusable system, plus its versatility for performing a wide range of missions. As presently configured, the Space Shuttle consists of a reusable orbiter, reusable solid rocket boosters, and an expendable external tank. The external tank provides cryogenic propellants (LO_2 and LH_2) to the orbiter main engines from liftoff until termination of the main engine burn, at which point the ET is staged from the orbiter. Separate compartments in the ET will be used to store approximately 1.55 million pounds of LO_2 and LH_2 (Fig. 1). The tank itself includes the propellant feedlines, valves, and pressurization system lines, as well as the controls for interfacing these with the orbiter.

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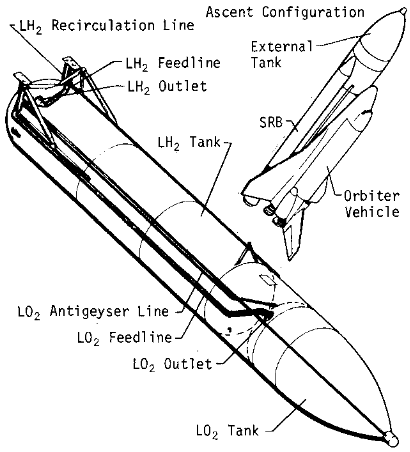

Fig. 1 Propellant feedline elements.

The overall mass fraction of the Space Shuttle is closely related to the mass fraction of the ET. As a result, maximizing the ET's mass fraction (i.e., the total weight of propellant at liftoff—including the flight performance reserves—divided by the gross weight of the tank) is a major design goal. One way to increase this mass fraction is to decrease the amount of nonusable propellant in the ET at orbiter-ET staging. Maximum use of the on-board propellant is a direct function of the ability to completely drain the propellant tanks prior to SSME shutdown. However, the potential for ingesting ullage gas into the feedline (i.e., dropout‡) is high during this period because of the imbalance between the gravitational and inertial forces acting on the propellant. The amount of propellant remaining in the tank when the ullage gas is ingested into the propellant feed system is nonusable propellant.

The LO_2 feedline contains approximately 11,000 lb of propellant at the inception of dropout. Optimizing the ET mass fraction requires that this propellant be drained without entraining gas even though ullage gas has already been ingested at the tank outlet. Maximizing the mass fraction of the ET therefore requires that careful attention be paid to the design of the LO_2 and LH_2 tank outlets and feedlines in order to minimize the amount of nonusable propellant at SSME cutoff.

A number of analytical methods are available to predict the amount of nonusable propellant associated with a specific outlet design and terminal drainage conditions, but these methods do not account for feedline effects downstream of the outlets and are sensitive to outlet-tank configuration relationships. Because of the inadequacies of existing methods, an experimental program was conducted to optimize the outlets and feedlines of the ET and minimize

‡Liquid dropout, which is a depression in the liquid surface at the center of the outflow line, is undesirable because it causes gas to enter the feedline with propellant still remaining in the tank.

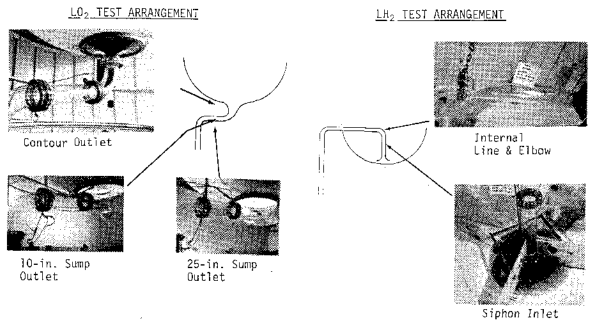

Fig. 2 ET scale-model test configurations.

Table 1 ET test configuration correlation

Parameter	External tank	Test configuration
Line diameter	17 in. (LO_2 line)	5.5 in. line (approx. ⅓ geometric scale)
Tank diameter	304 in.	120 in. (approx. ⅓ geometric scale)
Acceleration	3g (0.75%F)	1g (scaled by Froude no.)
Flowrate	1980 lb/sec (LO_2)	54 lb/sec (scaled by Froude no.)
	360 lb/sec (LH_2)	157 lb/sec (scaled by Froude no.)
Line configuration	n/a	same
Froude number	2.3 (LO_2)	same
	19.6 (LH_2)	same
Reynolds number	$1 \times 10^7 (LO_2)$	$1 \times 10^3 - 3 \times 10^5$

nonusable propellant. The specific objectives of the program were to: 1) determine the amount of nonusable propellant as a function of the configuration and operating conditions of the propellant feedlines and tank outlet; 2) determine the draining characteristics of the oxidizer and fuel feedlines as a function of their configurations and operating conditions; and 3) determine the relationship between the onset of two-phase flow (i.e., dropout) and the configuration of the tank outlet.

