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PRESSURANT REQUIREMENTS FOR DISCHARGE OF LIQUID METHANE FROM A 1.52-METER- (5-FT-) DIAMETER SPHERICAL TANK UNDER BOTH STATIC AND SLOSH CONDITIONS

by Richard L. DeWitt and Thomas O. McIntire

Lewis Research Center

Cleveland, Ohio 44135

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16. Abstract

Pressurized expulsion tests were conducted to determine the effect of various physical parameters on the pressurant gas (methane, helium, hydrogen, and nitrogen) requirements during the expulsion of liquid methane from a 1.52-meter- (5-ft-) diameter spherical tank and to compare results with those predicted by an analytical program. Also studied were the effects on methane, helium, and hydrogen pressurant requirements of various slosh excitation frequencies and amplitudes, both with and without slosh suppressing baffles in the tank. The experimental results when using gaseous methane, helium, and hydrogen show that the predictions of the analytical program agreed well with the actual pressurant requirements for static tank expulsions. The analytical program could not be used for gaseous nitrogen expulsions because of the large quantities of nitrogen which can dissolve in liquid methane. Under slosh conditions, a pronounced increase in gaseous methane requirements was observed relative to results obtained for the static tank expulsions. Slight decreases in the helium and hydrogen requirements were noted under similar test conditions.

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SUMMARY

Pressurized expulsion tests were conducted to determine the effect of various physical parameters on the pressurant gas requirements during the expulsion of liquid methane (LCH_4) from a 1.52-meter- (5-ft-) diameter spherical tank. Methane, helium, hydrogen, and nitrogen were used as pressurant gases. The necessary quantities of these gases to expel 90 percent of the LCH_4 propellant were studied as a function of expulsion time at a nominal operating pressure of 34.47×10^4 newtons per square meter (50 psia) using nominal inlet gas temperatures of 222 and 333 K (400° and 600° R). Also studied were the effects on methane, helium, and hydrogen pressurant requirements of various slosh excitation frequencies and amplitudes, both with and without slosh suppressing baffles in the tank. The experimental results for the static tank (nonslosh) expulsions were compared with results predicted by a previously developed analytical program.

The experimental results when using gaseous methane, helium, and hydrogen show that the predictions of the analytical program agreed well with the actual pressurant requirements for static tank expulsions. The analytical program could not be used for gaseous nitrogen expulsions because of the large quantities of nitrogen which can dissolve in liquid methane.

Unbaffled tank sloshing caused an increase in the amount of gaseous methane needed for expulsion. A slight decrease in requirements was encountered using gaseous helium and hydrogen because of LCH_4 propellant evaporation.

The addition of slosh suppressing baffles resulted in a further increase in the amount of gaseous methane pressurant. The quantities of noncondensible helium fell between the static tank and the unbaffled slosh expulsion requirements.

INTRODUCTION

During the past several years, a great deal of effort has been devoted to the problems associated with the pressurized discharge of a cryogenic liquid from a tank. The main objectives of these efforts have been toward optimization of a propellant tank pressurization system. One phase of this optimization is a precise determination of pressurant requirements for any given set of operating parameters (e.g., tank pressure, type and temperature of pressurant gas, liquid outflow rate, static tank or slosh conditions, etc.). This knowledge would allow the design of a pressurization gas storage system that carried only the weight of gas necessary to accomplish the mission.

Several investigators have developed analyses (e.g., refs. 1 and 2) which attempt to predict the pressurant gas requirements during the pressurized discharge of a cryogenic fluid from a static tank. These analyses, however, are either burdened with simplifying assumptions or involve parameters and terms about which little is generally known "a priori." Because of these limitations the validity of the analytical results has to be verified largely by correlations of experimental results. The dependence on experimental results becomes even greater when pressurant gas requirement predictions are considered for tank expulsions under liquid slosh conditions. No analytical effort was found in the literature to even generally predict pressurant requirements for this case.

Previous investigators at Lewis Research Center (refs. 3 to 7) have studied pressurant requirement predictions for expulsion of liquid hydrogen from static tanks of varying size and shape. The analysis of reference 1 was revised and extended (see appendixes A, B, and C in ref. 4) to serve as a correlating tool for the experimental data.

Considerable effort has recently been devoted to studying the future use of liquid methane (LCH_4) in land, air, and space vehicle applications because of its high density and handling characteristics. However, it was not known if the results of the previous liquid hydrogen expulsion investigations could be used for the case of gaseous methane (GCH_4) pressurant requirement predictions. Further, no data at all has been published with regard to pressurant requirement magnitudes and trends as functions of slosh frequencies and amplitudes imposed on the test tanks.

Therefore, an investigation was conducted at Lewis Research Center to experimentally determine the effect of various physical parameters on the pressurant gas requirements during the expulsion of LCH_4 from a 1.52-meter- (5-ft-) diameter spherical aluminum tank. The primary objective of these tests was to obtain experimental results (pressurant mass requirements as well as heat and mass transfer data) for static tank expulsions and correlate them with the analysis detailed in reference 4. Both complete and partial tank expulsions were conducted toward accomplishment of this objective. The second objective of the program was to obtain experimental data for expulsions under liquid slosh conditions and analyze these to determine the major reasons for the magnitudes and trends of the results. All tests were performed at a nominal tank pressure of 34.47×10^4 newtons per square meter (50 psia). A diffusing-type pressurant gas injector was used for all tests. Four different pressurant gases were used during these tank expulsion studies. The main test variables were as follows:

Variable	Range
Static tank expulsion	
Pressurant gas	CH_4, He, H_2, and N_2
Inlet gas temperature, K (^oR)	222 and 333 (400 and 600)
Liquid outflow rates, kg/sec (lb/sec)	1.01 to 2.93 (2.22 to 6.46)
Initial ullage (complete expulsions), percent	5
Initial ullage (partial expulsions), percent	5 or 50
Sloshing tank expulsion	
Pressurant gas	CH_4, He, and H_2
Inlet gas temperature, K (^oR)	222 and 333 (400 and 600)
Liquid outflow rates, kg/sec (lb/sec)	0.99 to 3.01 (2.170 to 6.630)
Initial ullage (complete expulsions), percent	5
Internal tank hardware	bare three concentric ring baffles
Slosh excitation frequency	0.716 Hz (constant) Natural throughout expulsion
Slosh excitation amplitude, cm (in.)	0.0 to ±2.23 (0.0 to ±0.88)

SYMBOLS

A_o constant in Benedict-Webb-Rubin equation, (atm)(m^6)/[(kg)(mole)]^2; (lb)(ft^4)/[(lb)(mole)]^2

a constant in Benedict-Webb-Rubin equation, (atm)(m^9)/[(kg)(mole)]^3; (lb)(ft^7)/[(lb)(mole)]^3

B_o constant in Benedict-Webb-Rubin equation, m^3/(kg)(mole); ft^3/(lb)(mole)

b constant in Benedict-Webb-Rubin equation, m^6/[(kg)(mole)]^2; ft^6/[(lb)(mole)]^2

C orifice coefficient

C_o constant in Benedict-Webb-Rubin equation, (atm)(K^2)(m^6)/[(kg)(mole)]^2; (lb)($^oR^2$)(ft^4)/[(lb)(mole)]^2

c constant in Benedict-Webb-Rubin equation, (atm)(K^2)(m^9)/[(kg)(mole)]^3; (lb)($^oR^2$)(ft^7)/[(lb)(mole)]^3

c_p specific heat at constant pressure, J/(kg)(K); Btu/(lb)(^oR)

c_v	specific heat at constant volume, J/(kg)(K); Btu/(lb)($^{\circ}$R)
D	orifice diameter, m; ft
F	molecular fraction
g	gravity acceleration, m/sec^2; ft/sec^2
h	specific enthalpy, J/kg; Btu/lb
M	mass, kg; lb
$\dot{M}$	mass flow rate, kg/sec; lb/sec
ΔM	differential mass, kg; lb
m	molecular weight
N	number of volume segments
P	pressure, N/m^2 or atm; lb/in.^{2} or lb/ft^2
ΔP	differential pressure, N/m^2; lb/in.^{2} or lb/ft^2
ΔP^*	orifice ΔP, N/m^2; lb/in.^{2}
Q	heat transfer, J; Btu
$\dot{Q}$	heat transfer rate, J/sec; Btu/sec
R	gas constant, (atm)(m^3)/(kg)(mole)(K); (psfa)(ft^3)/(lb)(mole)($^{\circ}$R)
T	temperature, K; $^{\circ}$R
t	time, sec
Δt	time increment, sec
U	internal energy, J; Btu
ΔU	differential energy, J; Btu
V	volume, m^3; ft^3
ΔV	volume increment, m^3; ft^3
$\bar{V}$	velocity, m/sec; ft/sec
v	specific volume, m^3/kg; ft^3/lb
W	work, J; Btu
X	percent of gas by weight
Y	expansion factor
z	elevation, m; ft
α	constant in Benedict-Webb-Rubin equation, m^9/[(kg)(mole)]^3; ft^9/[(lb)(mole)]^3

γ	constant in Benedict-Webb-Rubin equation, $m^6/[(kg)(mole)]^2$; $ft^6/[(lb)(mole)]^2$
δ	finite increment
μ	specific internal energy, J/kg; Btu/lb
ρ	density, kg/m^3; lb/ft^3
$\bar{\rho}$	effective density of gas in volume segment, $(kg)(mole)/m^3$; $(lbm)(mole)/ft^3$

Subscripts:

BL	bulk liquid
cond	condensed
D	dissolved gas
e	expulsion period
f	final state or condition
G	gas added to tank
GCH_4	gaseous methane
h	hold period
i	initial state or condition
L	liquid
n	summing index
P	analytical prediction
r	ramp period
SG	saturated gas
SL	saturated liquid
T	total quantity
t	transferred
U	ullage
w	wall
X	experimental
1	component designation

APPARATUS AND INSTRUMENTATION

Facility

All tests were conducted inside a 7.61-meter- (25-ft-) diameter spherical vacuum chamber (fig. 1) to reduce the external heat leak into the propellant tank to a low value. The vacuum capability of this chamber was approximately 8×10^{-7} torr. A general schematic of the test tank and associated equipment is shown in figure 2. A heat exchanger and blend valve subsystem capable of delivering pressurant gas at temperatures of 167 to 405 K (301° to 729° R) were used to control pressurant gas inlet temperature. The three-way bleed valve, immediately upstream of the test tank, was used prior to an expulsion to temperature condition the pressurizing gas and lines without contaminating the tank ullage. The LCH_4 outflow rate was controlled by remotely operated variable flow valves. The propellant outflow from the tank was returned to a storage Dewar. A ramp generator and control valve were used for controlling the initial rate of pressurization of the propellant tank. A closed loop pressurant gas flow control circuit was used to maintain constant tank pressure during the expulsion period.

Tank sloshing was accomplished using a hydraulically operated shaker controlled by a function generator which specified amplitude and frequency. The shaker was of sufficient size that the motion was independent of the tank and its contained propellant.

Liquid methane outflow rates were measured using a turbine-type flowmeter located

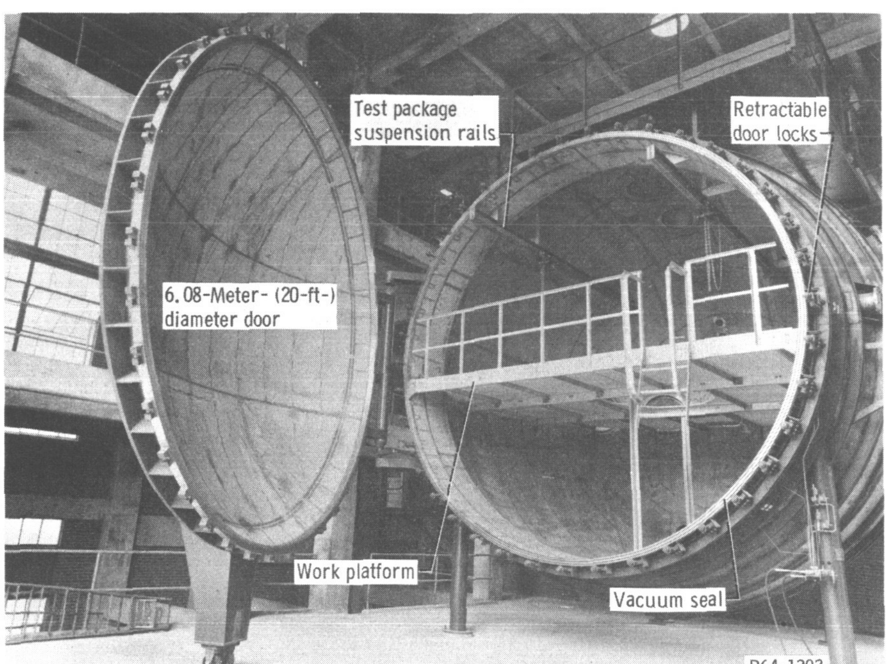


Figure 1. - 7.61-Meter- (25-ft-) diameter vacuum chamber.

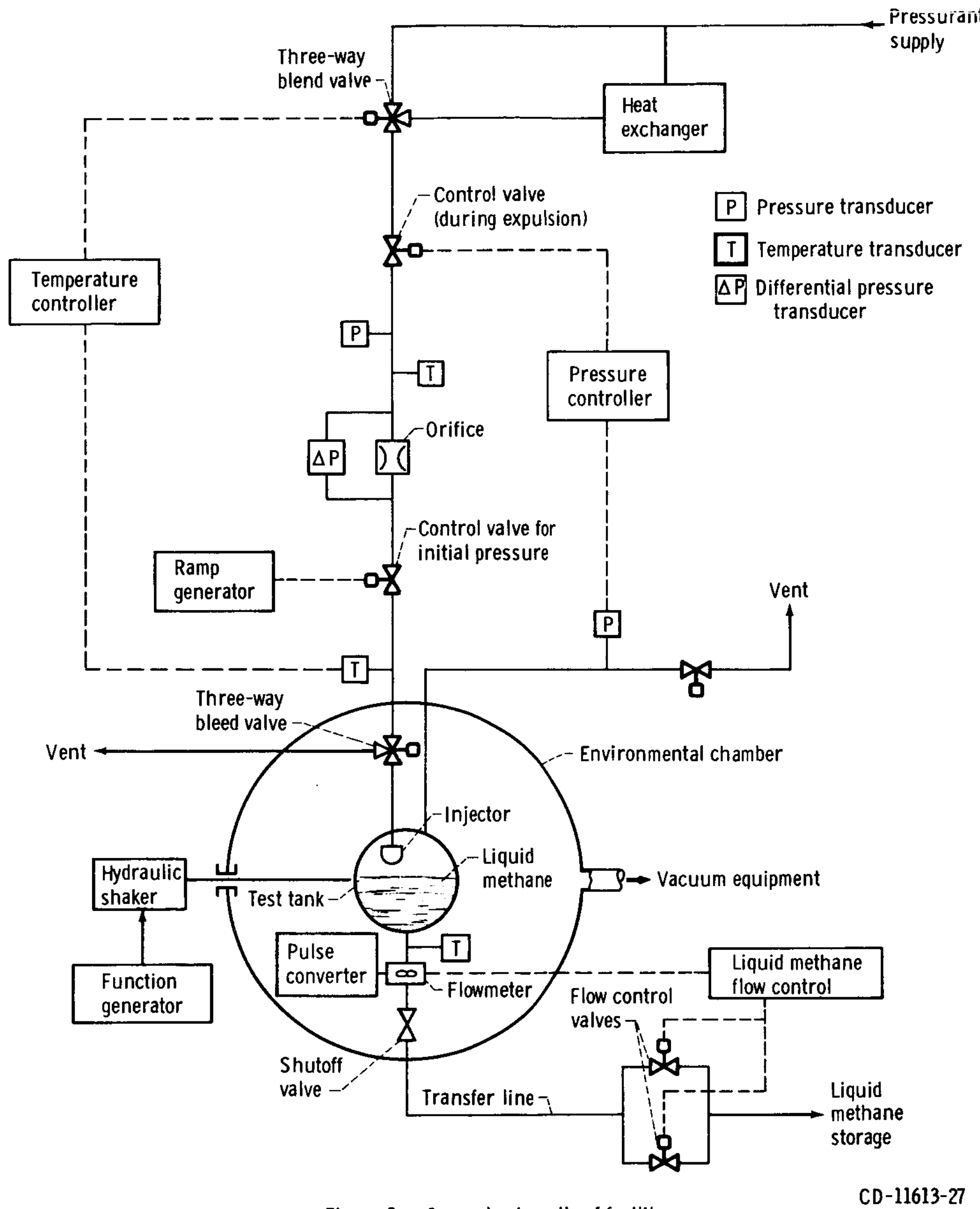


Figure 2. - General schematic of facility.

in the transfer line. The flowmeter was calibrated with water and the calibration projected for LCH_4. Pressurant gas inlet flow rates were determined by the use of an orifice located in the pressurant supply line. Tank, line, and differential pressures were measured with bonded strain-gage-type transducers.

Test Tank

The experimental work was conducted using a 1.52-meter- (5-ft-) diameter spherical aluminum tank. Figure 3 is a photograph of the test tank installed inside the vacuum chamber; and figure 4 is a closeup view of the same installation. The tank wall had an average thickness of 0.762 centimeter (0.30 in.). The lid housed the pressurant inlet and vent pipes and the electrical connections for all internal tank instrumentation. The lid, made of stainless steel, was 0.457 meter (18 in.) in diameter and 3.18 centimeters (1.25 in.) thick. The inner surface of the lid conformed to the contour of the tank and was covered with a 0.63 centimeter (0.25 in.) thick layer of cork to reduce absorption

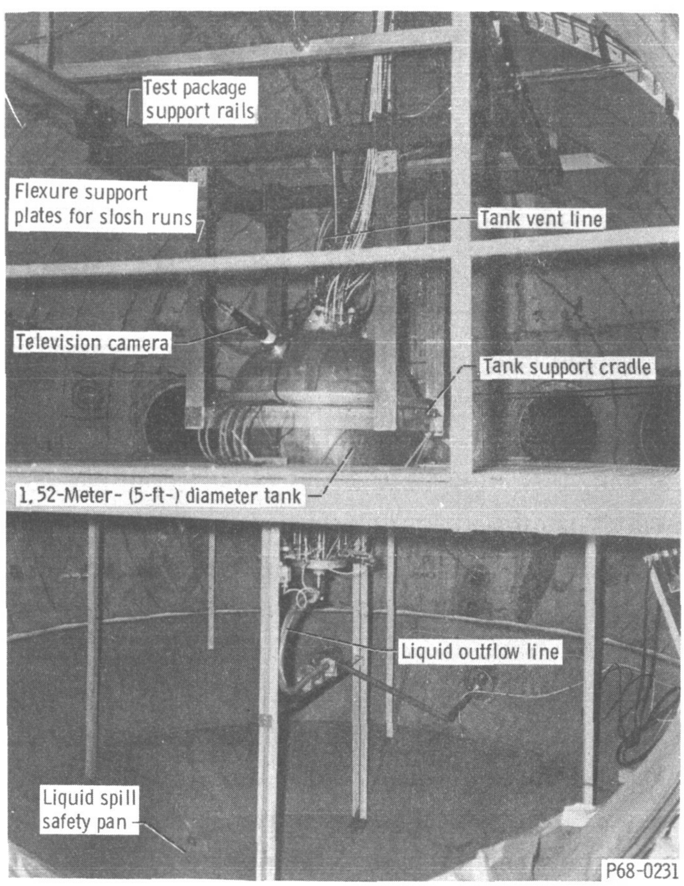


Figure 3. - 1.52-Meter- (5-ft-) diameter tank installed in vacuum chamber.

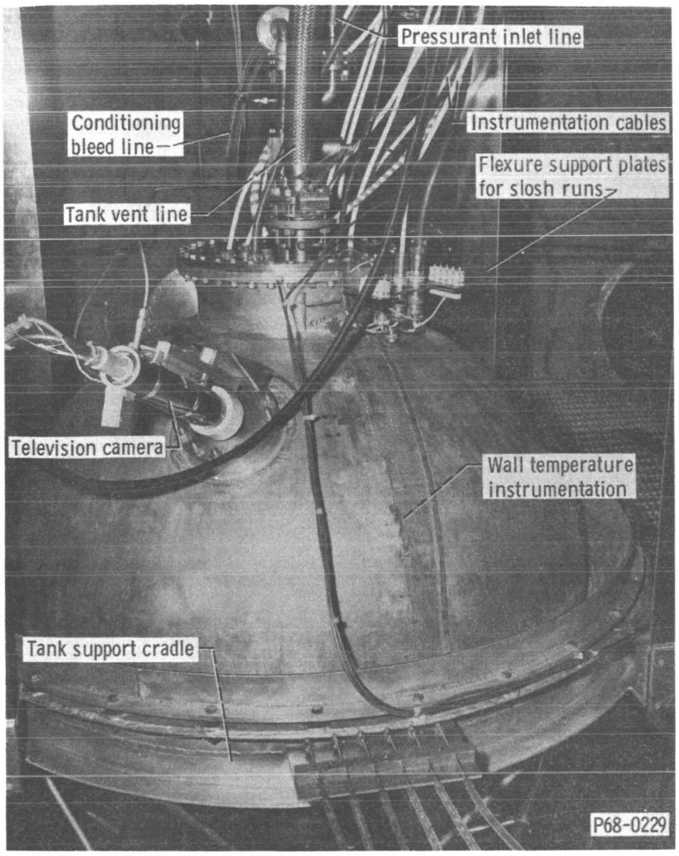


Figure 4. - Closeup of installed 1.52-meter- (5-ft-) diameter tank.

of heat from the pressurant gas in the ullage.

A view port and television camera were installed on the tank to allow observation of any physical processes occurring in the tank. Lighting of the tank interior was accomplished using 250-watt light bulbs mounted on the inner surface of the tank wall. Because of a fogging problem, as well as extraneous heating of the ullage and the liquid propellant, visual observation was limited to only short periods during the expulsion tests.

For a selected group of expulsion tests, slosh suppressing baffles were mounted inside the test tank. Of the three concentric ring baffles, the center one was located in the horizontal plane marking the middle of the tank; the upper and lower baffles were located 21.51 centimeters (8.47 in.) above and below the middle baffle.

The test tank was suspended, at its horizontal midpoint, by four flexure plates attached to the twin support rails of the environmental chamber. During slosh runs, the hydraulically operated shaker moved the test tank along a horizontal centerline directed from the front of the chamber to the back. Slosh input amplitudes were such that vertical movement of the tank during a slosh cycle was considered negligible.

Pressurant Gas Injector Geometry

A hemisphere injector (fig. 5) was used for all tests reported herein. This particular geometry was selected because it injects the pressurant uniformly in all directions into the ullage volume. This flow pattern minimizes ullage gas mixing and reduces heat transfer to the surface of the liquid propellant. The use of this injector was also encouraged by the favorable comparisons obtained between analytical predictions and experimental results during outflow testing conducted using liquid hydrogen (refs. 3 to 7).

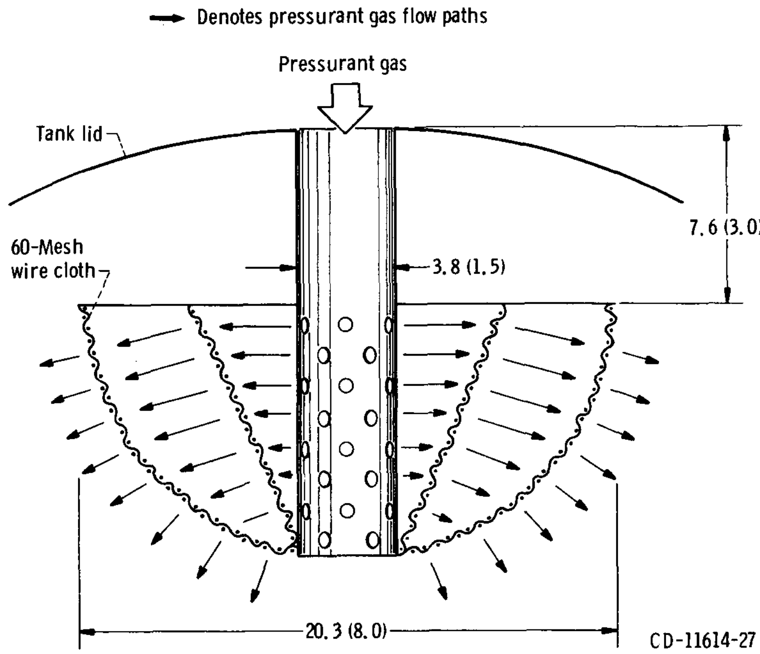


Figure 5. - Injector geometry for hemisphere injector. Open area, 176.8 square centimeters (27.4 in.^{2}). (All dimensions are in cm (in.).

Test Tank Instrumentation

Ullage gas temperatures, together with gas concentration measurements, were used to determine the mass and energy content of the tank ullage. Temperatures were measured with thermopiles and with platinum resistance sensors. Internal tank instrumentation is illustrated in figure 6.

A typical three-element thermopile unit and its associated wiring schematic are illustrated in figure 7(a). The thermopile units were constructed of 0.202 millimeter (0.008 in.) Chromel constantan wire. Vertical ullage gas temperature profiles were obtained by stacking the individual thermopile units as shown in figure 7(b). The support structure was made of thin perforated stainless steel to minimize heat conduction between thermopile stations as well as to minimize the total heat capacity of the rake. The spac-

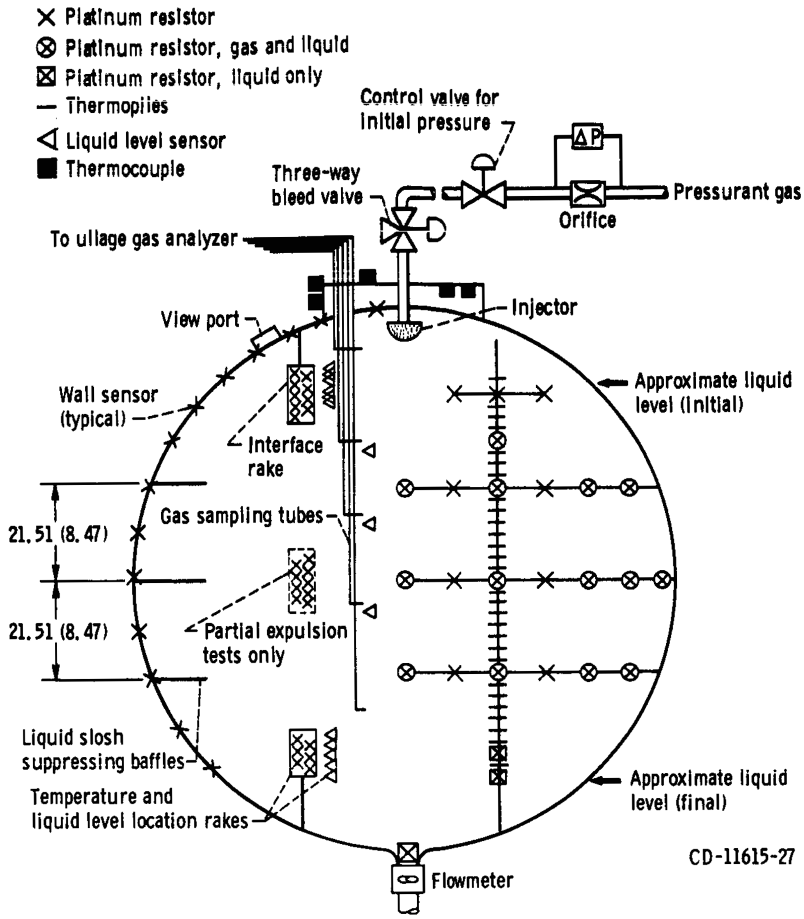
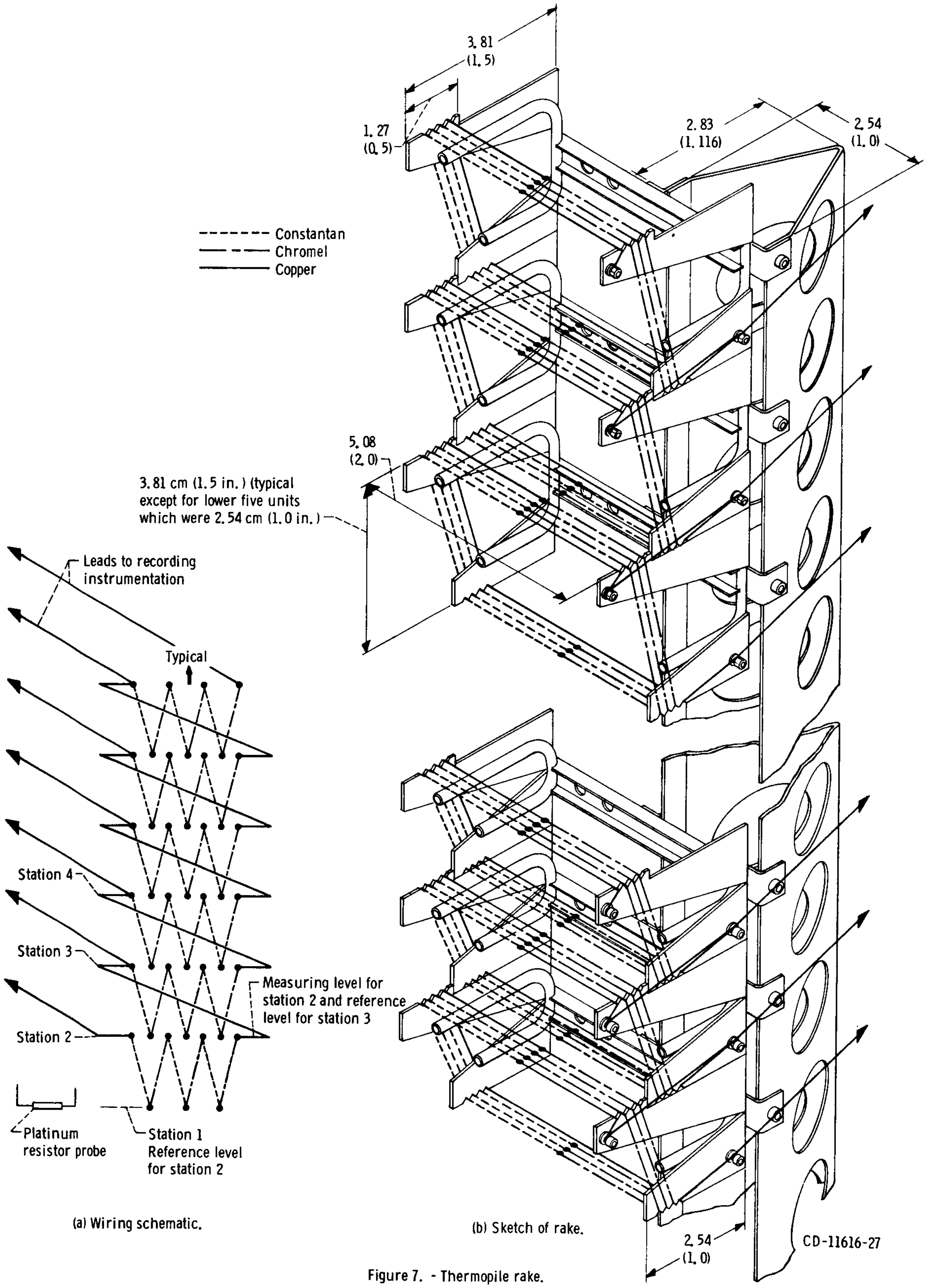


Figure 6. - Test tank instrumentation. (All dimensions are in cm (in.).)

ing between the reference and measuring levels for the top 30 thermopile units of the vertical rake was 3.8 centimeters (1.5 in.). The three units at the bottom of the rake had a spacing of 2.5 centimeters (1.0 in.). The purpose of the closer spacing was to obtain a better definition of ullage gas temperature near the interface at the end of expulsion.

Platinum resistance sensors, which were located at least every eighth station starting from the bottom of the rake, sensed the absolute temperature at their location and provided a reference for the thermopile above the location.

The horizontal instrumentation was composed solely of platinum resistance sensors spaced a maximum distance of 12.70 centimeters (5.00 in.) apart in a radial direction. Two platinum resistance sensors were used at most locations to measure liquid and/or gas temperatures for the ranges 105.6 to 133.3 K (190° to 240° R) and 39 to 278 K (70° to 500° R). These dual sensors permitted more accurate measurement of liquid and gas temperatures than could be achieved with one sensor covering the entire range. When ullage gas temperatures were higher than the upper limit of the 39 to 278 K (70° to



(a) Wiring schematic.

(b) Sketch of rake.

Figure 7. - Thermopile rake.

500° R) range, the range was extended by using a data channel of greater millivolt capacity. This "span selection" capability of the platinum resistance sensors also allowed close temperature measurements to be made in the liquid. This capability was needed inasmuch as a small error could influence the energy balance because of the high heat capacity of the liquid methane propellant. Figure 8 is a photograph of the vertical and horizontal temperature sensor rakes installed inside the test tank.

The initial static temperature profile near the liquid surface was determined by a fixed interface rake located either at the 5 or 50 percent level, depending on the type of run. This rake contained nine platinum resistance sensors spaced 0.76 centimeter (0.3 in.) apart. The normal range of these sensors was 105.6 to 133.3 K (190° to 240° R) over a 10-millivolt span. An accompanying set of liquid level sensors was used to verify that the initial propellant level was within range of the interface temperature rake. The final level of the propellant, at the end of expulsion, was also determined using a set of fixed hot wire level sensors.

Platinum resistance sensors were also used to determine tank wall temperatures at 14 locations and the liquid methane temperature at the flowmeter. In addition, there were two copper-constantan thermocouples on the neck of the tank and three on the tank lid.

Inlet pressurant gas temperatures were measured by a copper-constantan thermocouple mounted in the gas diffuser pipe at a location inside the tank.

All measurements were recorded on a high-speed digital system at a rate of 3125

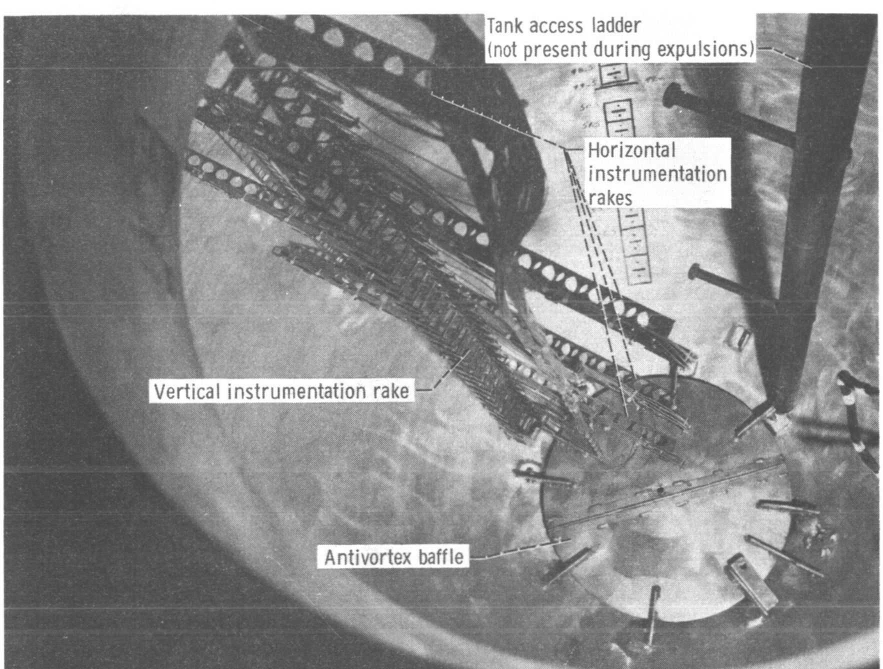


Figure 8. - Major internal tank instrumentation rakes.

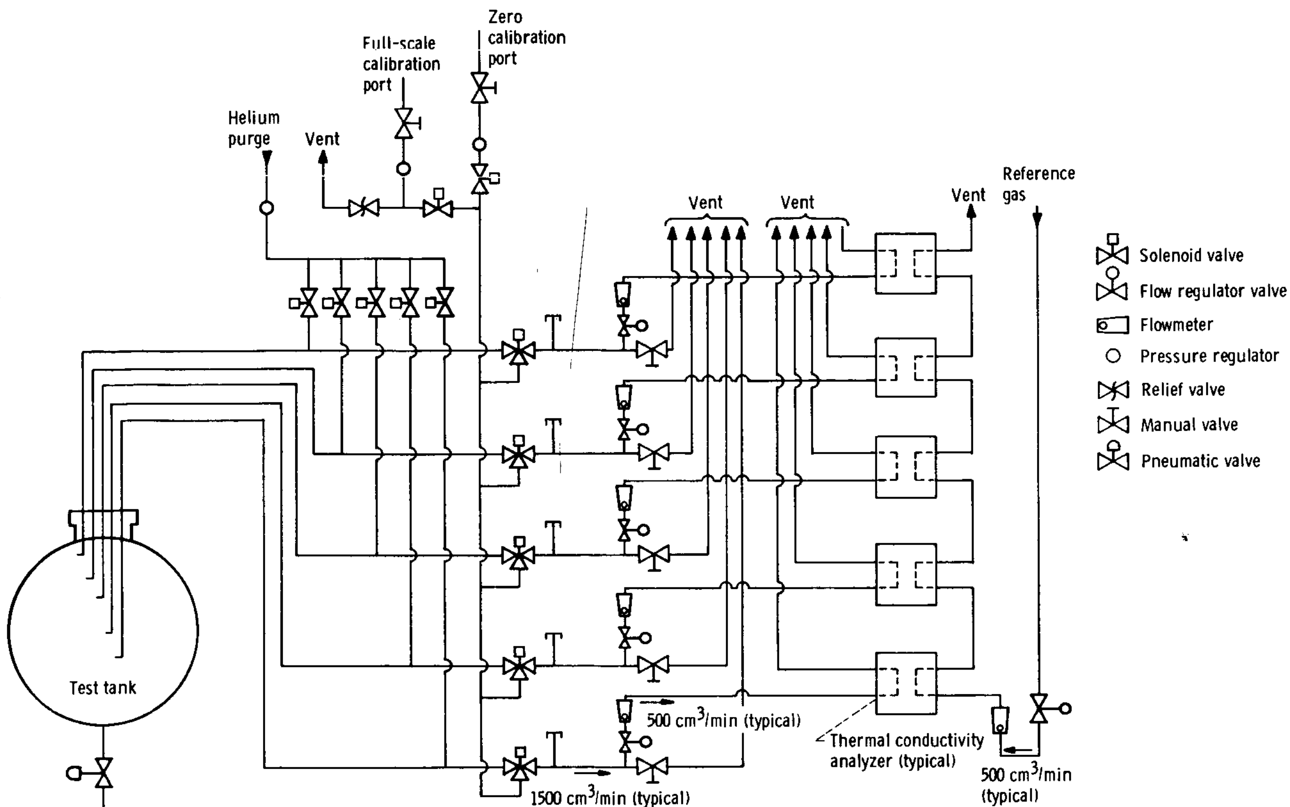
channels per second. Each channel was sampled every 0.064 second.

Concentrations

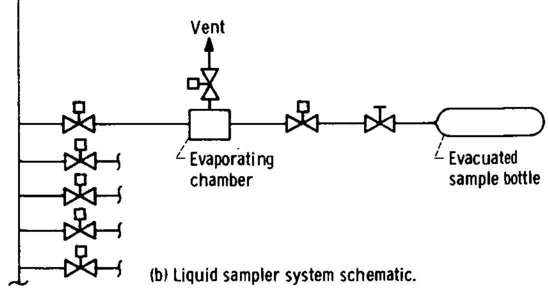
The concentration of ullage gas at five positions in the tank (fig. 6) was obtained by a gas sampling and analyzer system. A general schematic of this system is shown in figure 9. The sampling tubes had 0.157-centimeter (0.062-in.) outside diameters with a wall thickness of 0.030 centimeter (0.012 in.). To prevent liquid from entering the sampling tubes, a small helium gas purge was maintained in the tubes that were initially submerged in the liquid methane.

The operation of a typical sampling tube was as follows: After liquid passed the entrance of the sampling tube (during expulsion), the helium purge was stopped. The tank pressure then forced the gas sample through the tube to a flow regulator which maintained a flow of 500 cubic centimeters per minute into the thermal analyzer. The analyzer then compared the thermal conductivity of the ullage gas sample with that of 100 percent pure pressurant gas (also entering the analyzer at 500 cu cm/min). The output of the analyzer was continuously recorded on a direct reading oscillograph. The ullage gas concentration was then obtained by comparing the analyzer output with the output previously obtained when using known sample concentrations.

An attempt was made to determine the concentration of pressurant gas which dissolved into the liquid methane propellant. A general schematic of this system, which had a capacity of five discrete samples, is also shown in figure 9. The operation of taking a liquid sample was as follows: At some preselected time after the beginning of expulsion, the solenoid valve in a given sample line would be opened for approximately 2 seconds admitting some of the contaminated liquid methane into an electrically heated evaporating chamber. After pressure in the chamber had risen, indicating some sample vaporization, part of the gas was permitted to pass into an evacuated sample bottle. The remaining gas was then vented from the evaporation chamber. Samples were taken throughout the course of the test program. However, because of valve leakage and fractionation of the vaporized liquid, analysis of the sample bottles gave only a rough qualitative measure of liquid contamination. Since the data obtained were not usable for detailed analysis of dissolved pressurant, they will not be discussed further.



(a) Ullage gas sampler and analyzer system schematic.



(b) Liquid sampler system schematic.

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Figure 9. - Ullage gas and liquid propellant sampling systems.

PROCEDURE

The spherical test tank was filled from the bottom to approximately a 2 percent ullage condition. It was then topped off as necessary while the tank lid and peripheral support hardware reached steady-state temperatures.

Temperature conditioning of the pressurant inlet line was then started. Gas flow was established through the heat exchanger loop, through the control valves and orifice arrangement, and then up to the three-way bleed valve at the test tank inlet from where it was vented to the outside as shown in figure 2. The temperature control circuit shown in figure 2 was used to get the desired pressurant gas temperature level during the flow period. When the gas temperature conditioning was almost complete, the liquid level in the test tank was adjusted to a desired value ($\approx$5 percent ullage) by either topping or slow draining. The hot wire liquid level sensors were used to check the propellant level. The pressurant gas flow was then stopped, and the test tank was vented in preparation for an expulsion run. The automatic controllers and timers were preset with all the desired run and operating conditions (i.e., tank pressure level, length of ramp period, length of hold period, liquid outflow valve position, start time of the data recording equipment, slosh amplitude and frequency, etc.).

After starting the data recording equipment, the next step of the automatic run sequence was to take electrical calibrations on all pressure transducers. Immediately following this, the test tank was pressurized over a predetermined time period to the nominal operating pressure of 34.47×10^4 newtons per square meter (50 psia). Tank pressure was held constant for almost 25 seconds to stabilize internal temperatures. The tank expulsion period was then started. If the expulsion was to be made under slosh conditions, tank motion was initiated concurrent with the beginning of propellant outflow. During the expulsion, the pressurant gas temperature could be controlled either manually or by the closed loop automatic temperature control circuit. When the desired final propellant level in the tank had been reached, the expulsion was terminated. Hot wire liquid level sensors were used to determine this point in the expulsion period. The automatic sequencer then stopped the data recording equipment. The tank was vented and refilled in preparation for another test.

A set of partial tank expulsions was made during which only half the liquid propellant in the tank was expelled. The first set of these runs dealt with expulsion of only the upper half of the tank contents. The only difference between these runs and full tank expulsions was that propellant outflow was stopped at the 50 percent ullage level. For the second set of runs, starting at 50 percent ullage and expelling the tank until only 5 percent of the methane remained, a slightly different procedure was used. The tank was filled to approximately the 5 percent level while a small backpressure was maintained over the liquid. The methane was then drained, by self-pressurization, to the 50 percent ullage level in about 5 minutes. The tank was vented and the automatic run sequence was started. Because no pressurant was added during this draining period, the procedure ensured a 100 percent methane ullage and uniformity of wall temperatures from run to run.

DATA REDUCTION

Physical Description of Problem

An initially vented tank containing two-phase methane was ramp pressurized from 1 atmosphere to a new pressure by adding either GCH_4, gaseous helium (GHe), gaseous hydrogen (GH_2), or gaseous nitrogen (GN_2). The system was then allowed a short time (approximately 25 sec) to equilibrate after which liquid outflow was started. During the expulsion period, pressurant gas (at almost constant temperature) was added to the tank at a rate that maintained a constant tank pressure while expelling the liquid at a desired rate. The amount of pressurant gas required during the expulsion (or pressure ramp) is dependent on (1) the type of pressurant, (2) the volume and outflow rate of liquid displaced, (3) the heat transfer to the wall and liquid, (4) the amount of mass condensed or evaporated, (5) the presence or absence of tank movement (i.e., sloshing), and (6) the amplitude and frequency of slosh.

Mass Balance

A mass balance was performed on the ullage volume from an initial time t_i to a final time t_f as follows:

$$M_{U,f} = M_{U,i} + M_{G,i\to f} - M_{t,i\to f} \tag{1}$$

A discussion of how the terms of equation (1) were determined appears in the next three sections.

Pressurant gas added $M_{G,i\to f}$. - The weight of the actual pressurant gas added from any initial time t_i to any final time t_f was determined by numerical integration of the gas orifice equation

$$M_{G,i\to f} = \int_{t_i}^{t_f} YD^2C\sqrt{\rho\,\Delta P^*}\,dt \tag{2}$$

Ullage mass. - The initial ullage mass $M_{U,i}$ and final ullage mass $M_{U,f}$ were obtained by numerical integration of the particular density profiles as follows:

$$M_{U,i} = \int_{V_{U,i}} \rho \, dV \cong \sum_{n=1}^{N_i} \rho_{1,n} V_n + \sum_{n=1}^{N_i} \rho_{GCH_4} V_n \qquad \rho = f(T, F) \tag{3}$$

$$M_{U,f} = \int_{V_{U,f}} \rho \, dV \cong \sum_{n=1}^{N_f} \rho_{1,n} V_n + \sum_{n=1}^{N_f} \rho_{GCH_4} V_n \qquad \rho = f(T, F) \tag{4}$$

The internal tank volume was considered as 36 horizontal disk segments (corresponding to thermopile and other sensor locations). Each of these segments was in turn divided radially into a series of concentric rings, the number of which depended on the location of the radial temperature sensors and the vertical position of the disk segment being considered. These rings (202 in all) and the thin disks which were used near the starting interface comprised the V_n's in the previous calculations. In this manner, vertical temperature as well as radial temperature gradients could be incorporated into the mass calculations. The position of the liquid level prior to and after expulsion determined the number of gas volume rings (N_i and N_f) used in the ullage mass calculations.