Experimental Investigation

For previous U.S. space launch vehicles, both analytical techniques and scale-model tests have been used to optimize outlet designs. The general approach has been to use existing analytical techniques to establish the initial design, and to verify the design in a scale-model simulation, using subsequent flight data to modify and improve the analytical model. A detailed review of previous programs resulted in two conclusions: the effect of feedline geometry below the tank outlet had not been considered; and the available experimental data were not applicable to the design of the ET. To overcome these shortcomings, a new experimental investigation was conducted using a scale model of the propellant feed systems for the LO_2 and LH_2 tanks.

Existing data indicate that the shape of the aft dome of the tank and the position of the outlet relative to the tank's longitudinal axis are significant factors in determining the performance of the outlet. The LO_2 and LH_2 feedlines for the ET, shown in Fig. 1, are not simple configurations. The LO_2 feedline consists of an elbow adjacent to the tank outlet and a nearly horizontal section connected by a second elbow to a 100-ft vertical section. Design requirements dictate that the elbows have a ratio of bend radius-to-diameter equal to 1.5 and that the maximum slope of the line between the tanks be 9°. The LH_2 feedline contains both horizontal and vertical sections, in addition to elbows. The short length of this line and the low density of LH_2 allows this line to remain filled at terminal drainage without significantly affecting the mass fraction of the ET. However, the effect of this line's configuration on the initial gas ingestion height for the outlet must be known.

A preliminary analysis of the weight and envelope design constraints for the ET indicated that two different types of tank outlets should be used. The design requirements for the LO_2 tank could be satisfied by using an outlet attached to the exterior of the aft dome parallel to the tank's longitudinal axis. In contrast, the optimum outlet-feedline configuration for the LH_2 tank is a siphon outlet mounted within the tank, above the aft dome parallel to the tank's longitudinal axis. Consequently, both contoured and sump outlets were investigated.

The contoured outlet for the LO_2 tank was designed using a previously verified analytical technique[2,3] which simultaneously suppresses cavitation and dropout. The contoured outlet for the LO_2 tank, shown in Fig. 2, was configured using the terminal drainiage conditions of Table 1.

A review of existing literature did not reveal any directly applicable analyses for the design of a nondropout sump outlet. References 4-6, although not directly applicable, formed the basis of our LO_2 sump configuration. These references indicate that a design based on a sump-to-feedline Froude number ratio of 0.50 is acceptable, and that the dropout heights for a cylindrical sump with a cylindrical side outlet can be correlated by an equation of the type:

$$h/d = a_{l_{\text{tank}}} (b\, N_{FR}{}^{c}) \tag{1}$$

or

$$h/d = d_l (N_{FR})^{n} \tag{2}$$

where h is the dropout height, d is the diameter, and a_l, b, c, d_l, and n are empirical constants.

Two sump outlets (Fig. 2) were designed using the ET terminal drainage conditions presented in Table 1 as input parameters. Different sump diameters were used to define the effect of $N_{FR_{\text{sump}}}/N_{FR_{\text{feedline}}}$ on the initial dropout height relative to the tank bottoms.

A dimensional analysis approach was used to define the test conditions to be simulated. Since the process by which a liquid drains from a tank, at or near depletion, in a gravitational environment is characterized by the Froude number, the terminal drainage conditions for the ET could be duplicated in 1-g scale-model tests by maintaining N_{FR} similitude between the test configuration and that of the full-scale ET. Additional analysis indicated that the flow in the feedline was also a function of N_{FR}.

Similitude between the test model and the ET was maintained using the relationships:

$$N_{FR_{\text{ET}}} = N_{FR_M} \tag{3}$$

and

$$N_{FR} = \frac{\text{Gravitational Forces}}{\text{Inertial Forces}} = V^2/ad \tag{4}$$

where V is the velocity, a is the acceleration, d is the length variable, and the subscripts ET and M refer to the external tank and test configurations, respectively.