In the case of a two-component ullage, the density is a function of mixture concentration as well as temperature. Using concentration data obtained from the ullage gas sampling tubes, the molecular fraction of each gas was computed. These fractions were then used to obtain a set of weighted coefficients for the Benedict-Webb-Rubin (BWR) equation of state. The BWR equation, which is

$$P = RT\bar{\rho}_T + \left(B_o RT - A_o - \frac{C_o}{T}\right)\bar{\rho}_T^2 + (bRT - a)\bar{\rho}_T^3 + a\alpha\bar{\rho}_T^6 + \frac{c\bar{\rho}_T^3}{T^2}\left[\left(1 + \gamma\bar{\rho}_T^2\right)e^{-\gamma\bar{\rho}_T^2}\right] \tag{5}$$

was used to calculate the total molecular density $\bar{\rho}_T$ for each volume segment. This molecular density was converted to a mass density by the equation

$$\rho_T = (F_1 m_1 + F_{GCH_4} m_{GCH_4})\bar{\rho}_T \tag{6}$$

The densities of each pure component in each volume segment were then determined by

$$\rho_1 = F_1 m_1 \bar{\rho}_T \tag{7}$$

and

$$\rho_{GCH_4} = F_{GCH_4} m_{GCH_4} \bar{\rho}_T \tag{8}$$

These densities were used in the ullage mass equations (3) and (4).

Mass transfer. - The mass transfer was calculated from equation (1) as a result of knowing $M_{U,i}$, $M_{U,f}$, and $M_{G,i \to f}$; that is,

$$M_{t,i \to f} = M_{U,i} + M_{G,i \to f} - M_{U,f} \tag{9}$$

If $M_{t,i \to f}$ was a positive quantity, mass was considered leaving the ullage volume (i.e., condensation and/or solution).

Energy Balance

For the thermodynamic system consisting of the entire tank and its contents (tank + ullage gas + liquid), the first law of thermodynamics for an increment of time Δt may be written as

$$dU_T = (\delta M_G)\left(\mu_G P_G v_G + \frac{\bar{V}_G^2}{2g} + z_G\right) - (\delta M_L)\left(\mu_L + P_L v_L + \frac{\bar{V}_L^2}{2g} + z_L\right) + \delta Q - \delta W \tag{10}$$

The kinetic and potential energy terms are small in comparison with the other energy terms and are neglected in this development. If $h = \mu + Pv$ is substituted, equation (10) becomes

$$dU_T = (\delta M_G)h_G - (\delta M_L)h_L + \delta Q - \delta W \tag{11}$$

For this system, there is no external work done so $\delta W = 0$ and the final form of equation (10), therefore, becomes

$$dU_T = (\delta M_G)h_G - (\delta M_L)h_L + \delta Q \tag{12}$$

Equation (12) can be integrated over any time period. The physical interpretation of the quantities in equation (12) is as follows:

$$\underbrace{\int_{U_i}^{U_f} dU_T}_{\substack{\text{Change in} \\ \text{system energy (tank +} \\ \text{gas + liquid)}}} = \underbrace{\int_{t_i}^{t_f} \dot{M}_G h_G \, dt}_{\substack{\text{Energy input} \\ \text{by pressurant} \\ \text{gas inflow}}} - \underbrace{\int_{t_i}^{t_f} \dot{M}_L h_L \, dt}_{\substack{\text{Energy leaving through} \\ \text{liquid outflow}}} + \underbrace{\int_{t_i}^{t_f} \dot{Q} \, dt}_{\substack{\text{Energy from} \\ \text{environment} \\ \text{(heat leak from} \\ \text{conduction, convection, and} \\ \text{radiation)}}} \tag{13}$$

A discussion of how the terms of equation (13) were evaluated follows.

Energy input by pressurant gas inflow. - The first term in equation (13) may be evaluated as follows:

$$\int_{t_i}^{t_f} \dot{M}_G h_G \, dt \cong \sum_{n=1}^{n=(t_f-t_i)/\Delta t} \dot{M}_{G,n} h_{G,n} \, \Delta t \tag{14}$$

The pressurant flow rate $\dot{M}_G$ was determined from equation (2). The specific enthalpy of the inlet gas was evaluated at the inlet temperature and pressure at each time increment Δt.

Energy leaving by liquid outflow. - The energy of the liquid that leaves the system can be evaluated as follows:

$$\int_{t_i}^{t_f} \dot{M}_L h_L \, dt \cong \sum_{n=1}^{n=(t_f-t_i)/\Delta t} \dot{M}_{L,n} h_{L,n} \, \Delta t \tag{15}$$

The liquid flow rate $\dot{M}_L$ was determined from the turbine flowmeter. The specific enthalpy of the liquid was evaluated at the outlet temperature. The reference statepoint for liquid enthalpy was chosen so that the previous summation would be small when the outlet temperature equalled the original liquid temperature. This was done to eliminate the problem of using the difference of large numbers.

Energy input from environment. - The rate of energy input into the tank from the environment was assumed to be the same for all cases and was determined from a boiloff test. This test indicated a nominal value of 0.685×10^3 joules per second (0.65 Btu/sec) should be used. This value included heat input by radiation, convection, and conduction through pipes and supports. Therefore

$$\int_{t_i}^{t_f} \dot{Q}\, dt \cong 0.685\times10^{3}\,(t_f - t_i) \tag{16}$$

Change in system energy. - The change in system energy can be separated into three categories: (1) change in ullage energy, (2) change in liquid energy, and (3) change in wall energy. Stated mathematically,

$$dU_T = dU_U + dU_L + dU_w \tag{17}$$

Change in ullage energy. - The change in ullage energy over any given time interval $t_i \rightarrow t_f$ is obtained by subtracting the internal energy at time t_i from the internal energy at time t_f; that is,

$$\int_{U_{U_i}}^{U_{U_f}} dU_U = \Delta U_U = \left(U_U\right)_{t_f} - \left(U_U\right)_{t_i} \tag{18}$$

Making use of the relation $\mu = h - Pv$ gives

$$\int_{U_{U_i}}^{U_{U_f}} dU_U = \sum_{V_f} \rho_U \left(h - \frac{P}{\rho_U}\right)\Delta V_U - \sum_{V_i} \rho_U \left(h - \frac{P}{\rho_U}\right)\Delta V_U \tag{19}$$

The ullage gas density was determined using equations (5) and (6). The enthalpy values for equation (19), in the case of a two-component ullage, were determined by summing the products of the weight fraction of each pure component and its specific enthalpy at the temperature and pressure conditions existing in the particular volume segment being considered.

Change in liquid energy. - The change in energy of the liquid in the tank can be determined in a manner similar to the change in ullage energy; that is,

$$\int_{U_{L_i}}^{U_{L_f}} dU_L = \Delta U_L = \left(U_L\right)_{t_f} - \left(U_L\right)_{t_i} \tag{20}$$

or

$$\int_{U_{L_i}}^{U_{L_f}} dU_L = \sum_{V_f} \rho_L \left(h_L - \frac{P}{\rho_L}\right)\Delta V - \sum_{V_i} \rho_L \left(h_L - \frac{P}{\rho_L}\right)\Delta V \tag{21}$$

The liquid density and enthalpy are functions of pressure and temperature. However, in some of the expulsions, mass transfer contaminated the liquid with nonmethane pressurant. Since the integrating routines assume the liquid to be pure methane, the extra heat of solution due to the mass transfer must be accounted for separately. The mass of dissolved gas was calculated by knowing how much pressurant was added to the tank during the entire pressurization expulsion process as well as the quantity of pressurant specie in the ullage at the end of expulsion. Because of the small range of temperatures involved, the dissolved gas was assumed to be at a single temperature of 112 K (202° R). The energy contribution of the nitrogen pressurant was assumed equal to the specific energy of liquid nitrogen (LN_2) at the LCH_4 bulk temperature value. For lack of better information, the energy contribution of the hydrogen pressurant was taken equal to the specific energy of hydrogen gas at the LCH_4 bulk temperature.

Change in wall energy. - The change in wall energy was determined by applying the first law of thermodynamics to an element of the wall:

$$\int_{U_{w_i}}^{U_{w_f}} dU_w = \Delta M_w \int_{T_i}^{T_f} c_v\, dt, \qquad c_v = c_v(T) \tag{22}$$

The total change of the wall is then

$$\Delta U_w \cong \sum_{M_w} \left[\Delta M_w \int_{T_i}^{T_f} c_v(T) dT\right] \tag{23}$$

Total energy change of system. - For convenience, equation (17) is substituted into equation (13)

$$\int_{t_i}^{t_f} \frac{d}{dt} (U_U + U_L + U_w) dt = \int_{t_i}^{t_f} \dot{M}_G h_G\, dt - \int_{t_i}^{t_f} \dot{M}_L h_L\, dt + \int_{t_i}^{t_f} \dot{Q}\, dt \tag{24}$$

Rearranging terms gives

$$\underbrace{\int_{t_i}^{t_f} (\dot{M}_G h_G + \dot{Q})dt}_{\substack{\text{Total energy added} \\ (\Delta U_T)}} = \underbrace{\int_{t_i}^{t_f} (\dot{M}_L h_L \, dt + dU_L)}_{\substack{\text{Total change in liquid} \\ \text{in tank plus liquid ex-} \\ \text{pelled energy } (\Delta U_L)}} + \underbrace{\int_{t_i}^{t_f} dU_U}_{\substack{\text{Total} \\ \text{change in} \\ \text{ullage en-} \\ \text{ergy } (\Delta U_U)}} + \underbrace{\int_{t_i}^{t_f} dU_w}_{\substack{\text{Total} \\ \text{change in} \\ \text{wall en-} \\ \text{ergy } (\Delta U_w)}} \tag{25}$$

Dividing through by ΔU_T gives

$$1 = \frac{\Delta U_L}{\Delta U_T} + \frac{\Delta U_U}{\Delta U_T} + \frac{\Delta U_w}{\Delta U_T} \tag{26}$$

The data presented herein are in the form of these ratios which show the relative distribution of the total energy input.

RESULTS AND DISCUSSION

Static Tank Expulsions

General. - Complete tank expulsions were made using GCH_4, GHe, GH_2, and GN_2 pressurants. The test parameters were inlet gas temperature and expulsion time. Expulsion time is the total time required to expel liquid from a 5 to a 95 percent ullage condition. Therefore, each data point represents a complete expulsion.

The experimentally determined pressurant gas requirements, as well as heat transfer data, were compared to analytically predicted results to determine the range of application of the analytical program. The analysis used is detailed in appendixes A, B, and C of each of the references 4 to 7. Two modifications were made to the contents of these appendixes. First, the ramp analysis was not employed at all; and secondly, a mass condensation term was added for the expulsions made using GCH_4 pressurant. The mass condensed was assumed equal to the tank wall mass exposed during expulsion times its integrated specific energy over the range between the bulk and saturation temperatures divided by the latent heat of evaporation; that is

$$M_{t,P} = \frac{\sum \left[\Delta M_w \int_{T_{BL}}^{T_{SL}} c_p \, dT_w \right]}{h_{SG-SL}} \tag{27}$$

The analytical results are presented in figures together with the corresponding experimental results. Comparisons are generally given in terms of an average deviation which is defined as

$$\frac{1}{\bar{N}} \sum_{\bar{N}} \left[\frac{|(\text{Experimental value}) - (\text{Analytical value})|}{(\text{Experimental value})} \right] (100) \tag{28}$$

where $\bar{N}$ is the number of data points in a given set of test conditions.

The results obtained using GCH_4 will be discussed first; the tests employing GHe and GH_2 will follow, and the three expulsions using GN_2 will conclude discussion of static tank expulsions. The test parameters, as well as the mass and energy balances for all four groups of data, appear in tables I and II.

Methane pressurant. - The quantity of GCH_4 required for the expulsion period is shown in figure 10 for two different inlet temperatures. For a given inlet gas temperature, there is an increasing pressurant requirement for increasing expulsion time. The longer the pressurant gas is exposed to cold surroundings, the greater the loss in pressurant energy. Also noteworthy on the figure is the amount of GCH_4 condensed. The quantities shown are between 27.7 and 32.6 percent of the total pressurant required for the expulsion period. The reason for this high condensation value is due to the considerable difference between the bulk liquid temperature and the saturation temperature corresponding to the 34.5×10^4-newton-per-square-meter (50-psia) ullage pressurant gas. As the tank wall is uncovered by the receding liquid during expulsion, it is still essentially at bulk liquid temperature. Methane pressurant in the ullage can condense on this wall until enough heat has been transferred to raise the wall temperature above the saturation temperature corresponding to the ullage gas.

The analytical predictions for the pressurant required for each expulsion are shown as solid symbols in figure 10. The best agreement between the analytical and experimental mass added curves is obtained for the fastest expulsion times. As expulsion time increases, the analysis underpredicts the amount of gas needed. The average deviation, however, of the analytical predictions from the experimental values is only 8.2 percent; the maximum deviation is 12.9 percent. The prime reason for this disagreement is the lack of a good analytical model for the mass transfer. The estimated amount (eq. (27)) of condensed pressurant was allowed to be a function of gas and wall properties only. It

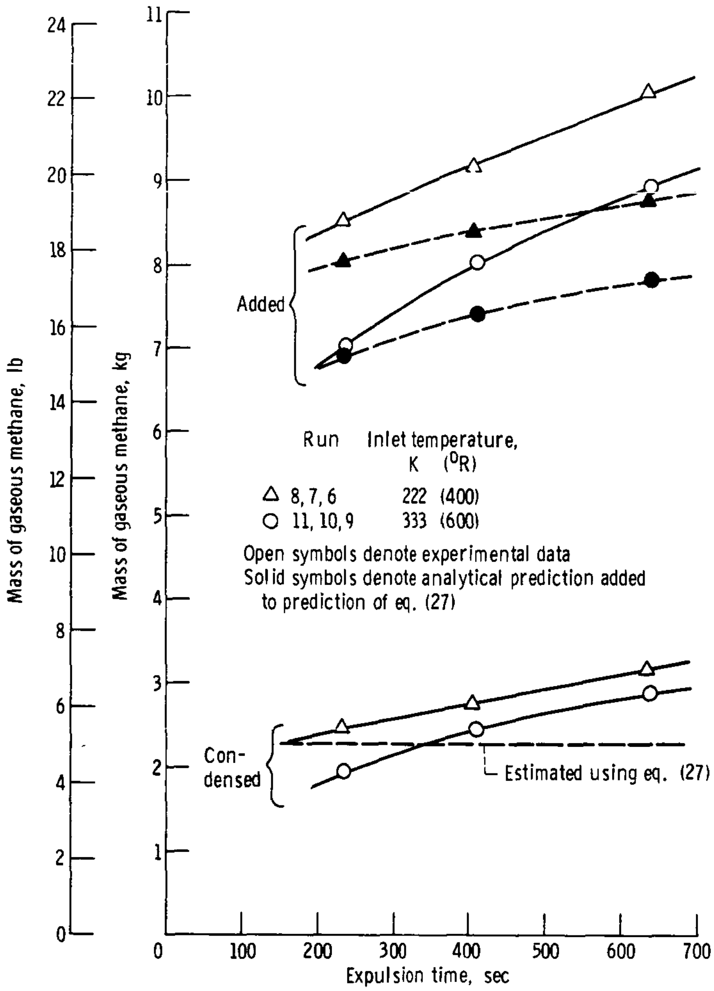


Figure 10. - Mass required during static tank expulsions using GCH_4 pressurant as a function of expulsion time. Tank pressure, 34.47×10^4 newtons per square meter (50 psia).

did not allow for variations of expulsion time or pressurant inlet temperature. This is an admitted deficiency, considering the experimental data in hand.

The time history of the GCH_4 pressurant flow rate for a typical expulsion is shown in figure 11. Time histories for the other expulsion runs have the same general shape. Note that the flow rate is fairly constant with only a small rise near the middle of the run. This rise is believed due to the greater heat lost by the pressurant gas to the thickened girth section of the tank. In the next two sections of the RESULTS AND DISCUSSION, GCH_4 flow rates will be shown which are in sharp contrast with figure 11.

Figure 12 shows the distribution of the total energy added to the tank via the incoming pressurant and the environment during the expulsion period. For the 222 K (400° R) runs, the greatest energy sink is the ullage gas ($\Delta U_{U,X}$), followed closely by the tank wall ($\Delta U_{w,X}$). For the 333 K (600° R) runs, these roles are reversed and the tank wall

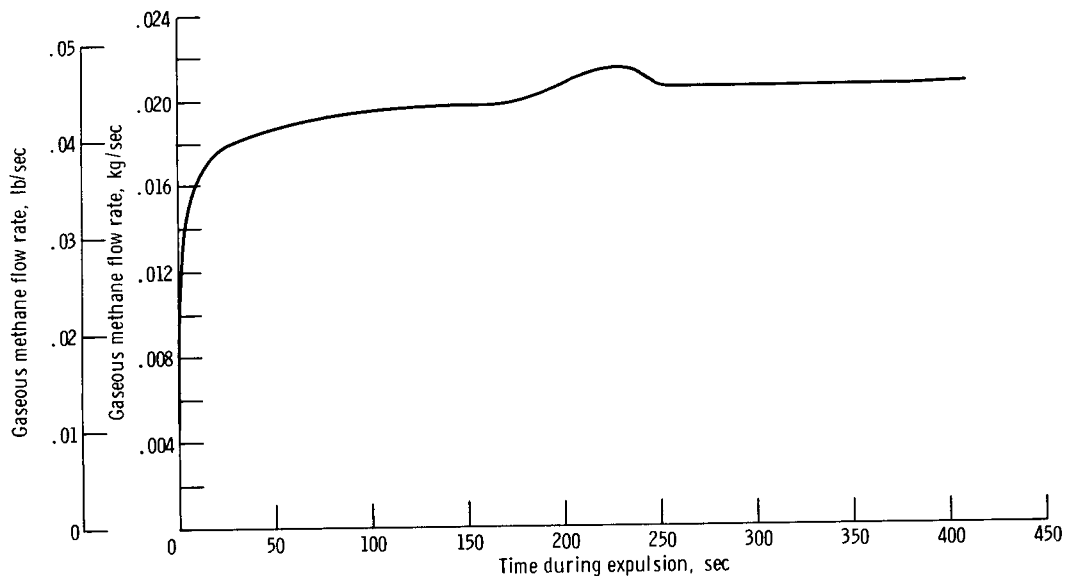
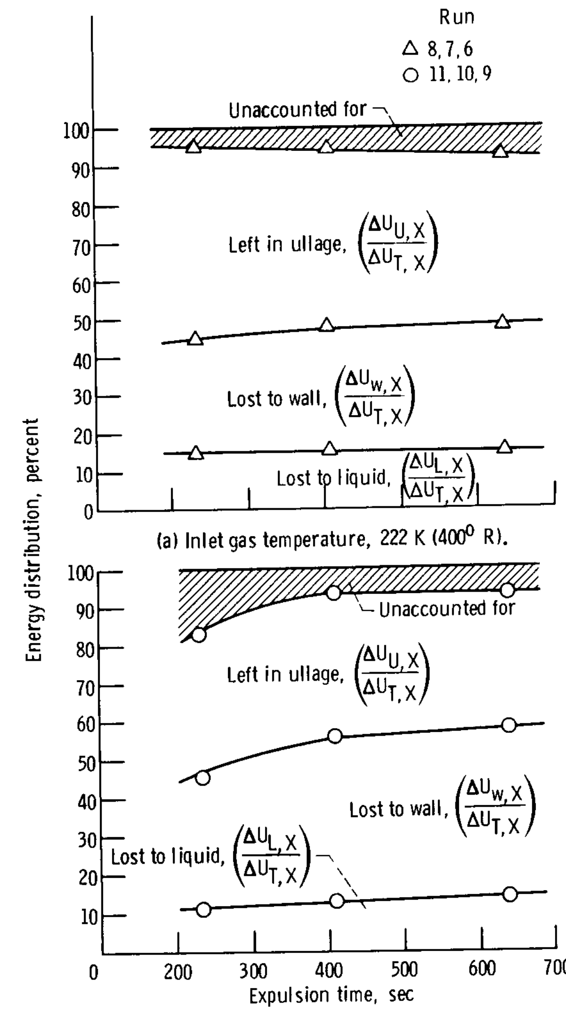


Figure 11. - Time history of GCH_4 pressurant flow rate during static tank expulsion. Tank pressure, 34.47×10^4 newtons per square meter (50 psia); inlet temperature, 333 K (600^0 R); run 10.

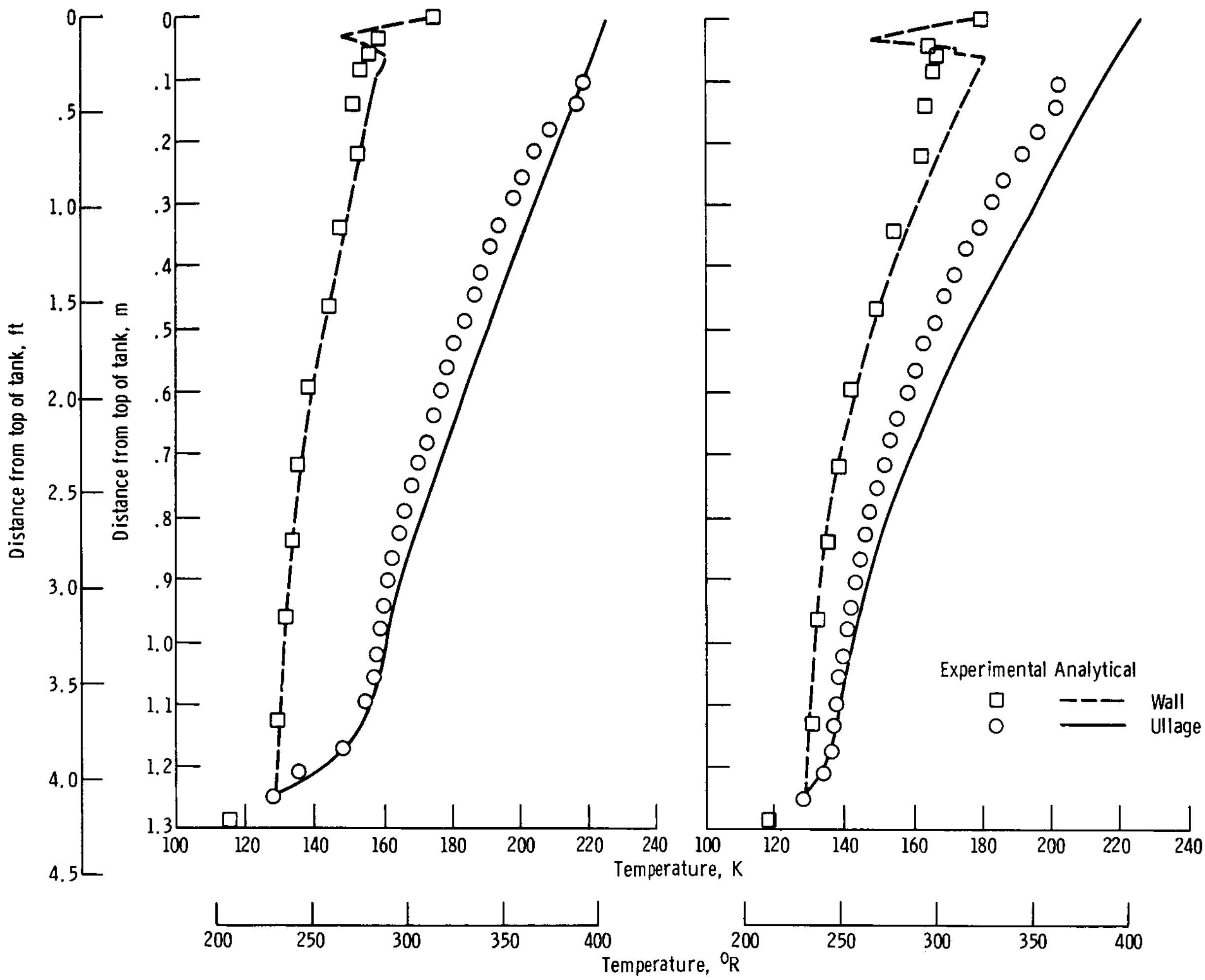


(a) Inlet gas temperature, 222 K (400^0 R).