The length variable in Eq. (4) can be defined either as the feedline diameter or the tank diameter. Defining it as the feedline diameter makes N_{FR} constant until dropout occurs. Consequently, the diameter of the feedline was selected as the length variable in determining the scale factor for the test model. The optimum feedline for the test hardware had an internal diameter of 5.5 in., which resulted in a scale factor of 0.3235.

Table 2 Test configuration conditions

Feedline diameter	5.5 in.
Tank diameter	10 ft
Simulation fluid	water
Shape of tank dome	√2 elliptical
Feedline material	Plexiglas

Table 3 Test conditions

Test no.	W_{design}, gpm	W_{test}, gpm	Froude no. (design)	Froude no. (test)
A1	304	282→ 385	1.15	1.2→ 1.5
B1	430	335→ 480	2.3	2.5→ 2.9
C1	859	830→ 965	9.2	8.6→11.7
D1	1215	1110→1250	18.4	15.6→19.1
E1	1489	1230→1325	27.6	19.1→22.0
F1	Max	1290→1420	n/a	20.9→25.9

For the terminal drainage conditions shown in Table 1, the Froude number for the LO_2 tank is 2.29 and the corresponding Froude number for the LH_2 tank is 19.6. The required flowrates for the tests were determined from Eq. (4), the model scale factor, and the following equation:

$$\dot{w} = \frac{\pi\rho}{4}\left(d^5 a N_{FR_{ET}}\right)^{1/2} \quad (5)$$

where $\dot{w}$ is the flowrate, ρ is the density of the fluid, d is the feedline diameter, and a is the acceleration.

The flowrate required to simulate the N_{FR} for the LO_2 tank was 430 gpm (54 lb/sec), and that for the LH_2 tank was 1245 gpm (157 lb/sec). The correlation between the parameters for the ET and the scale model is summarized in Table 1.

The geometry of the LO_2 and LH_2 tanks was simulated by using a 10-ft-diam cylindrical tank with a √2 elliptical dome similar to that proposed for the ET tank domes. The use of this tank permitted an approximate simulation of the tank dome-outlet geometry, which the pretest analysis showed was important. Figure 2 depicts the test configuration of the LO_2 and LH_2 tanks, tank outlets, and feedlines.

Water was used as the test fluid. A gravity flow system was used since the variable flowrate enables N_{FR} similitude to be maintained without pressurizing the system. All feedlines and outlets were fabricated from Plexiglas so that high-speed photography could be used to record the flow conditions within the system. The test configuration conditions are summarized in Table 2.

The data obtained from the tests included high-speed photographic films, flowrates, pressures, and temperatures of the fluid. Six interconnected cameras were used to provide complete system coverage. The flowrates and temperatures were continuously recorded on analog recorders during each test.

The outlet/feedline configurations were tested over a range of conditions that allowed the performance of the outlet to be determined at off-design conditions. A comparison of predicted and actual test conditions is presented in Table 3.

The photographic data from each test were used to determine the occurrence of dropout within an accuracy of ± 0.0083 sec, and the temperatures and flowrates were used to establish the exact values of N_{RE} and N_{FR} at dropout for a specific outlet configuration. In addition, the liquid-gas mixing length in the feedline during terminal drainage was determined for each configuration at identical vertical positions within the feedline to eliminate the effects of time-dependent flow changes when determining the length of two-phase flow.

Results

Initial tests with the vertical feedline were used to isolate the effects of flow conditions in the vertical feedline from effects caused by the tank outlets and horizontal feedline sections. These tests were designed to eliminate flow initiation-induced distortions of the liquid-gas interface. A subsequent analysis of the interface data showed that the length of the liquid-gas interface (i.e., liquid-gas mixing length was strongly dependent on N_{FR} and less dependent on N_{RE}.

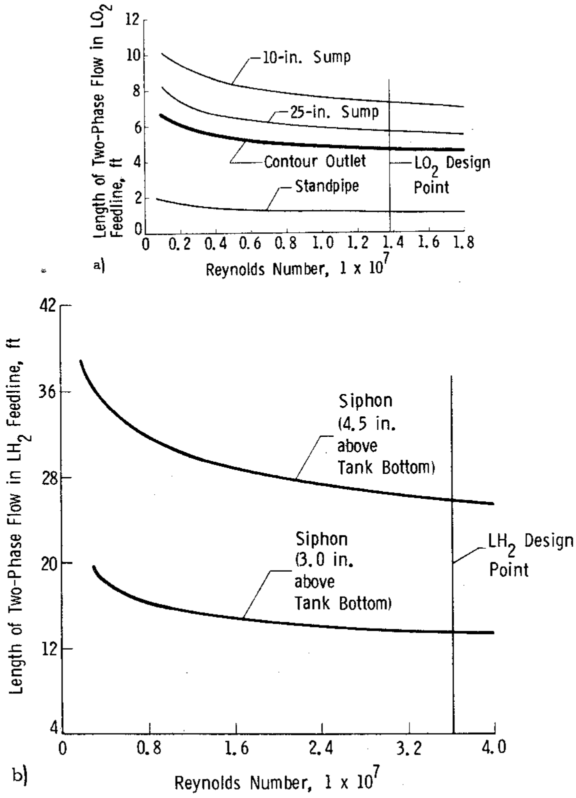

Fig. 3 Length of two-phase flow in a) LO_2 and b) LH_2 feedlines.

Contour Shape

The results of these tests indicate that, for the LH_2 feedline, the contour of the siphon inlet has less effect on the length of the liquid-gas interface in the feedline than that for the LO_2 feedline. In all cases, the sump yielded a significantly longer feedline interface than the contoured outlet.

Interface Length

The interface lengths (liquid-gas mixing lengths) for the outlet/feedline configurations were compared using the following relationship to correlate the test data:

$$h_L = 0.5 C_l L_{eff} N_{FR} (0.0032 + 0.221 N_{RE}^{-0.237}) \quad (6)$$

where h_L is the length of the liquid-gas interface, C_l is an empirical constant, and L_{eff} is the effective length of the straight pipe, including bends and inlet effects. This correlation was subsequently used to predict the interface lengths shown in Fig. 3.

A comparison of the data for the vertical feedline with those obtained for the outlet/feedline configurations shows that the horizontal feedline sections and elbows in the LO_2 and LH_2 feedlines significantly influence the length of the liquid-gas interface. A similar comparison for the sump and contoured outlet indicates that the contour has negligible effect on the length of the interface. The interface length for the sump outlet/feedline configuration increase as the sump diameter decreases.

Dropout

The level of liquid in the tanks for each outlet/feedline configuration at the initiation of dropout is presented in Fig. 4 as