(b) Inlet gas temperature, 333 K (600^0 R).

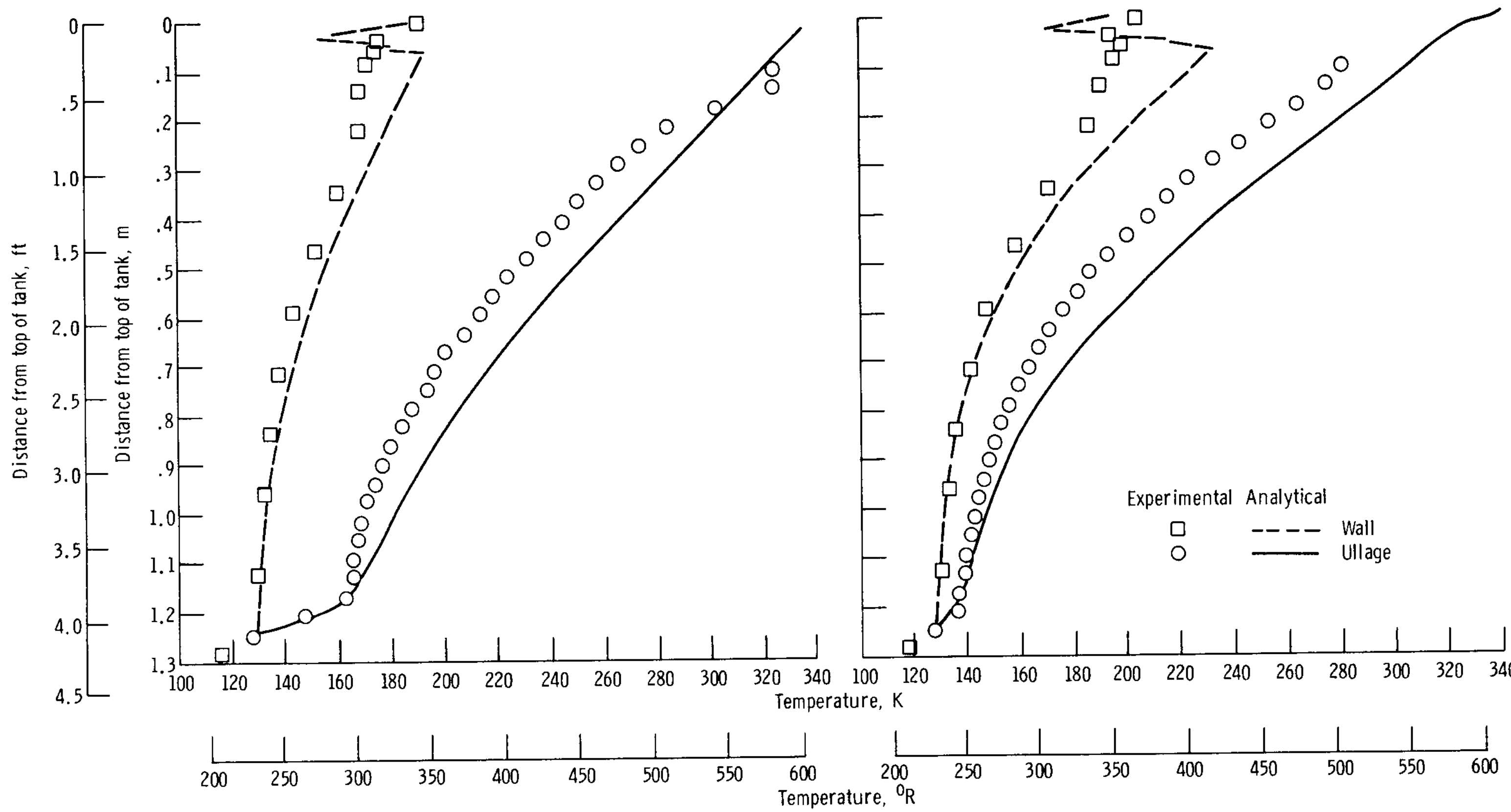
Figure 12. - Energy distribution for expulsion period for static tank tests using GCH_4 pressurant as a function of expulsion time, Tank pressure, 34.47×10^4 newtons per square meter (50 psia).

becomes the largest energy sink. For all cases, between 72 and 80 percent of the total energy added to the tank was either absorbed by the tank wall or remained in the ullage. The correlation between analysis and experimental data, therefore, depends largely on the ability of the analysis to predict final wall and ullage gas temperature profiles. These temperature profiles are, in turn, used to determine the increase in wall and ullage energy and the final ullage mass. A comparison of the analytical and experimental temperature profiles are shown in figures 13 and 14 for the four extremes of expulsion time and temperature. The agreement is best for the 231-second 222 K (400° R) expulsion where the maximum deviation was only 7.8 K (15° R) for the gas temperature and 5.6 K (10° R) for the wall temperature. In the worst case, the 638-second 333 K (600° R) expulsion, the maximum deviation of the gas temperature was 28.9 K (52° R) and 25 K (45° R) for the wall. These differences are approximately the same as those



(a) Run 8; expulsion time, 231 seconds. (b) Run 6; expulsion time, 633 seconds.

Figure 13. - Comparison of analytical and experimental gas and wall temperatures using GCH_4 pressurant. Tank pressure, 34.47×10^4 newtons per square meter (50 psia); inlet temperature, 222 K (400° R).



(a) Run 11; expulsion time, 234 seconds.

(b) Run 9; expulsion time, 638 seconds.

Figure 14. - Comparison of analytical and experimental gas and wall temperatures using GCH_4 pressurant. Tank pressure, 34.47×10^4 newtons per square meter (50 psia); inlet tmperature, 333 K (600^0 R).

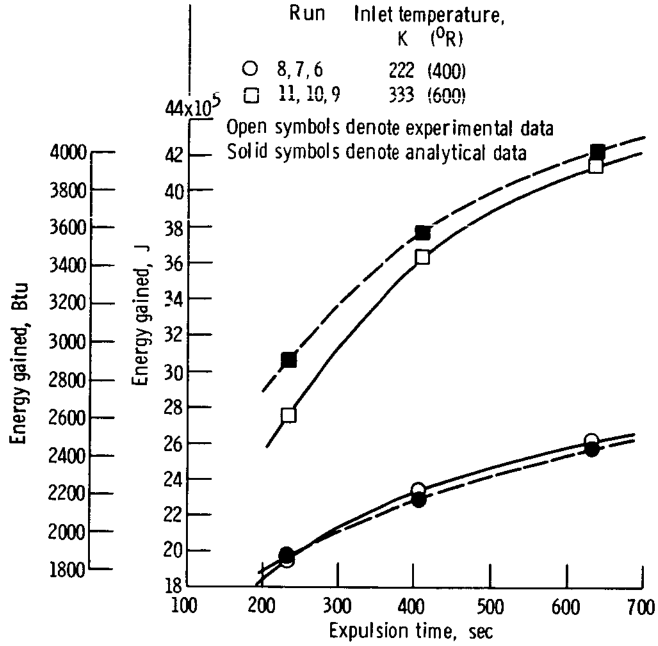


Figure 15. - Energy gained by wall during static tank expulsions using GCH_4 pressurant as a function of expulsion time. Tank pressure, 34.47×10^4 newtons per square meter (50 psia).

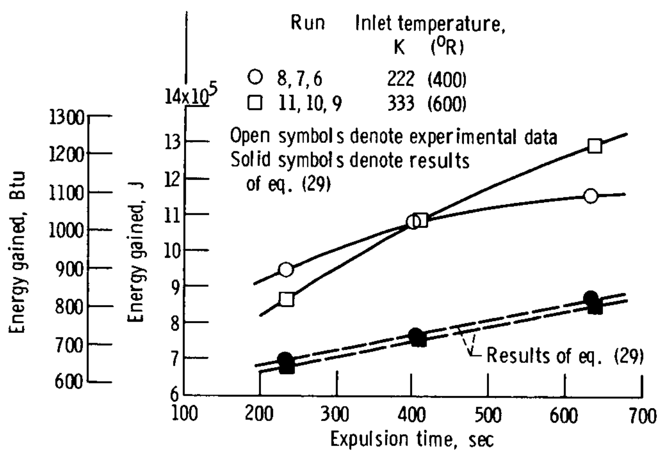


Figure 16. - Energy gained by liquid during static tank expulsions using GCH_4 pressurant as a function of expulsion time. Tank pressure, 34.47×10^4 newtons per square meter (50 psia).

obtained between analytical and experimental data for the work with LH_2 tanks described in references 4 to 7.

Figure 15 displays the agreement between the analytically predicted and experimentally determined energy gained by the tank wall ($\Delta U_{w,P}$ and $\Delta U_{w,X}$, respectively). The agreement is considered good for the 222 K (400° R) expulsions but only fair for the 333 K (600° R) runs. The deviation for the higher temperature runs is attributed to the complicating effects of the neck, flanges, and tank lid which were hard to model analytically. These portions of the tank constituted approximately 22 percent of the total tank mass.

The heat lost to the LCH_4 propellant is a small percentage of the total heat added to the tank during expulsion. Further, it is relatively constant over the range of test runs conducted. The average percentage of heat lost $\Delta U_{L,X}/\Delta U_{T,X}$ is 13.7; the range is between 10.9 and 15.1 percent (see fig. 12). Figure 16 displays the agreement between the approximated energy and the experimentally determined energy gained by the LCH_4 propellant ($\Delta U_{L,P}$, $\Delta U_{L,X}$). For purposes of analysis in this report, the approximate heat lost to the liquid $\Delta U_{L,P}$ was set equal to

$$P\,\Delta V + \frac{1}{2}\,(\text{Environmental heating}) + M_t(\mu_{SL}) \qquad (29)$$

This expression makes the approximated heat to the liquid independent of inlet gas temperature. The small differences in the approximated heat values for the 222 K (400° R) and the 333 K (600° R) runs in figure 16 are due to small differences in the tank pressure and the amount of LCH_4 expelled during each run. The experimentally determined liquid energy term $\Delta U_{L,X}$ includes the work energy of approximately 515×10^3 joules (488 Btu). When this work term and the environmental heating are subtracted from the experimentally determined liquid energy term $\Delta U_{L,X}$, the remaining energy is only 24 percent of that contributed by the amount of GCH_4 condensed during the run. This fact tends to support the contention of the analytical model that the tank wall is the primary medium for condensation.

The liquid outflow temperature-time histories for the 333 K (600° R) runs are plotted in figure 17. The lack of any substantial rise in temperature until the very end of expulsion (e.g., less than 0.28 K (0.5° R) after completion of 92 percent of the expulsion time), verifies that the layer of heated liquid is very thin. Later, in the second and third sections of the RESULTS AND DISCUSSION, LCH_4 outflow temperatures will be shown which are in sharp contrast with figure 17.

GHe and GH_2 pressurants. - The quantities of GHe and GH_2 required for the expulsion period are shown in figure 18 for two different inlet gas temperatures. The mass curves for the two pressurants are almost identical in trends and differ in magnitude by

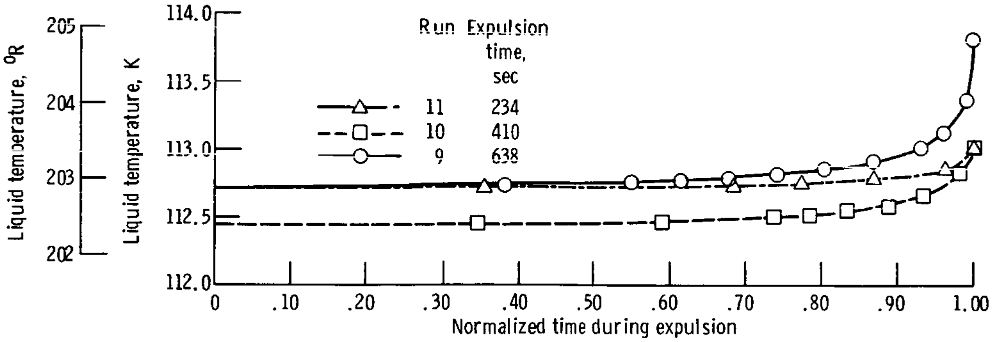


Figure 17. - Temperature of liquid methane at tank outlet as a function of normalized time during expulsion. Tank pressure, 34.47×10^4 newtons per square meter (50 psia); inlet temperature, 333 K (600° R).

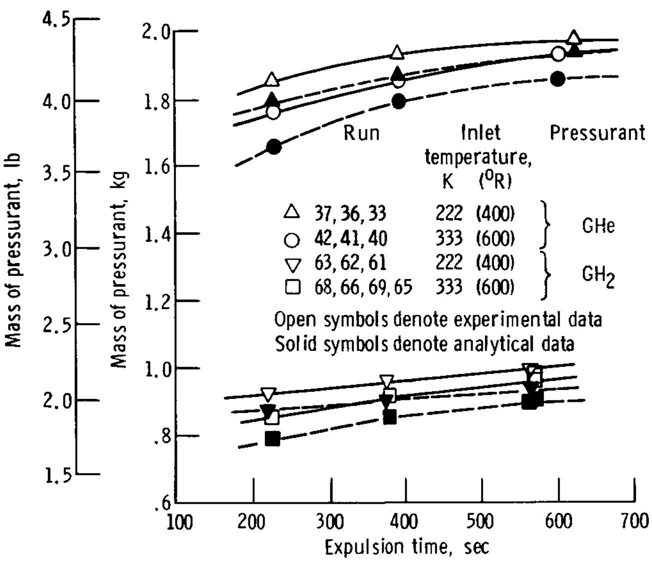


Figure 18. - Mass required during static tank expulsions using GHe and GH_2 pressurant as a function of expulsion time. Tank pressure, 34.47×10^4 newtons per square meter (50 psia).

a factor of two due basically to the molecular weight difference. For a given inlet gas temperature, the expected trend of increasing pressurant requirements for increasing expulsion times is present. The effect on gas requirements for an increase of 111 K (200° R) is only a maximum of 5.3 percent for GHe and 7.7 percent for GH_2. The maximum increase in requirements due to the parameter expulsion time is only 10.3 percent for GHe and 13 percent for GH_2. The curves for mass added are tending to level off toward the 600-second expulsion time and both the 222 K (400° R) and 333 K (600° R) lines appear asymptotic to nearly the same value. The major reason for this is the fact that, for long expulsions, the ullage gas temperatures are in near equilibrium with the wall temperatures for most of the volume of the tank. Gas and wall temperatures will be discussed further later in this section.

The analytical predictions for mass added are also shown in figure 18. The agreement between analysis and experiment is considered good. The average deviation for all the GHe expulsions was 3.6 percent; the average when considering the GH_2 data was 6.3 percent. For the 222 K (400° R) inlet temperature runs, the average deviation was 2.8 percent for the GHe data and 5.7 percent for GH_2. The maximum deviation was 3.3 percent when using GHe and 6.0 percent for GH_2. The 333 K (600° R) cases are a little worse with the average deviation being 4.4 and 6.8 percent for GHe and GH_2 pressurants, respectively. The maximum deviation was 5.9 percent for GHe and 8.0 percent for GH_2.

As stated earlier in the report, the composition of the ullage gas was determined by gas sample data at the end of each section of the complete pressurization cycle (i.e., at the ends of the ramp period, the hold period, and the expulsion period). Determination of the ullage composition at the end of the ramp and hold periods was, at best, difficult because only the outlet of the highest gas analyzer station was uncovered. At these two times in the pressurization cycle, the composition was determined by a three-point curve constructed as follows: the composition was defined as 100 percent pressurant gas at the top of the tank, equal to the analyzer reading at the level of the sampling station, and defined as 38 percent GHe or 23 percent GH_2 at the liquid methane interface. This last definition is an engineering approximation of the vapor equilibria for GHe-LCH_4 and GH_2-LCH_4 systems. The three data points were then connected by straight lines and the amount of mass of each component of the ullage gas was determined.

This technique was considered acceptable to furnish data for computing the energy content of the ullage gases at the start of expulsion since a 10 percent error in this energy hardly affected the total change of the ullage energy over the expulsion period (introduced less than 1 percent error). This technique was also used in the computation to determine the mass of liquid methane evaporated into the ullage during the expulsion period. However, when used to furnish data for computing the quantities of GHe and GH_2 dissolved in the LCH_4 propellant at the end of the ramp and hold periods, this technique led, in several of the runs, to the obviously erroneous conclusion that helium and hydrogen were evaporated out of the assumed pure LCH_4 propellant. This conclusion forced the calculation of dissolved GHe or GH_2 to be considered over the entire pressurization cycle (i.e., ramp time + hold time + expulsion time). As a result, the amount of helium or hydrogen dissolved was computed using only the end of expulsion data and the preramp data. The end of expulsion data was obtained using data from all the gas sampling tubes; the preramp data used the fact that only GCH_4 existed in the ullage prior to the beginning of the ramp period.

Figure 19 displays the ullage gas concentration curves for the 222 K (400° R) runs obtained from the gas sampling tubes at the end of expulsion. As can be seen in the figure, only the bottom sensor read any significant concentration of methane, and it was al-

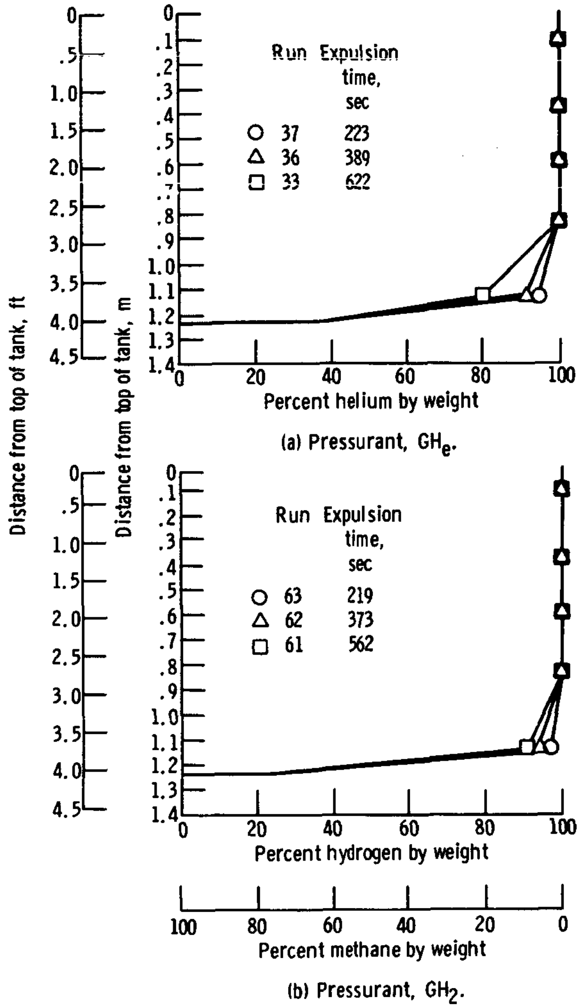


Figure 19. - End of expulsion ullage gas concentrations for static tank expulsions using GHe and GH_2 pressurant. Tank pressure, 34.47×10^4 newtons per square meter (50 psia); inlet temperature, 222 K (400° R).

ways a small amount. Using this data, and the fact that only GCH_4 existed in the ullage prior to the beginning of the ramp, the mass of GHe and GH_2 dissolved in the LCH_4 propellant was calculated. Figure 20 displays the amounts dissolved in a percentile manner relative to the total amount of pressurant added during the complete pressurization cycle. The authors consider these quantities accurate only within ±2 ordinate units. This figure is presented only to show that the amounts of pressurant gases dissolved are small and that there is a trend toward dissolving slightly more pressurant as expulsion time increases.

Figure 21 displays the mass of methane evaporated during the GHe and GH_2 pressurization runs. Because of the method of measurement, the authors consider these quantities accurate only within ±0.045 kilogram (±0.1 lb). As a result, small variations

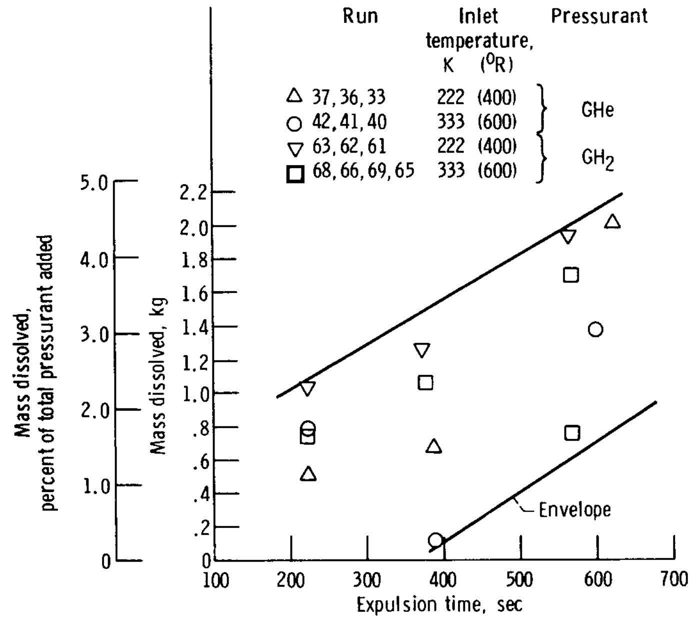


Figure 20. - Percent GHe or GH_2, dissolved in propellant, of total pressurant added during each complete static tank run as a function of expulsion time. Tank pressure, 34.47×10^4 newtons per square meter (50 psia).

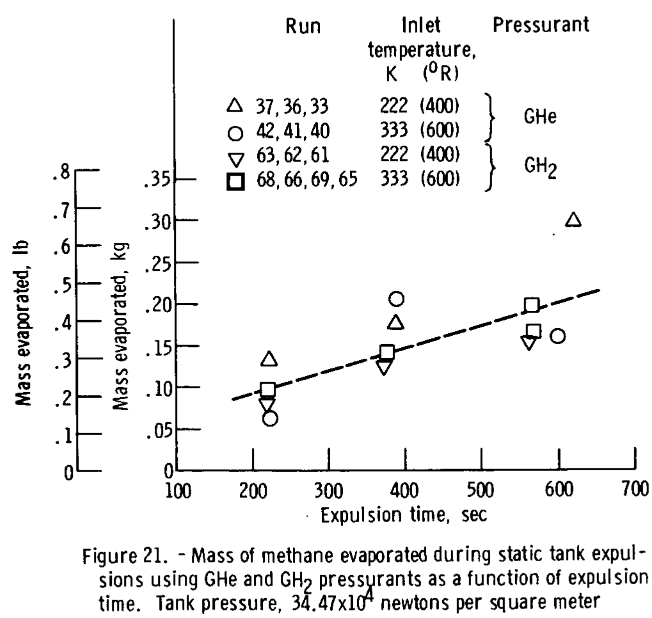


Figure 21. - Mass of methane evaporated during static tank expulsions using GHe and GH_2 pressurants as a function of expulsion time. Tank pressure, 34.47×10^4 newtons per square meter (50 psia).

should not be considered significant. As expected, liquid methane was evaporated into the ullage during all runs, but the most significant thing is that all values are small. The maximum latent heat involved is only 14.2×10^4 joules (134 Btu). This amounts to, at the worst, 5.6 percent of the total heat added to the tank during expulsion. The averaged latent heat considering all 13 runs, is only 2.2 percent of the total heat added to the tank during the expulsion period.