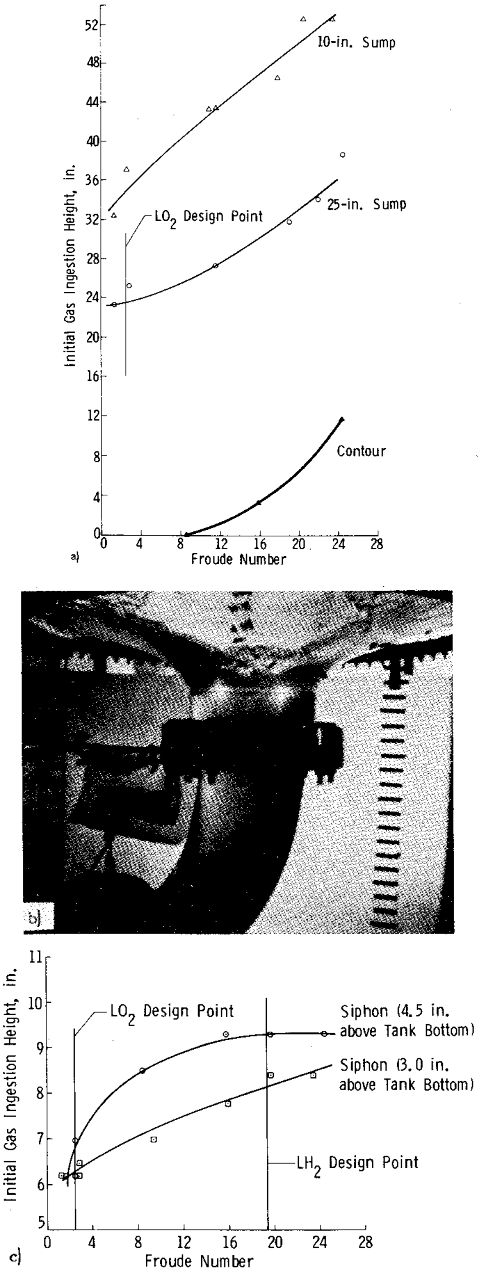

Fig. 4 Initial gas ingestion heights for LO_2 and LH_2 tank outlet designs: a) tank outlet designs; b) gas ingestion height for LO_2 contour outlet; c) siphon outlet designs.

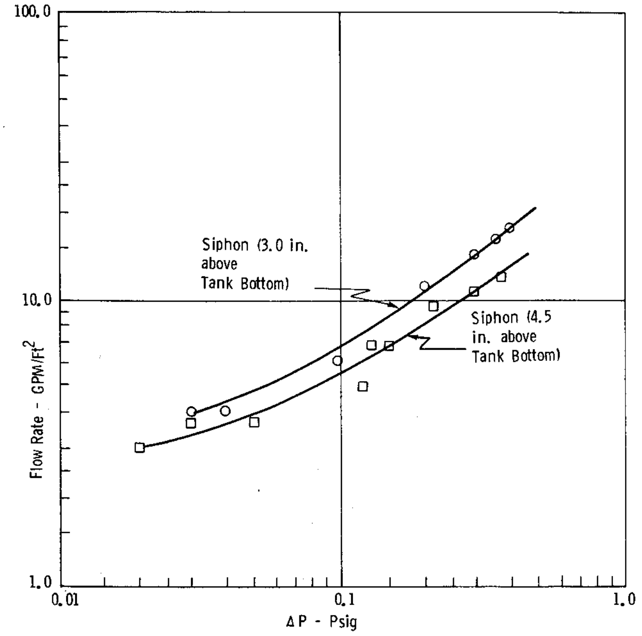

Fig. 5 Pressure drop for siphon inlet.

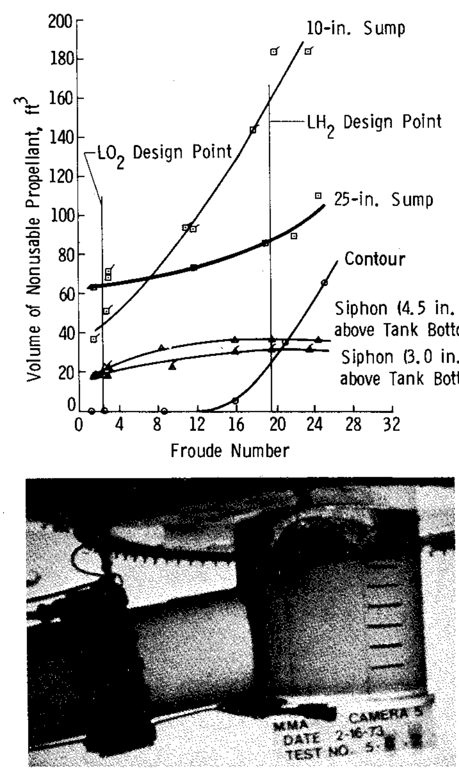

Fig. 6 Nonusable propellant in LO_2 and LH_2 tanks.

a function of N_{FR}. The reference point for determining these levels was the theoretical tank bottom (i.e., the point where the tank's longitudinal axis penetrates the aft dome). The contour outlet has a zero dropout height for values of N_{FR} ranging from 0 to 8.0, which encompasses the anticipated design conditions for the ET and possible off-design operational conditions during terminal drainage. These data verify the pretest assumption that the contour outlet could be configured to eliminate dropout. However, the data for the sump outlet indicate that a significant dropout height exists at any N_{FR}, and that this height can be as large as 34 in. at the LO_2 design-point N_{FR} of 2.29. In addition, the effect of changing the sump design to increase the value of $N_{FR_{sump}}/N_{FR_{feedline}}$ is to increase the dropout height for the sump. If the overall ET design contraints could be satisfied by mounting the outlet on the tank dome, and then the contoured outlet could be designed for the LH_2 design point N_{FR} of 19.6 with a zero dropout height.