Figures 22 and 23 show the distribution of the total energy added to the tank via both the incoming GHe or GH_2 pressurant and the heat input from the environment during the expulsion period. For the 222 K (400° R) GHe runs, the amount of heat lost to the tank

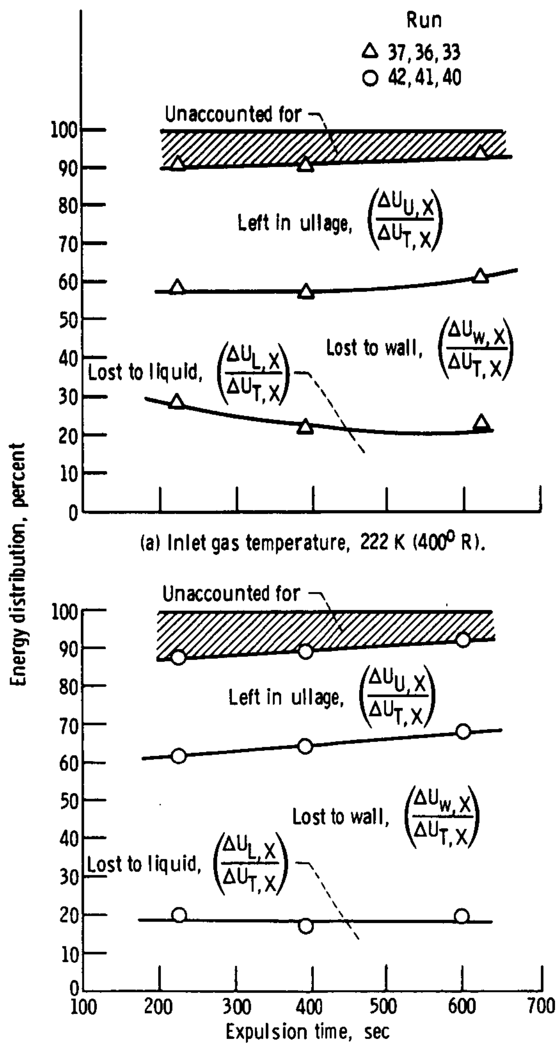
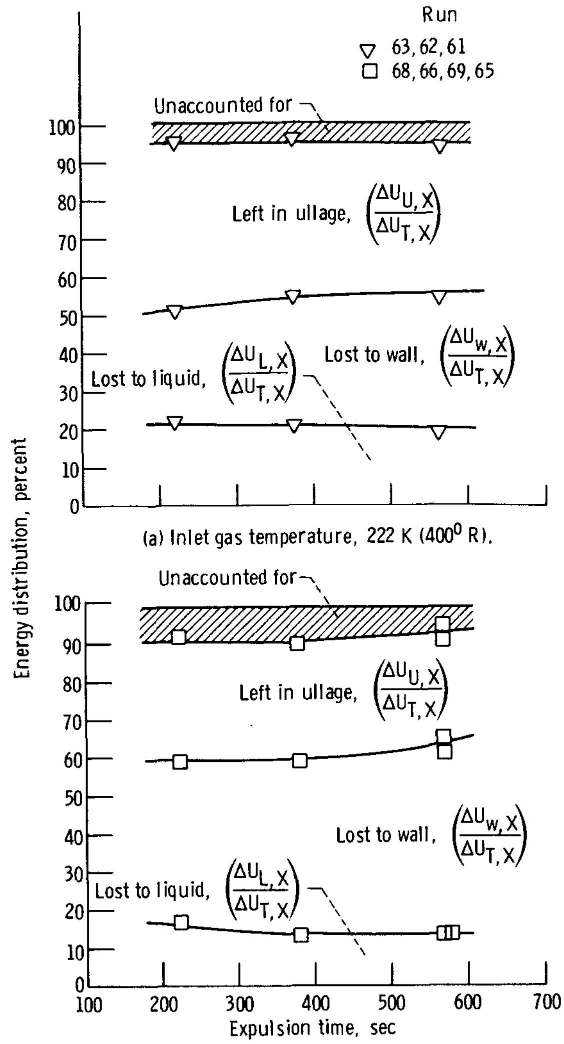


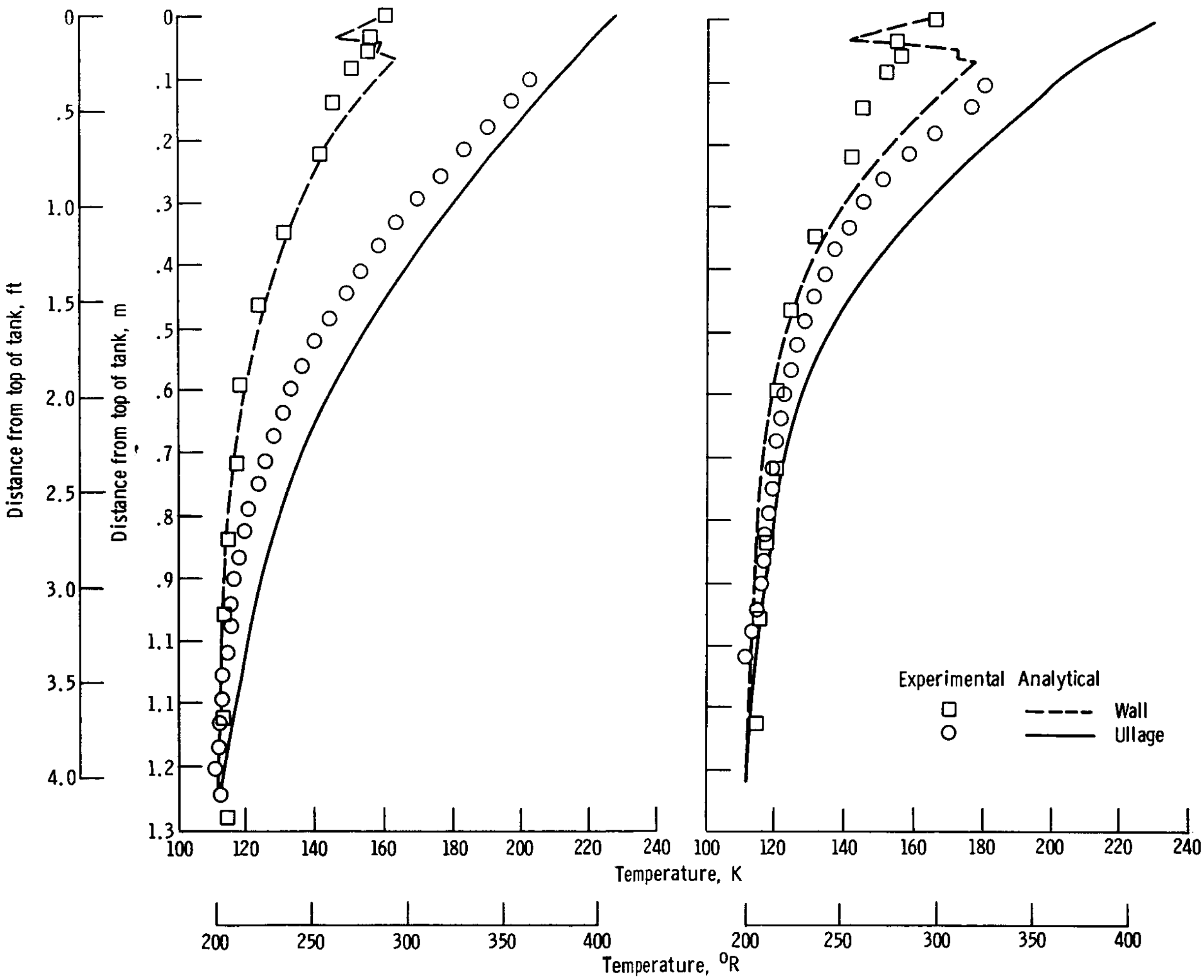
Figure 22. - Energy distribution for expulsion period for static tank tests using GHe pressurant as a function of expulsion time. Tank pressure, 34.47×10^4 newtons per square meter (50 psia).



(b) Inlet gas temperature, 333 K (600° R).

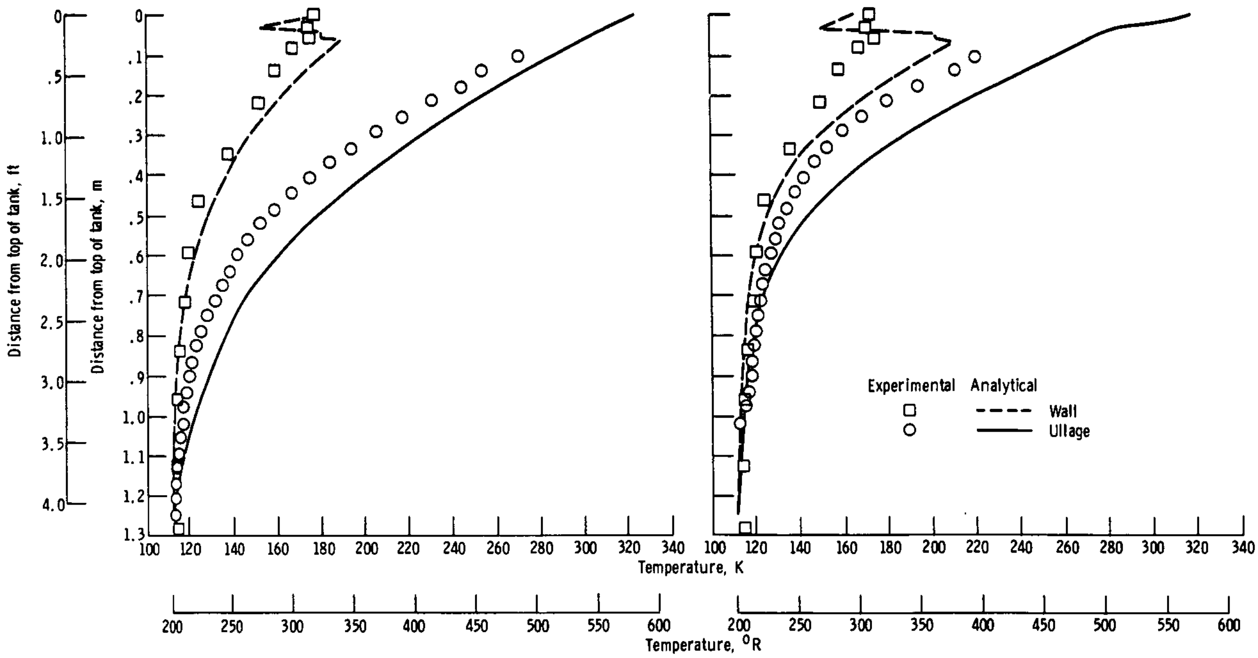
Figure 23. - Energy distribution for expulsion period for static tank tests using GH_2 pressurant as a function of expulsion time. Tank pressure, 34.47×10^4 newtons per square meter (50 psia).

wall $\Delta U_{w,X}$ was approximately equal to the amount left in the ullage $\Delta U_{U,X}$ at the end of expulsion. When 222 K (400° R) GH_2 was used, the greatest energy sink was the ullage gas $\Delta U_{U,X}$ followed fairly closely by the tank wall $\Delta U_{w,X}$. For the 333 K (600° R) runs, the largest energy sink for both gases is the tank wall $\Delta U_{w,X}$. The absolute value of the ullage energy is nearly independent of expulsion time and pressurant inlet temperature. It should be noted, however, that the absolute value of the ullage energy is greater for hydrogen than for helium because of the greater specific heat of hydrogen. For all runs (GHe and GH_2), between 63 and 81 percent of the total energy added to the tank during expulsion was either absorbed by the tank wall $\Delta U_{w,X}$ or remained in the



(a) Inlet temperature, 222 K (400° R).

Figure 24. - Analytical and experimental gas and wall temperatures at end of expulsion for static tank runs using GHe pressurant. Tank pressure, 34.47×10^4 newtons per square meter (50 psia).



(b-1) Run 42; expulsion time, 224 seconds.

(b-2) Run 40; expulsion time, 599 seconds.

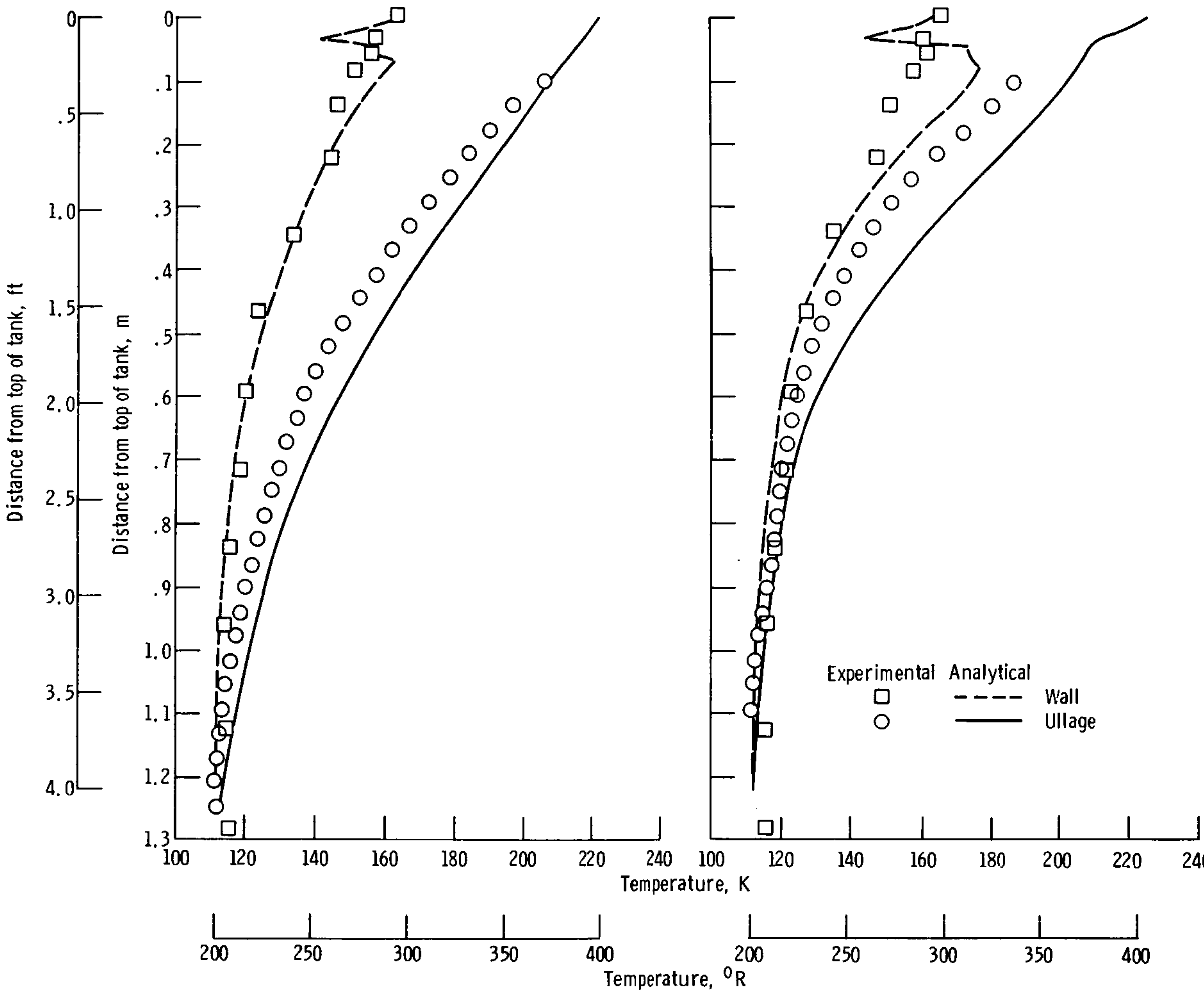
(b) Inlet temperature, 333 K (600° R).

Figure 24. - Concluded.

ullage $\Delta U_{U,X}$. These results are consistent with those mentioned earlier for the gaseous methane runs.

Figures 24 and 25 display the agreement between analytically predicted ullage gas and wall temperatures against those experimentally measured. The plots are for the longest and shortest expulsions for both pressurants at 222 K (400° R) and 333 K (600° R) inlet temperatures. Generally, the analytical predictions agreed fairly well with experimental values for the long expulsions. As a result, fairly good agreement was obtained between predicted and experimentally determined mass requirements for these runs. The worst disagreement between predicted and experimental ullage gas temperatures occurs for the short expulsion runs. Further, this difference is in the region of the greatest gas mass (i.e., near the bottom of the ullage volume where the majority of the mass of ullage gas is concentrated). As a result, use of the analytically predicted temperature profile in determining the mass of ullage gas present for the short expulsions results in a smaller quantity than obtained when the integration is performed using experimental temperature measurements. This disagreement of temperature profiles is thought to be the major reason for underprediction of pressurant requirements for the fast expulsion runs.

The result of the differences between predicted and experimental tank wall heat gains

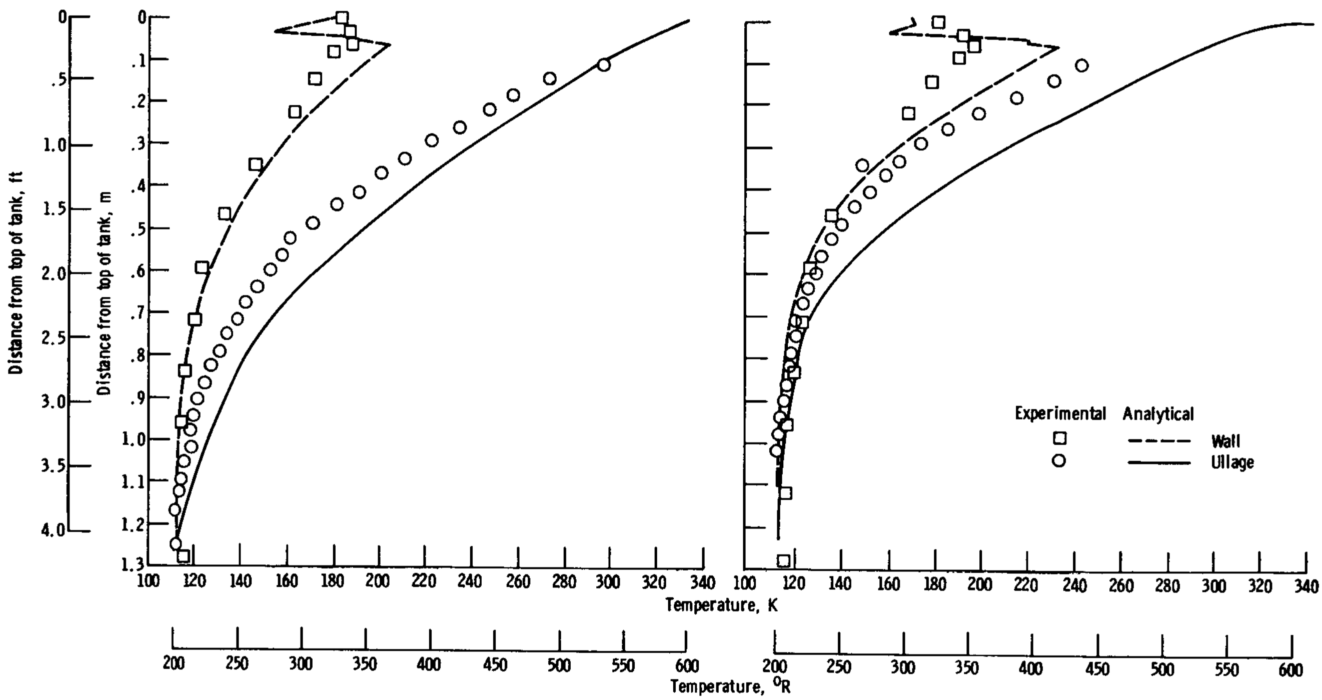


(a-1) Run 63; expulsion time, 219 seconds.

(a-2) Run 61; expulsion time, 562 seconds.

(a) Inlet temperature, 222 K (400° R).

Figure 25. - Analytical and experimental gas and wall temperatures at end of expulsion for static tank runs using GH_2 pressurant. Tank pressure, 34.47×10^4 newtons per square meter (50 psia).



(b-1) Run 68; expulsion time, 222 seconds.

(b-2) Run 69; expulsion time, 566 seconds.

(b) Inlet temperature, 333 K (600° R).

Figure 25. - Concluded.

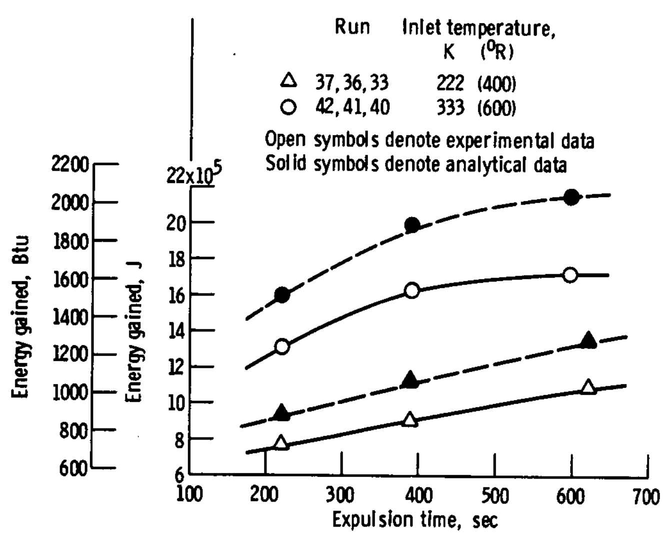


Figure 26. - Energy gained by wall during static tank expulsions using GHe pressurant as a function of expulsion time. Tank pressure, 34.47×10^4 newtons per square meter (50 psia).

is shown in figures 26 and 27. The predicted amount of heat lost to the tank wall $\Delta U_{W,P}$ is always greater than that experimentally measured $\Delta U_{W,X}$. Further, this difference becomes larger as expulsion time increases. These same results could also be arrived at by considering the agreement between the analytically predicted and experimentally measured wall temperature profiles in figures 24 and 25. In all cases, the predicted wall temperature in the more massive lid area is higher than the experimentally measured values. Further, this difference also becomes larger for the longer expulsion time runs. The maximum deviation between predicted and experimental tank wall heat gains for the GHe pressurant runs is 25 percent; for the GH_2 runs, the value is 17 percent. The average deviation considering all runs was 18.3 percent.

The heat lost to the LCH_4 propellant is the smallest percentage of the total heat added to the tank during expulsion. The experimental ($\Delta U_{L,X}$) and predicted ($\Delta U_{L,P}$) values of heat transferred are plotted in figure 28 for both pressurant gases. For purposes of analysis in this report, the approximate heat lost to the liquid $\Delta U_{L,P}$ was set equal to

$$P\,\Delta V + \frac{1}{2}\,(\text{environmental heating}) \tag{30}$$

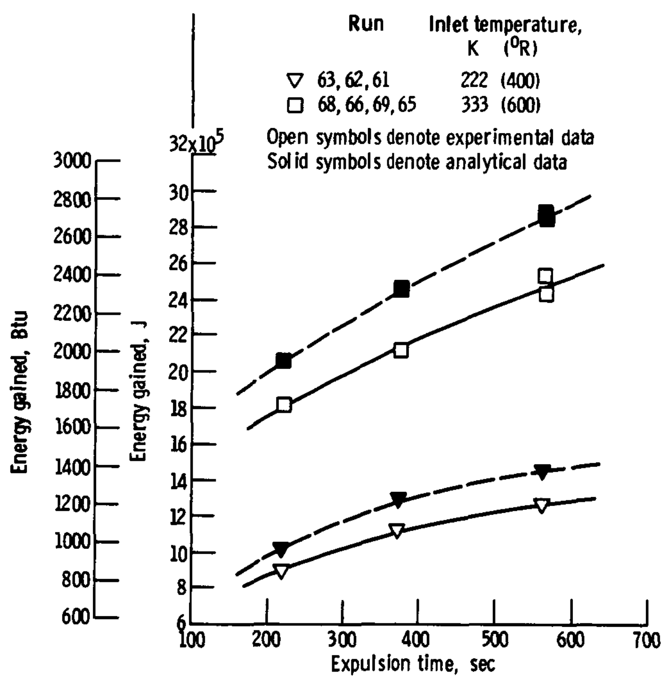


Figure 27. - Energy gained by wall during static tank expulsions using GH_2 pressurant as a function of expulsion time. Tank pressure, 34.47×10^4 newtons per square meter (50 psia).

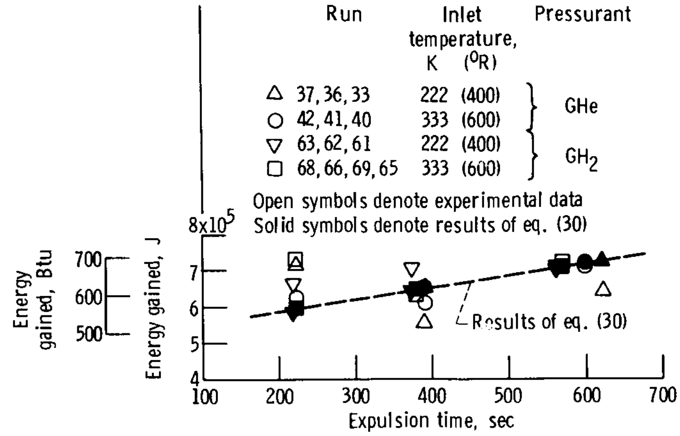


Figure 28. - Energy gained by liquid during static tank expulsions using GHe and GH_2 pressurants as a function of expulsion time. Tank pressure, 34.47×10^4 newtons per square meter (50 psia).

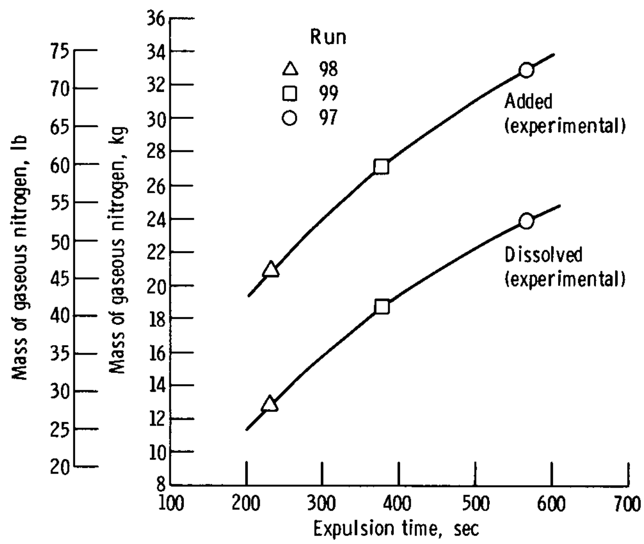


Figure 29. - Mass required during static tank expulsions using GN_2 pressurant as a function of expulsion time. Tank pressure, 34.47×10^4 newtons per square meter (50 psia); inlet temperature, 333 K (600° R).

The agreement between this approximation and experimental data verifies that this assumption is quite acceptable.

Nitrogen pressurant. - Gaseous nitrogen was used to determine its suitability for use in ground facilities or where the cost of helium is prohibitive. The quantity of GN_2 required for the expulsion period is shown in figure 29 for an inlet gas temperature of 333 K (600° R). The rise in requirements as a function of expulsion time is very pronounced. The most noteworthy point in the figure is the amount of GN_2 which dissolves in the LCH_4 propellant. These quantities are between 61.2 and 72.5 percent of the pressurant gas added during the expulsion period. The analytical model used so far was inadequate regarding large mass transfer processes in the system. No attempt was made to correlate this difference between analysis and experiment.

Figure 30 displays the time histories of the GN_2 flow rates during the three expulsions. These curves show a high peak during the first part of the expulsion process as the GN_2 dissolves rapidly into the increasing liquid surface area. The flow rates then taper off as the remaining liquid propellant warms and becomes more saturated with nitrogen.

In the case of nitrogen-liquid methane mixtures, the density of the mixture is higher than the density of pure liquid methane. Figure 31 shows the density of a N_2-LCH_4 mixture as a function of temperature and nitrogen concentration. Densities were calculated using reference 8. Further, equilibrium data for a completely mixed N_2-LCH_4 system was obtained for a temperature of 116.7 K (210° R) from reference 9. Using the original

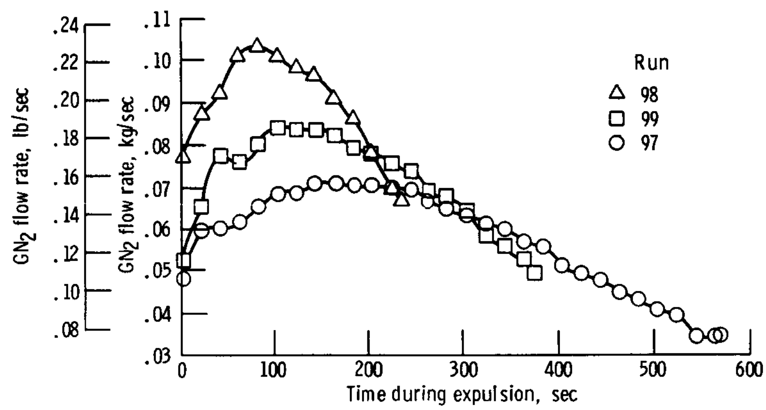


Figure 30. - Time history of GN_2 pressurant flow rate during static tank expulsions. Tank pressure, 34.47×10^4 newtons per square meter (50 psia); inlet temperature, 333 K (600° R).

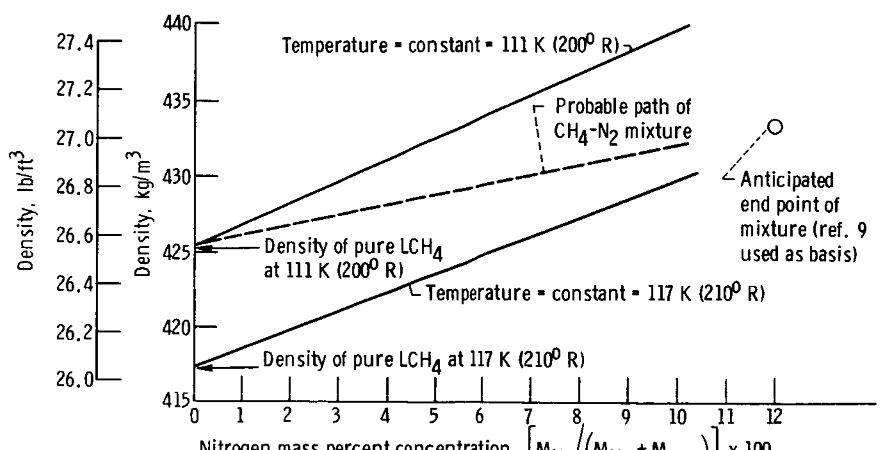


Figure 31. - Density of nitrogen-liquid methane mixtures as a function of nitrogen mass percent. Tank pressure, 34.47×10^4 newtons per square meter (50 psia).

amount of LCH_4 in the tank, as well as the mixture density calculation in reference 8, the density of the mixture at the 116.7 K (210° R) equilibrium condition was computed. This mixture density can be considered the probable endpoint for the density changes going on in the LCH_4 propellant during nitrogen pressurized expulsion. Starting off with pure LCH_4, and keeping in mind the endpoint of mixing, a probable density increase path can be added to figure 31. The resulting unstable density gradient caused by the addition of nitrogen to the mixture makes the liquid in the tank self-mixing. The total amount dissolved is limited by the rate of this mixing and by the fact that the equilibrium concentration decreases as the mixed liquid warms. The fact that pronounced mixing is occurring in the propellant is brought out in figure 32, which is a time history of the liquid temperature at the tank outlet. As can be seen in the figure, the outlet liquid temperature starts increasing immediately after the beginning of expulsion.

This self-mixing characteristic of the nitrogen-methane mixtures just about precludes use of nitrogen as a usable pressurant in liquid methane fuel systems. Because of the mixing, pure methane cannot be expected at the entrance to a combustion device and, further, cavitation problems could be expected in the fuel system components between the pressurized propellant tank and the combustion device.

Figure 33 displays the distribution of the total energy added to the tank via the incoming pressurant and the heat input from the environment during the expulsion period. The greatest energy sink is the liquid ($\Delta U_{L,X}$) which absorbed, on the average, 48.0 percent of the heat added. The experimentally determined liquid energy term $\Delta U_{L,X}$ includes the work energy of approximately 515×10^3 joules (488 Btu). This work term, and the environmental heating term, constitute only 9 to 14 percent of the liquid energy term $\Delta U_{L,X}$. The rest of the energy to the liquid is due to the dissolved nitrogen and its heat of solution.

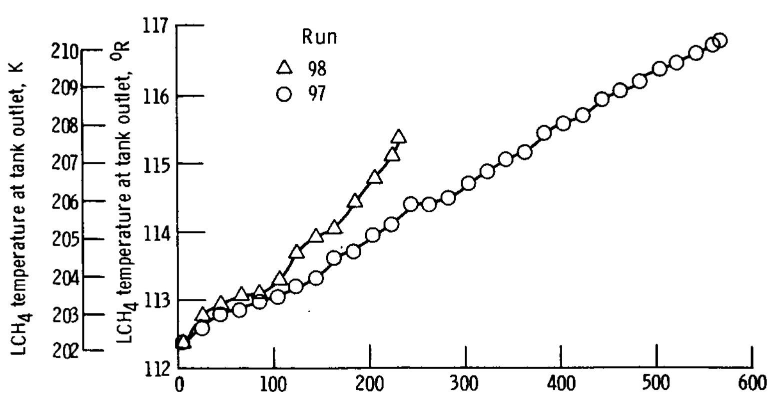


Figure 32. - Time history of LCH_4 temperature during static tank expulsions using GN_2 pressurant. Tank pressure, 34.47×10^4 newtons per square meter (50 psia); inlet temperature, 333 K (600° R).

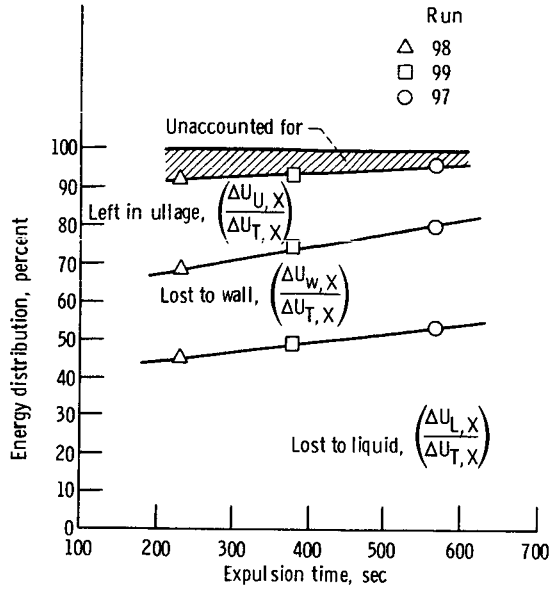


Figure 33. - Energy distribution in 1.52-meter- (5-ft-) diameter tank at end of expulsion period using GN_2 pressurant. Tank pressure, 34.47×10^4 newtons per square meter (50 psia); inlet temperature, 333 K (600° R); static tank expulsions.

Slosh Expulsions, Unbaffled Tank

General. - Complete tank expulsions were made using GCH_4, GHe, and GH_2 pressurants. The main test parameters were inlet gas temperature and expulsion time. All expulsions in this group were made while the tank was being oscillated at an amplitude of ±2.23 centimeters (±0.88 in.) and at a frequency corresponding to the natural frequency of the liquid remaining in the tank. Starting at the beginning of expulsion, the slosh amplitude was increased linearly from 0.0 to ±2.23 centimeters (0.0 to ±0.88 in.) over approximately a 60-second time period. The purpose of the ramped amplitude was to allow the GCH_4 over LCH_4 expulsions to be made without a fall off in tank pressure at the beginning of expulsion. Excessive liquid propellant splashing resulted if the full slosh amplitude was imposed on the tank immediately at the start of expulsion. This splashing resulted in excessive cooling of the ullage gas and a dropoff in the tank pressure. The slosh amplitude of ±2.23 centimeters (±0.88 in.) was chosen so that the slosh force parameter given in reference 10 (and hence slosh wave height) would be at a maximum value.

The experimentally determined pressurant gas requirements, as well as heat and mass transfer data, for these slosh tests are compared to similar data for the static tank tests of the first section. The major objectives are to point out marked differences between the sets of data and the reasons for the differences. No analytical predictions were made for the slosh runs in this group.

The results obtained using GCH_4 will be discussed first, followed by the tests employing GHe and GH_2. The main test parameters, as well as the mass and energy balances for the three major groups of data, appear in tables III and IV.

Methane pressurant. - The quantity of GCH_4 required for the expulsion period is shown in figure 34 for the two different inlet temperatures. The requirements for static tank expulsions are also shown as a reference. As with the static tank expulsions, both increasing expulsion time and decreasing inlet gas temperatures cause a rise in the amount of required pressurant. Both of these parameters had a greater effect under slosh conditions in contrast to the small effects for the static tank cases. Compared to the static tank runs, the pressurant requirements for these slosh expulsions were increased, on the average, by a factor of 3.1 for the 222 K (400° R) inlet temperature and a factor of 2.7 at 333 K (600° R). Of prime interest is the quantity of condensed pressurant. On the average, condensation increased by a factor of 7.6 for the 222 K (400° R) runs and by a factor of 5.7 for the 333 K (600° R) cases over values obtained for static tank work at comparable temperatures. These amounts of condensation are 74.3 and 67.7 percent of the total pressurant required during expulsion for the warm and cold inlet temperature runs, respectively. These percentages are up significantly from the 27 to 33 percent values obtained during the static tank runs. Condensed pressurant was the main reason for the large increase in expulsion pressurant requirements. The increased condensation is expected because the tank walls are continually being washed by the liquid propellant. An area of tank wall would be uncovered by the slosh wave and would provide

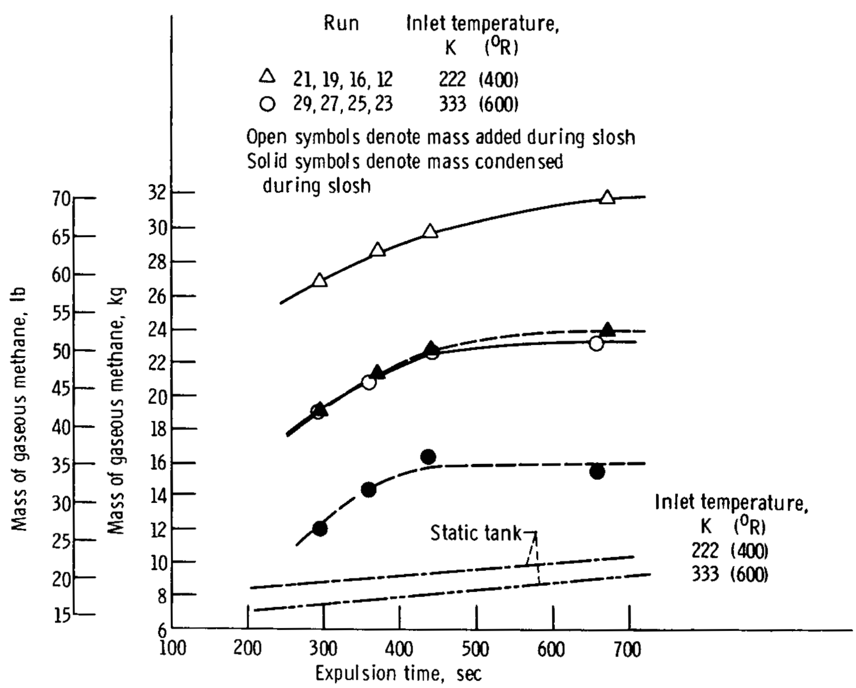
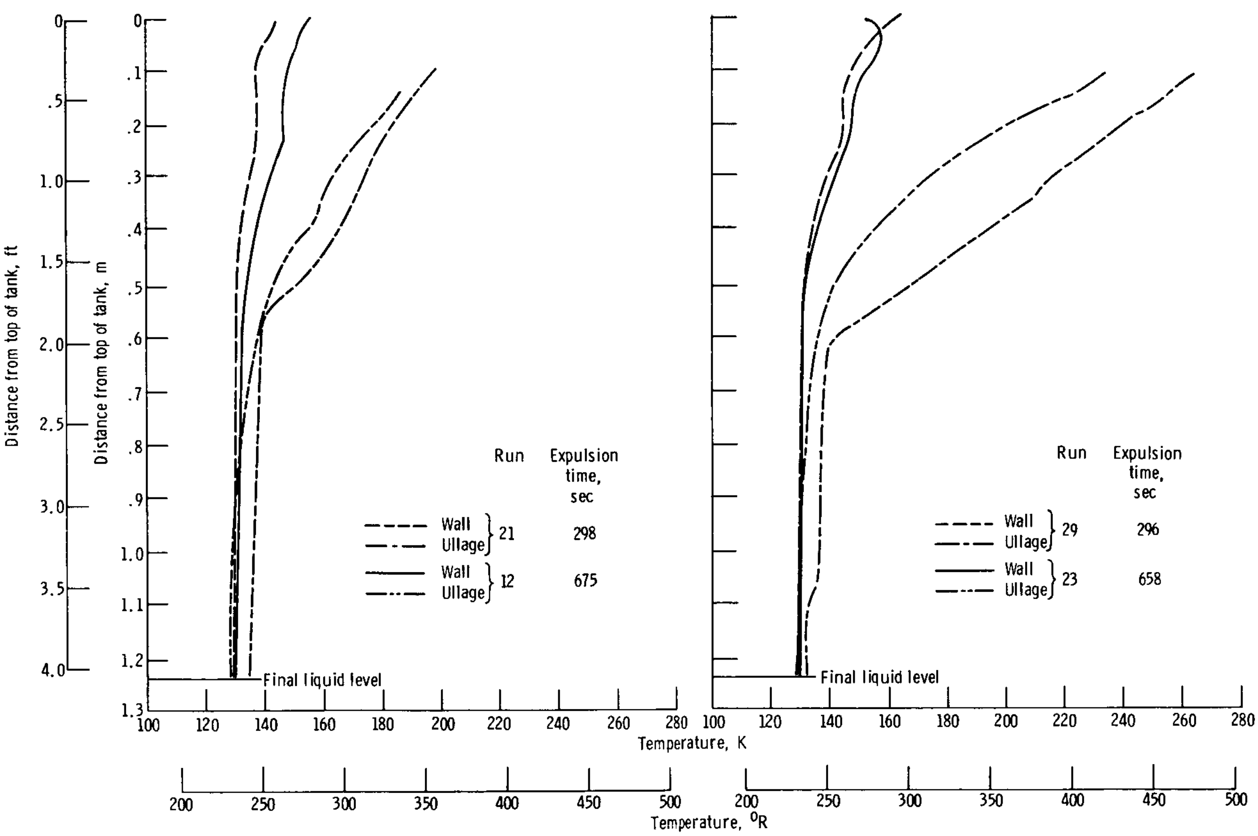


Figure 34. - Mass required during unbaffled slosh expulsion using GCH_4 pressurant as a function of expulsion time. Tank pressure, 34.47×10^4 newtons per square meter (50 psia).

a condensing surface for the GCH_4 pressurant. Some of this heat transferred to the wall is then absorbed into the liquid propellant when a slosh wave again sweeps over that area of tank wall. Additional heat was transferred to the LCH_4 because of some propellant splashing. This splashing occurred mainly because of slosh wave "curl-over" forced by tank wall curvature in the upper hemisphere of the tank. This wave curling was visually observed over short viewing periods during tank expulsion. Figure 35 displays the experimental gas and wall temperature profiles for the shortest and longest expulsions at each of the two inlet gas temperatures. When these profiles are compared to those of figures 13 and 14, considerably less wall heating is evident. In addition, much colder ullage temperatures are present in the lower reaches of the tank indicating more heat loss by the pressurant than in the static tank runs.

The increase in propellant heating was the result of splashing (direct heat transfer from the gas to the liquid droplets) as well as condensation of the methane pressurant. There was no way in which to evaluate the magnitude of these additional heat gains. The net result of all these heat and mass transfer processes, coupled with mixing occurring in the liquid because of sloshing, was a significant amount of liquid heating - a fact dis-



(a) Inlet temperature, 222 K (400° R).

(b) Inlet temperature, 333 K (600° R).

Figure 35. - Experimental gas and wall temperatures at end of expulsion for unbaffled slosh expulsions using GCH_4 pressurant. Tank pressure, 34.47×10^4 newtons per square meter (50 psia).

cussed later in this section.

The time history of the GCH_4 pressurant flow rate for a 333 K (600° R) fast expulsion is shown in figure 36. The flow rate required for a static tank expulsion (fig. 11) has been added for comparison purposes. Besides being considerably higher than the flow rate for a static expulsion, the flow rate for the unbaffled slosh condition is not linear. The majority of flow is required at the beginning of expulsion and the rate drops off as the expulsion proceeds. The initial peak would have been even higher except that the slosh amplitude was ramped over a 60-second period after the beginning of LCH_4 outflow. This ramping allowed the expulsion to reach a steady-state condition without an uncontrollable pressure collapse occurring in the tank ullage. For this run, the tank pressure dropped 24.13×10^3 newtons per square meter (3.5 psi) immediately after start of expulsion, then as the closed loop pressurant flow system responded, the pressure rose 13.79×10^3 newtons per square meter (2.0 psi) above the desired steady-state value. After this initial 10-second cycle of variation, the tank pressure rapidly attenuated to a cyclic variation of less than $\pm3.45\times10^3$ newtons per square meter (±0.5 psi). During the last third of the expulsion, the tank pressure remained steady at 33.4×10^4 newtons per square meter (48.4 psia). This flow history points out the fact that a GCH_4 pressurization system design, when slosh conditions are expected in the tank, would have to be able to handle significantly higher flow rates than those which would be calculated by simply dividing the total gas requirement by the expulsion time.