The dropout height for the LH_2 siphon outlet is a function of N_{FR} and the height of the inlet above the aft dome of the tank. The rate at which the dropout height increases actually diminishes as N_{FR} increases due to the effect of increasing the inlet pressure losses. Together with those of Ref. 1, the test data indicate that the optimum compromise between dropout height and inlet pressure losses for the LH_2 siphon outlet is a contoured inlet located 4.5 in. above the aft dome (Fig. 5).

Nonusable Propellant

As shown in Fig. 6, the amount of nonusable propellant in the oxidizer and fuel tanks was determined as a function of the tank outlet design using the data of Fig. 4 and height-volume tables for the tanks. A comparison of the data at the

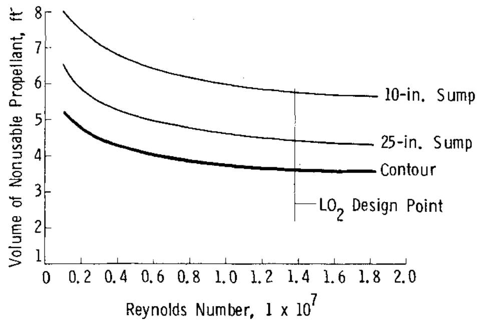

Fig. 7 Nonusable propellant in LO_2 feedline.

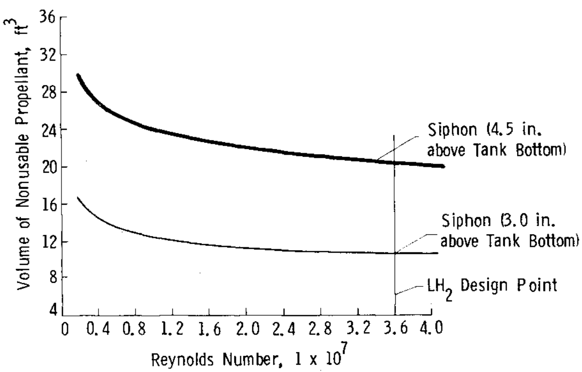

Fig. 8 Nonusable propellant in LH_2 feedline.

LO_2 tank design point indicates that the contour outlet reduces the amount of nonusable propellant to zero. Using a sump outlet would result in approximately 40 ft^3 of nonusable propellant, depending on the exact sump design.

The nonusable propellant in the LO_2 and LH_2 feedlines (Figs. 7 and 8) was determined from the data shown in Fig. 3, the diameter of the ET feedlines, and the propellant quality. The amount of nonusable propellant in the LO_2 feedline was 25 to 50% less for the contour outlet than for either sump design. Reducing the height of the siphon inlet reduces the amount of nonusable poropellant in the feedline. Locating the siphon inlet for the LH_2 tank 4.5 in. above the tank dome is the optimum position when inlet pressure loss effects are considered.

Conclusions

1) The contour outlet minimizes the amount of nonusable propellant in the LO_2 tank and feedline during terminal drainage.

2) Increasing the value of $N_{FR_{\text{sump}}}/N_{FR_{\text{feedline}}}$ for the sump outlet increases the amount of nonusable propellant in the LO_2 tank and feedline.

3) Decreasing the $N_{FR_{\text{sump}}}/N_{FR_{\text{feedline}}}$ ratio for the sump outlet increases the weight and volume of the outlet.

4) Elbows, outlets, and horizontal sections of feedline increase the length of the liquid-gas interface within the feedline. The resulting interface length is a function of N_{FR}, N_{RE} and the exact outlet configuration of the feedline, and can be calculated from

$$h_L = 0.5 C_l L_{\text{eff}} N_{FR} (0.003 + 0.22 N_{RE}{}^{-0.237})$$

5) The use of a contoured outlet for the LO_2 tank provides latitude in accommodating off-design operation without increasing the amount of nonusable propellant.

6) Using a siphon outlet with a contoured inlet located 4.5 in. above the aft dome of the LH_2 tank maximizes the mass fraction of the LH_2 tank by minimizing the combined effects of nonusable porpellant, inlet pressure losses, and structural weight over those obtained with external outlets on the aft dome.

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