Figure 37 shows the distribution of total energy added to the tank during the expulsion period via both the incoming pressurant and the heat input from the environment. In sharp contrast to the static tank runs, the majority of energy is lost to the liquid propel-

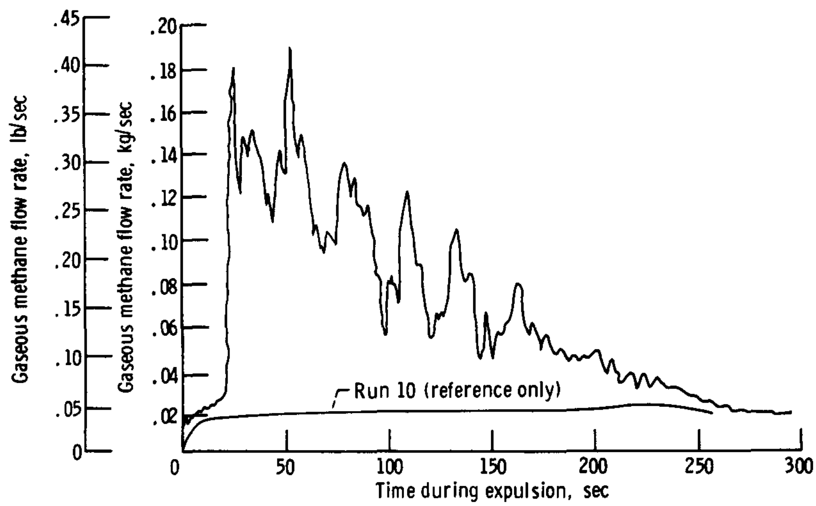
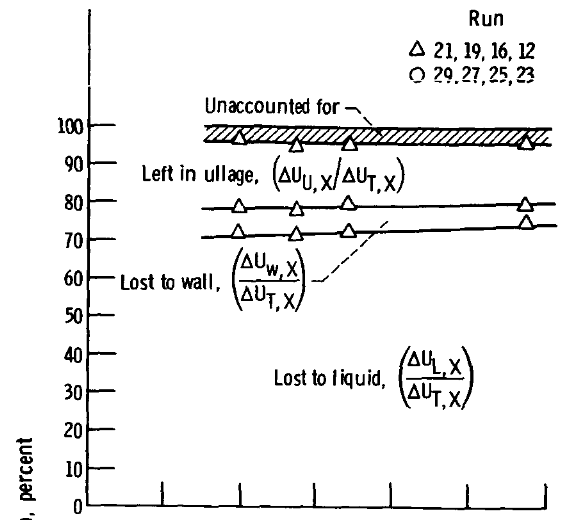
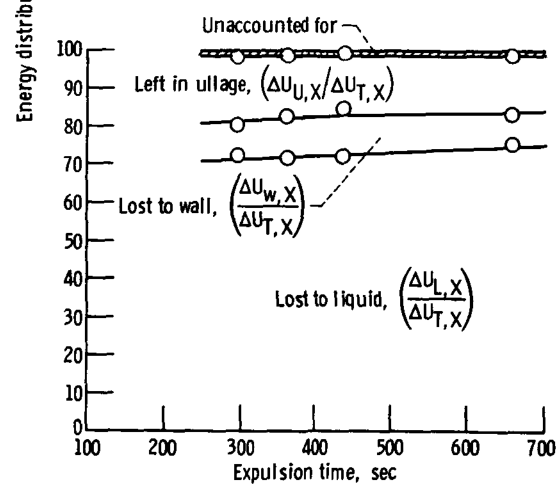


Figure 36. - Time history of GCH_4 pressurant flow rate during unbaffled slosh expulsion. Tank pressure, 34.47×10^4 newtons per square meter (50 psia); inlet temperature, 333 K (600° R); run 29.



(a) Inlet gas temperature, 222 K (400° R).



(b) Inlet gas temperature, 333 K (600° R).

Figure 37. - Energy distribution for GCH_4 pressurant in 1.52-meter- (5-ft-) diameter tank at end of unbaffled slosh expulsion period as a function of expulsion time. Tank pressure, 34.47×10^4 newtons per square meter (50 psia).

lant $\Delta U_{L,X}$. Figure 38 shows the total energy added as well as the amount lost to the LCH_4 propellant during expulsion. As can be seen, the energy absorbed by the liquid $\Delta U_{L,X}$ is not strongly dependent on pressurant temperature. This implies to the authors that the heat absorbed by the liquid is controlled essentially by the amount of wall washing and the amount of splashing occurring in the tank. Transferring this absorbed heat into a bulk temperature increase is dependent on the degree of mixing occurring in the liquid. This mixing was considered to be the same for both the cold and hot gas runs at a given expulsion time. Since the amount of energy lost is the same for both temperatures, the smaller amounts of pressurant required for the 333 K (600° R) runs was, therefore, a direct consequence of the greater specific energy content of the gas at that temperature.

Figure 39 is a plot of the liquid outflow temperature-time histories for both the cold and hot inlet gas temperature runs. There is no major difference in the curves at 222 K (400° R) inlet temperature when compared with those for 333 K (600° R). The thermal lag in the liquid temperature rise is seen to be almost the same for all runs. The major point to be made is how much of the liquid is heated. This state point change in the liquid could very easily give rise to cavitation problems in a LCH_4 propellant system servicing a combustion device.

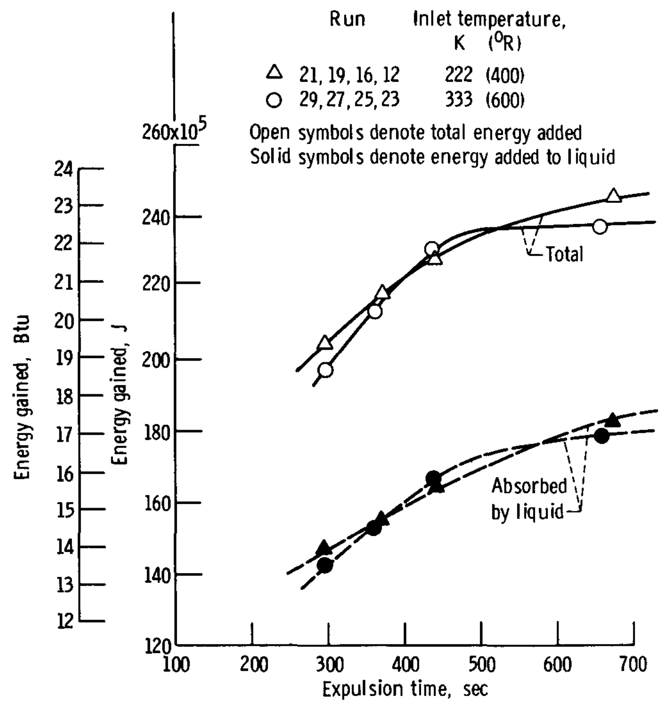


Figure 38. - Comparison of total energy added and energy added to liquid as a function of expulsion time for unbaffled slosh runs using GCH_4 pressurant. Tank pressure, 34.47×10^4 newtons per square meter (50 psia).

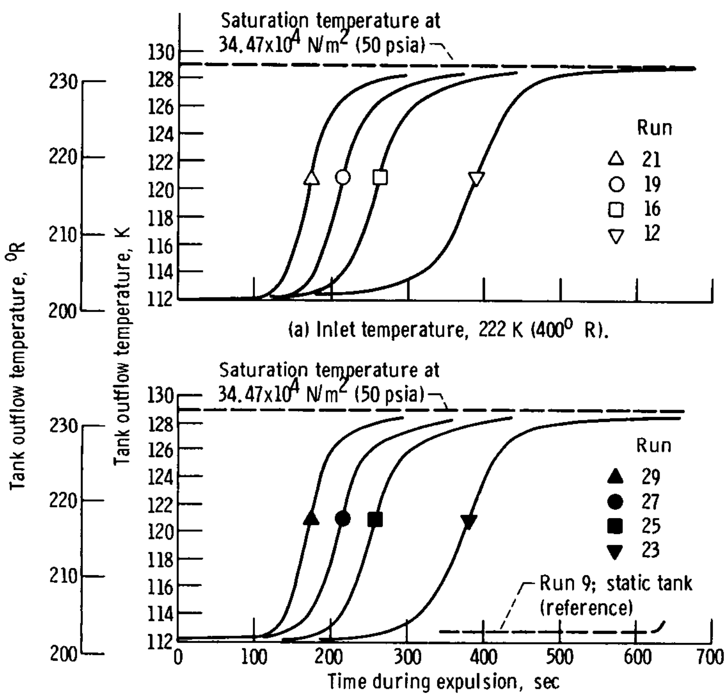


Figure 39. - Time history of LCH_4 outflow temperature during unbaffled slosh runs using GCH_4 pressurant. Tank pressure, 34.47×10^4 newtons per square meter (50 psia).

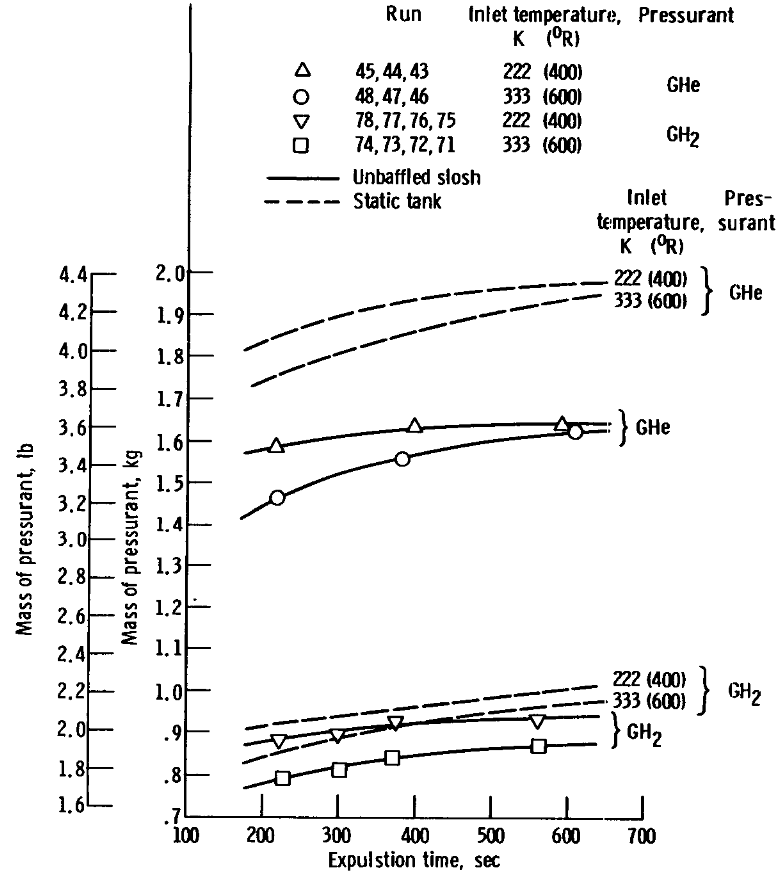


Figure 40. - Mass required during unbaffled slosh expulsion using GHe and GH_2 pressurants as a function of expulsion time. Tank pressure, 34.47×10^4 newtons per square meter (50 psia).

GHe and GH_2 pressurants. - The quantities of GHe and GH_2 required for the unbaffled slosh expulsions are shown in figure 40 for the two different inlet gas temperatures. The requirements for static tank expulsions are also shown as a reference. The usual trends of increasing gas requirements for increasing expulsion time and decreasing inlet gas temperature are present. The significant point of the figure is that less pressurant is required for expulsion under slosh conditions compared to static tank expulsions. This is because of the evaporation of significant amounts of liquid methane propellant as will be shown in a later figure. The average decrease in GHe pressurant requirements for the slosh runs relative to static tank expulsions is 15.7 percent at 222 K (400° R) and 16.2 percent at 333 K (600° R). The average decrease in GH_2 requirements was 4.6 and 8.3 percent at 222 and 333 K (400° and 600° R), respectively.

Figure 41 displays the experimental gas and wall temperature profiles for the shortest and longest GHe expulsions at each of the two inlet temperatures. When these profiles are compared to those of figures 24(a) and (b), less wall heating is evident. In addition, slightly colder ullage temperatures are present in the lower reaches of the tank indicating more ullage mixing than in the static tank runs. These results are also typical

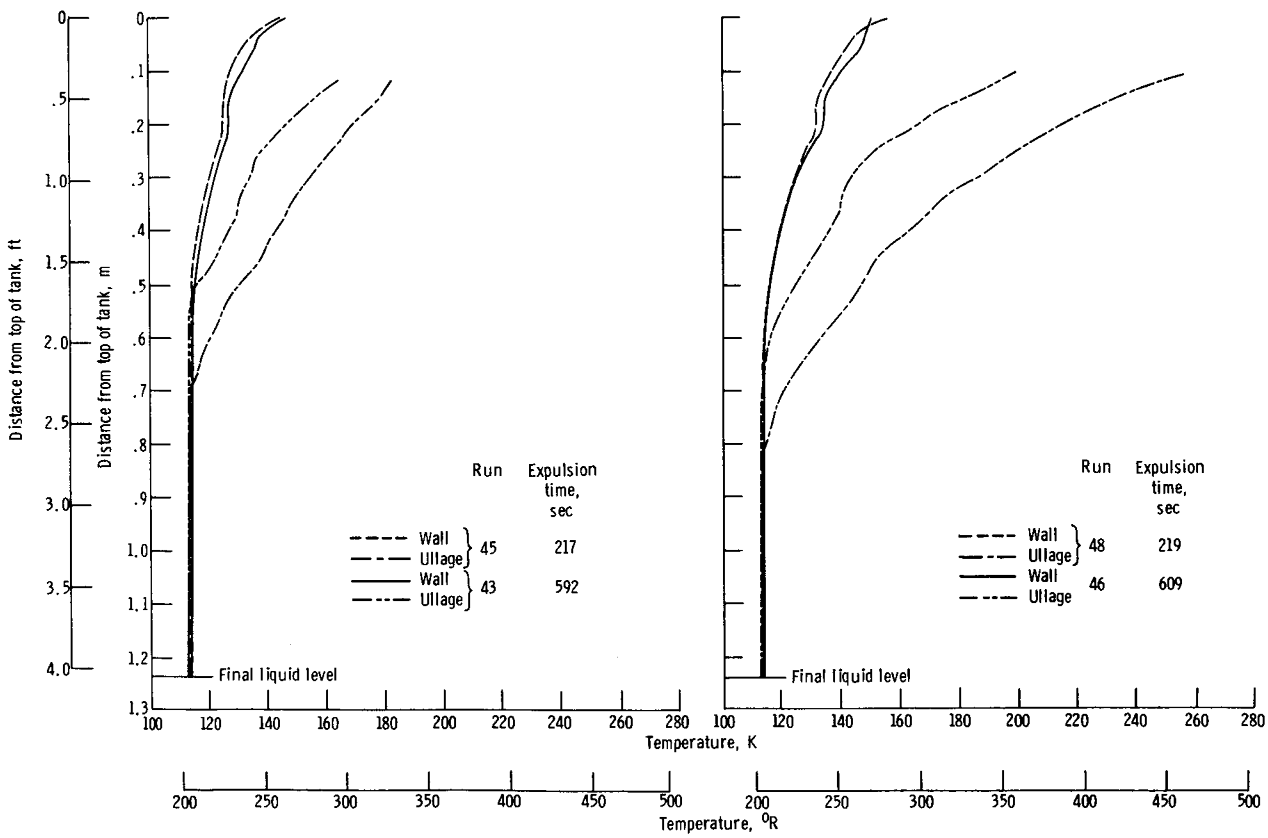


Figure 41. - Experimental gas and wall temperatures at end of expulsion for unbaffled slosh expulsions using GHe pressurant. Tank pressure, 34.47×10^4 newtons per square meter (50 psia).

for the GH_2 expulsions.

Figure 42 displays the ullage gas concentration curves for the 222 K (400° R) runs obtained from the gas sampling tubes at the end of expulsion. As can be seen in the figure, significant percentages of GCH_4 are present throughout the ullage volume. A study of the figure will also reveal that the percentage of GCH_4 at a given location generally increases for longer expulsion time runs. Using this data, both the mass of GCH_4 in the ullage and the amounts of GHe and GH_2 dissolved in the LCH_4 propellant were calculated. Figure 43 displays the mass of methane evaporated during the expulsions for both the GHe and GH_2 pressurization runs. As can be seen in the figure, no significant differences exist in the quantities evaporated for the four sets of data. As per the concentra-

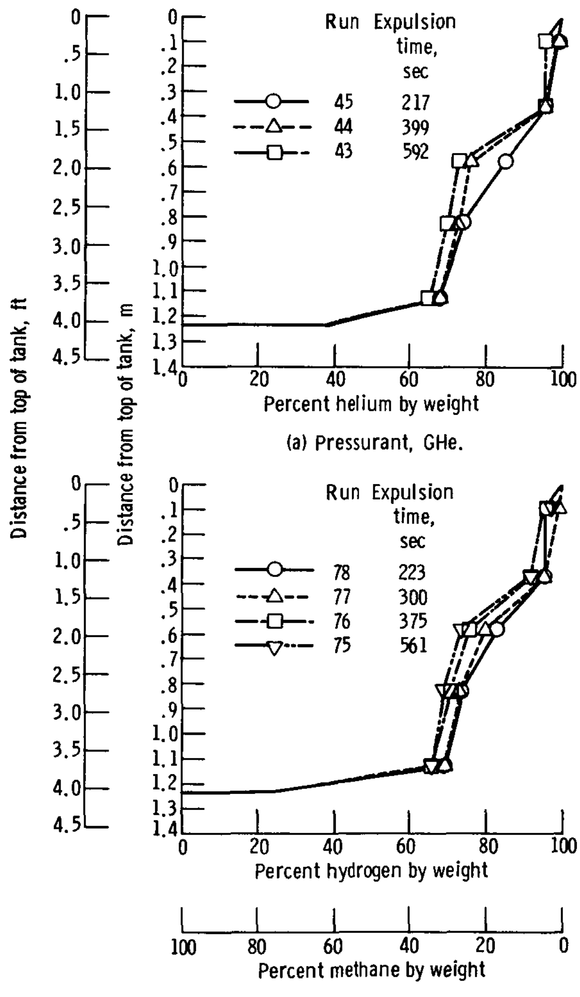


Figure 42. - End of expulsion ullage gas concentrations for unbaffled slosh expulsions using GHe and GH_2 pressurant. Tank pressure, 34.47×10^4 newtons per square meter (50 psia); inlet temperature, 222 K (400° R).

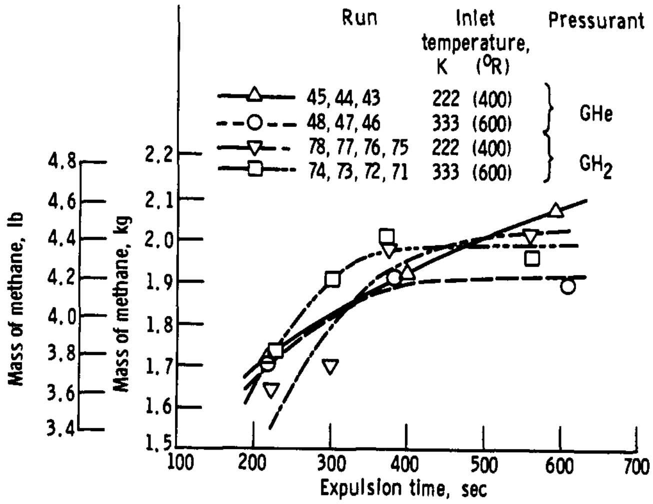


Figure 43. - Mass of methane evaporated during unbaffled slosh expulsion using GHe and GH_2 pressurants as a function of expulsion time. Tank pressure, 34.47×10^4 newtons per square meter (50 psia).

tion data curves, the trend of increasing evaporation with increasing expulsion time is present.

Because of solubility, the mass transfer is not just one way. Figure 44 displays the amounts of GHe and GH_2 dissolved in the LCH_4 propellant. The quantities are displayed in a percentile manner relative to the total amount of pressurant added during the complete pressurization cycle. Because the specification of instantaneous interface location added another degree of uncertainty to the mass balances, the authors consider the dissolved gas quantities accurate only within ±3 ordinate units. As a result of this uncertainty, the authors did not consider any heat contribution to the liquid by the dissolved GHe. The data for dissolved GH_2, even though rough, indicates the expected trend of increasing dilution for longer expulsions. Further, a comparison of figure 44 with figure 20 shows that more hydrogen was dissolved during the slosh runs than during the static tank expulsions. The heat contribution to the liquid by this dissolved hydrogen was considered in the energy balance for these slosh runs.

Figures 45 and 46 show the distribution of the total energy added to the tank via both the incoming GHe or GH_2 and the heat input from the environment during the expulsion period. On a percentage basis, the ullage is the predominant heat sink for both pressurant gases. The results of the slosh runs show that the ullage and wall energy sinks account for between 53.3 and 73.0 percent of the total energy added to the tank during all runs. This is similar to the static tank case where the ullage and wall sinks were also predominant. The percentage gained by the wall during the slosh runs is sharply reduced when compared to static tank tests. Finally, the energy absorbed by the LCH_4 propellant is only slightly greater for the slosh runs compared to the static tank tests.

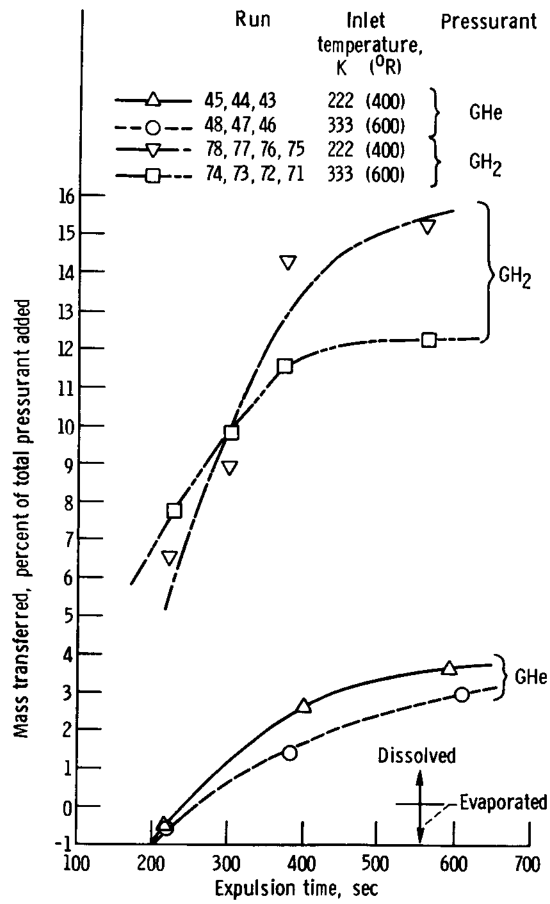
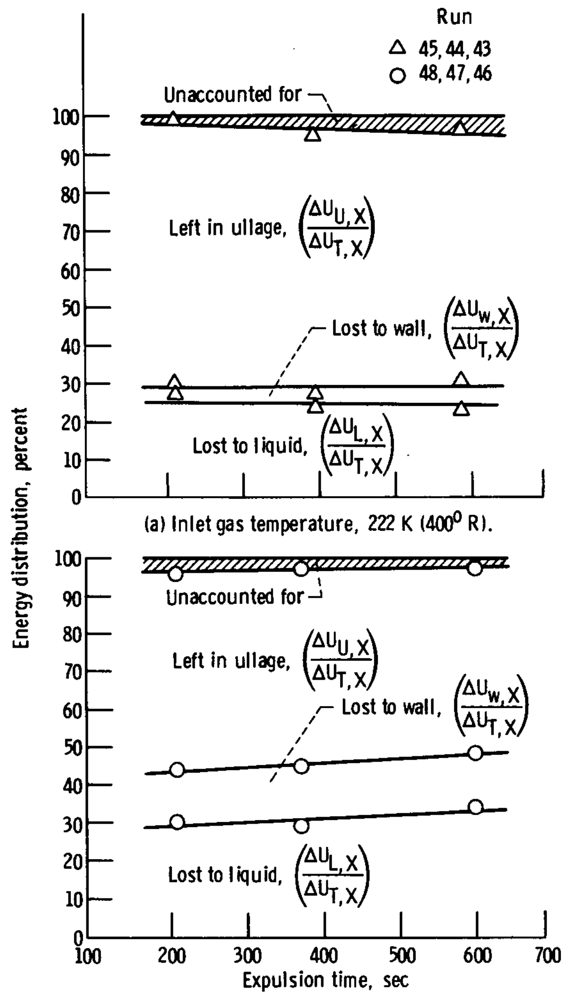


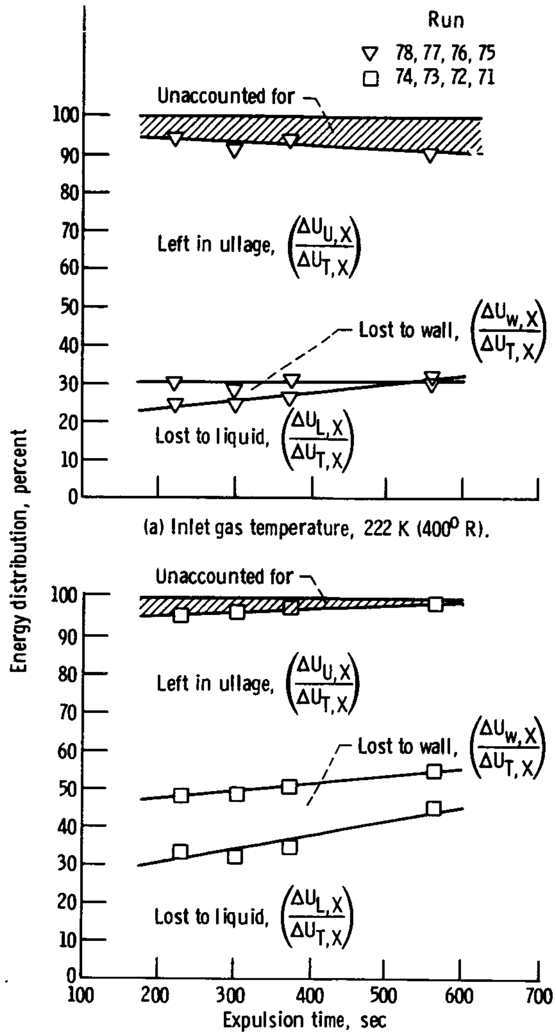
Figure 44. - Percent GHe or GH_2, dissolved in propellant, of total pressurant added during each complete unbaffled tank run as a function of expulsion time. Tank pressure, 34.47×10^4 newtons per square meter (50 psia).



(a) Inlet gas temperature, 222 K (400° R).

(b) Inlet gas temperature, 333 K (600° R).

Figure 45. - Energy distribution for expulsion period for unbaffled slosh tests using GHe pressurant as a function of expulsion time. Tank pressure, 34.47×10^4 newtons per square meter (50 psia).



(b) Inlet gas temperature, 333 K (600° R).

Figure 46. - Energy distribution for expulsion period for unbaffled slosh tests using GH_2 pressurant as a function of expulsion time. Tank pressure, 34.47×10^4 newtons per square meter (50 psia).

Figure 47 displays nominal 400-second time histories of the LCH_4 outflow temperatures. One history was taken from each of the four sets of expulsion runs. For all four curves, the increase in liquid temperature relatively early in the expulsion indicates that mixing in the LCH_4 extends significantly down into the propellant. Heat addition to the liquid propellant continued essentially throughout the 333 K (600° R) expulsions. The 222 K (400° R) runs, however, begin to show a dropoff in outflow temperature starting about halfway through. Tank pressure variations, caused by the inherent response of the pressurant flow control system, can only account at most for a variation of 0.03 K (0.06° R) and hence were ruled out as a possible cause for the variations in the liquid outflow temperature histories. The temperature dropoffs exhibited by the 222 K (400° R) inlet temperature runs imply to the authors that liquid cooling, because of methane evaporation, is predominating at least toward the last half of the expulsion period. The work term $P\,\Delta V$ of approximately 515×10^3 joules (488 Btu) and half the environmental heating term are between 72 and 130 percent of the liquid energy term $\Delta U_{L,X}$ for these runs. Hence, for the 222 K (400° R) runs, the cooling effect on the propellant of the evaporating methane is either greater than, or nullifies a significant part of, the heat gained by the liquid because of continued washing of the tank wall and direct heat addition from the pressurant gas. In any event, the net change in temperature of the propellant is quite small as was the case for the static tank expulsions.

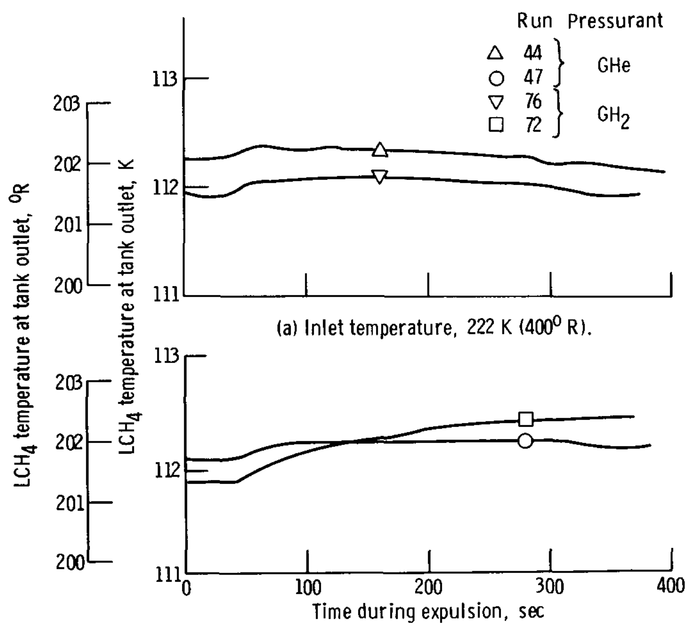


Figure 47. - Time history of LCH_4 outflow temperature during unbaffled slosh runs using GHe and GH_2 pressurants. Tank pressure, 34.47×10^4 newtons per square meter (50 psia).

Slosh Expulsions, Baffled Tank

General. - Three concentric ring slosh baffles were installed in the tank to retard liquid motion. The exact position of these baffles is shown in figure 6. Complete tank expulsions were made using only GCH_4 and GHe pressurants. The main test parameters were inlet gas temperature and expulsion time. All expulsions in this group were made while the tank was being oscillated at an amplitude of ±2.23 centimeters (±0.88 in.) and at a frequency corresponding to the natural frequency of the liquid remaining in an unbaffled tank (i.e., same conditions as used in the unbaffled tank). Slosh amplitude was also linearly ramped for these runs from 0.0 to ±2.23 centimeters (0.0 to ±0.88 in.) over approximately a 60-second time period.

The experimentally determined pressurant gas requirements, as well as heat and mass transfer data for these slosh tests, are compared to similar data for both the static tank tests and the slosh tests previously mentioned. The main objectives are to point out

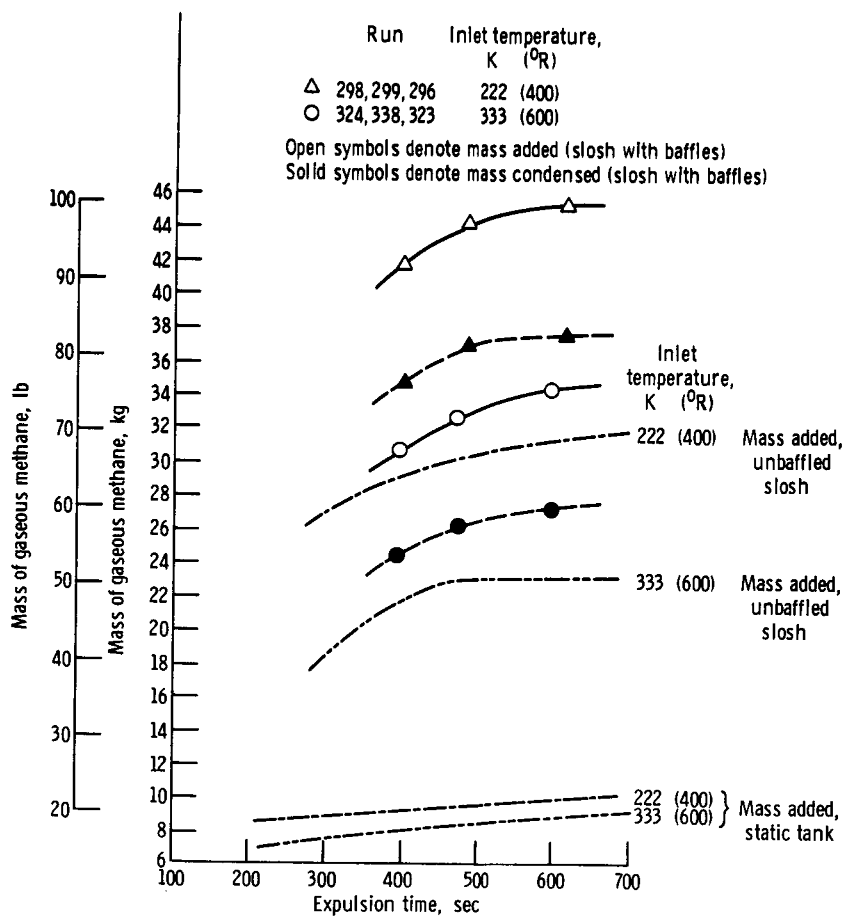


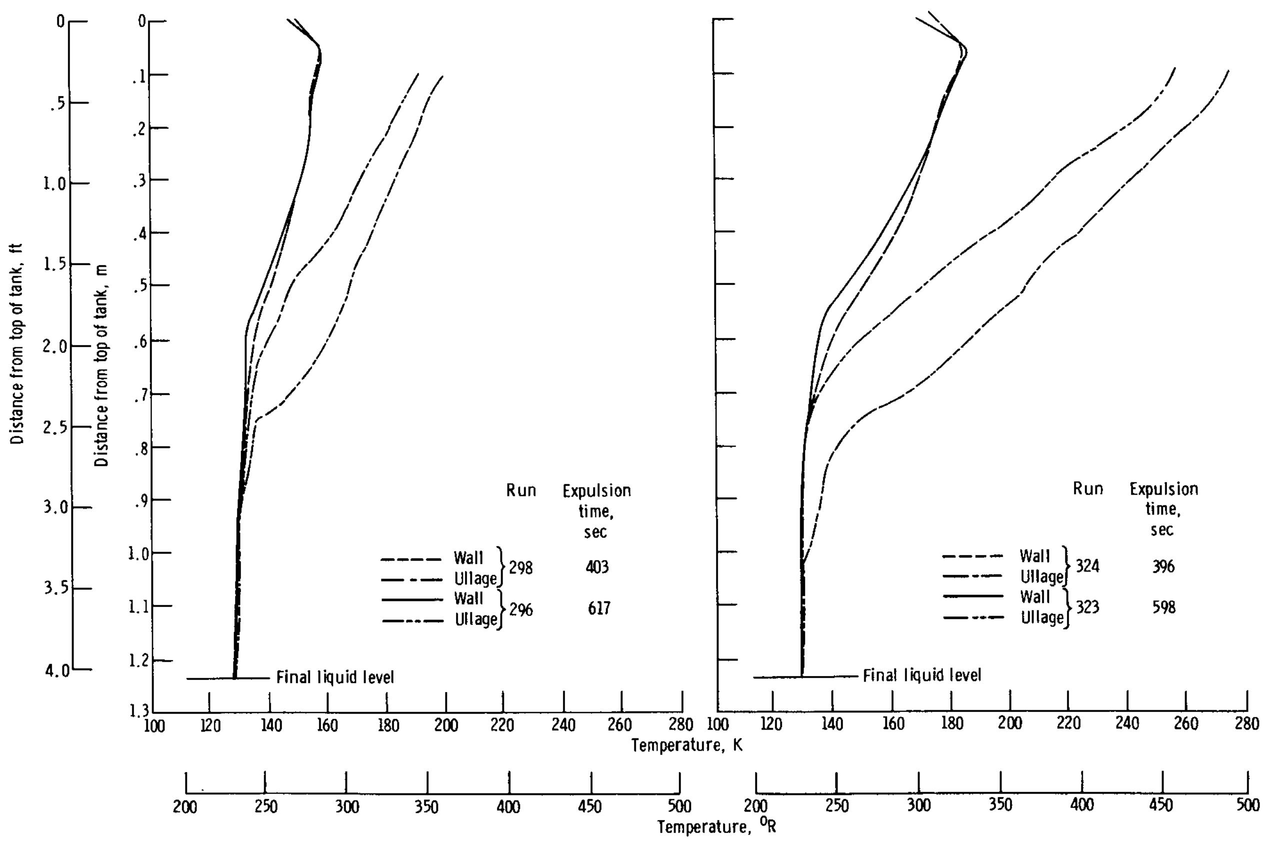
Figure 48. - Mass required during baffled slosh expulsion using GCH_4 pressurant as a function of expulsion time. Tank pressure, 34.47×10^4 newtons per square meter (50 psia).

marked differences between the sets of data and the reasons for the differences. No analytical predictions were made for the slosh runs in this group.

The results obtained using GCH_4 will be discussed first followed by the tests employing GHe pressurant. The main test parameters, as well as the mass and energy balances for the two major groups of data, appear in tables V and VI.

Methane pressurant. - The quantity of GCH_4 required for the expulsion period is shown in figure 48 for the two different inlet temperatures. The requirements for both the static tank and the unbaffled slosh expulsions are shown for reference. As with all previous work, both increasing expulsion time and decreasing inlet gas temperatures cause a rise in the amount of pressurant. Further, the pressurant requirements and the mass condensed are significantly increased for baffled slosh over the unbaffled tank case. Compared to the static tank runs, the requirements for baffled slosh were increased, on the average, by a factor of 4.6 for the 222 K (400° R) inlet temperature and a factor of 3.9 at 333 K (600° R).

The quantity of condensed pressurant is again of prime importance. On the average, condensation increased during baffled slosh by a factor of 12.30 for the 222 K (400° R)



(a) Inlet temperature, 222 K (400° R).

(b) Inlet temperature, 333 K (600° R).

Figure 49. - Experimental gas and wall temperatures at end of baffled slosh expulsions using GCH_4 pressurant. Tank pressure, 34.47×10^4 newtons per square meter (50 psia).

runs and by a factor of 9.85 for the 333 K (600° R) cases over values obtained for static tank work at comparable temperatures. Condensed pressurant was again the main reason for the large increase in overall expulsion pressurant requirements. Figure 49 displays the experimental gas and wall temperature profiles for the shortest and longest expulsions at each of the two inlet gas temperatures. When compared to figure 35, it can be seen that more heat is lost to the tank wall during the baffled slosh runs. The temperature profiles in the ullage gas are generally warmer than in the unbaffled expulsions.

As in the unbaffled slosh case, washing of the tank walls was still encountered during baffled slosh. The tank wall area washed per unit time was reduced due to the presence of the baffles. A portion of this lost area was made up by the surface area of the baffles which were also periodically exposed and then submerged again as the liquid propellant was being expelled. However, the addition of the baffles resulted in more liquid splashing than was encountered in the unbaffled slosh runs. The extra splashing was, of course, visually observed over short viewing periods during tank expulsion. It is the opinion of the authors that even though the reduced washing would dictate a reduction in the amount of pressurant condensed on the tank wall, the extra splashing resulted in a significant additional amount of ullage gas condensation as well as some additional propellant heat gain because of direct heat transfer from the pressurant gas. This extra heat and mass gain by the propellant was rapidly mixed into the main bulk because of propellant agitation due to the presence of the baffles. The momentum energy of the slosh wave, after the wave would strike a baffle, was considered dissipated in greater eddy currents in the liquid propellant. Unfortunately, there was no way in which to evaluate the contribution of each of these extra mass and heat transfer effects. Their net result, coupled with the extra mixing occurring in the liquid propellant, was significantly more liquid heating than encountered during unbaffled slosh.

The time history of the GCH_4 pressurant flow rate for a 333 K (600° R) fast expulsion is shown in figure 50. The flow rate required for a static tank expulsion (fig. 11)

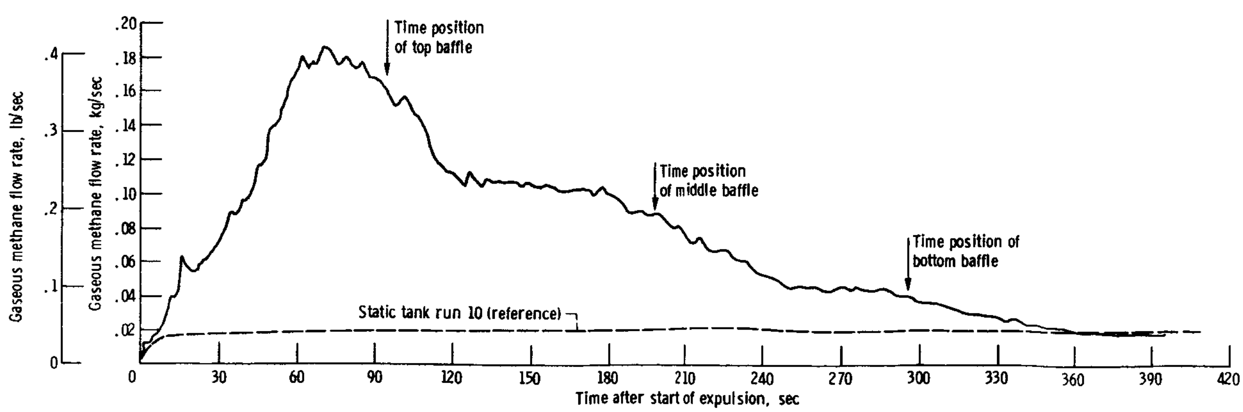


Figure 50. - Time history of GCH_4 pressurant flow rate during baffled slosh expulsion. Tank pressure, 34.47×10^4 newtons per square meter (50 psia); inlet temperature, 333 K (600° R); natural frequency slosh input; slosh amplitude, ±2.18 centimeters (±0.86 in.); run 324.

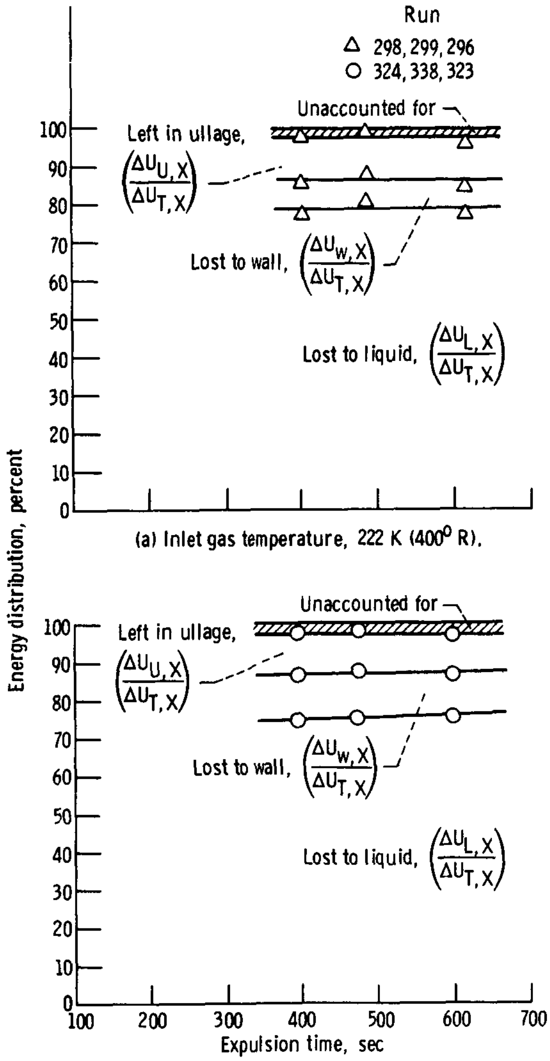


Figure 51. - Energy distribution for expulsion period for baffled slosh tests using GCH_4 pressurant as a function of expulsion time. Tank pressure, 34.47×10^4 newtons per square meter (50 psia).

has been added for comparison purposes. The characteristics of this baffled slosh flow rate curve are comparable to those shown for the unbaffled tank expulsion (fig. 36). The majority of flow is required at the beginning of expulsion and the rate also drops off as the expulsion proceeds. The maximum flow rate is higher, however, and exists for a much longer period of time during baffled slosh. It should be noted that this peak flow rate would have been higher except the imposed slosh amplitude was ramped over a 60-second period after the beginning of LCH_4 outflow. As in the case of the unbaffled slosh runs, a vehicle pressurization system designed for use under these conditions would have to be capable of handling a flow much greater than the rate calculated by simply dividing the total gas requirement by the expulsion time.

Figure 51 shows the distribution of total energy added to the tank during the expulsion period. Only minor differences exist between these distributions and comparable data for the unbaffled slosh tests. A slightly greater percentage of heat was lost to the liquid propellant and a smaller percentage was left in the ullage. These results were considered due to the extra splashing of the liquid propellant. The percentage of heat lost to the tank wall was slightly higher than that lost during unbaffled slosh. This result is expected because of less wall washing during the baffled expulsions.

Figure 52 is a plot of the liquid outflow temperature-time history for a baffled slosh expulsion. Histories for an unbaffled slosh run and a static tank expulsion have been added for comparison. The major points to be made are (1) how much of the liquid is heated and (2) that more liquid is heated for the run made with baffles. This figure serves to support the earlier hypothesis regarding greater liquid mixing occurring because of the presence of slosh baffles in the tank. Finally, the inference made in the

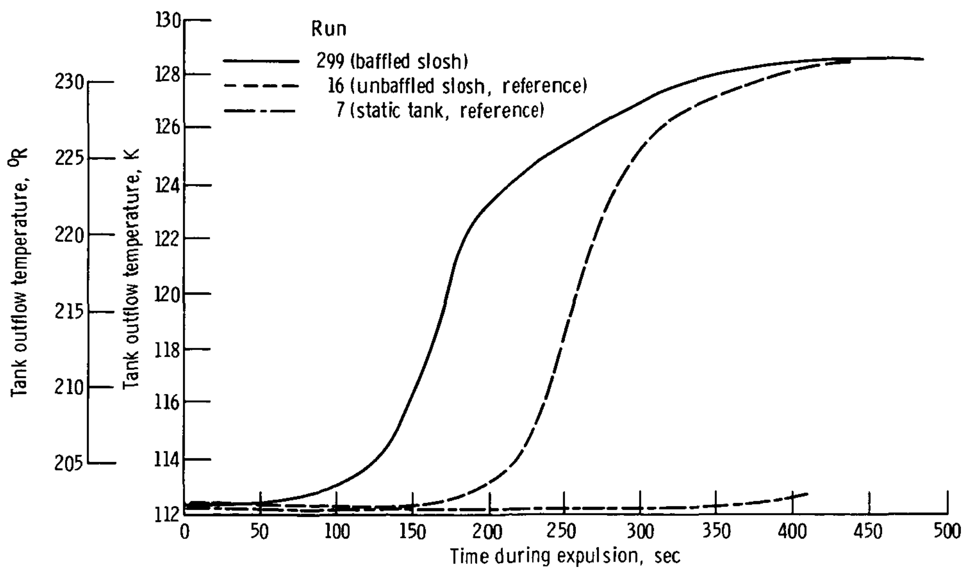


Figure 52. - Time history of LCH_4 outflow temperature during baffled slosh test using GCH_4 pressurant. Tank pressure, 34.47×10^4 newtons per square meter (50 psia); inlet temperature, 222 K (400° R).

section Slosh Expulsions, Unbaffled Tank, with regard to possible cavitation problems in a LCH_4 propellant system servicing a combustion device may be reiterated here.

GHe pressurant. - The quantity of GHe required for the expulsion period is shown in figure 53 for the two different inlet temperatures. The requirements for both the static tank and the unbaffled slosh expulsions are shown for reference. The usual trend of increasing gas requirements as a function of expulsion time and inlet temperature is present. The pressurant requirements for this set of runs are less than those required for static expulsions but slightly greater than the unbaffled slosh requirements. This was most probably due to the slightly greater heating of the tank walls. Gaseous methane evaporation is again the reason for these requirements being less than needed for the static expulsions. Slightly less evaporation was recorded for the baffled tank compared to the bare tank under slosh conditions. The average decrease in GHe pressurant requirements for these baffled slosh runs relative to the static tank expulsions is 12.9 percent at 222 K (400° R) and 14.1 percent at 333 K (600° R).

Figure 54 displays the experimental gas and wall temperature profiles for the shortest and longest expulsions at each of the two inlet gas temperatures. When compared to figure 41, it can be seen that the wall profiles are warmer indicating they absorbed more heat during the baffled runs because of the lesser amount of wall washing by the liquid propellant. The ullage gas profiles are very similar between the baffled and unbaffled expulsions. In fact, it is difficult to say that any significant difference exists.

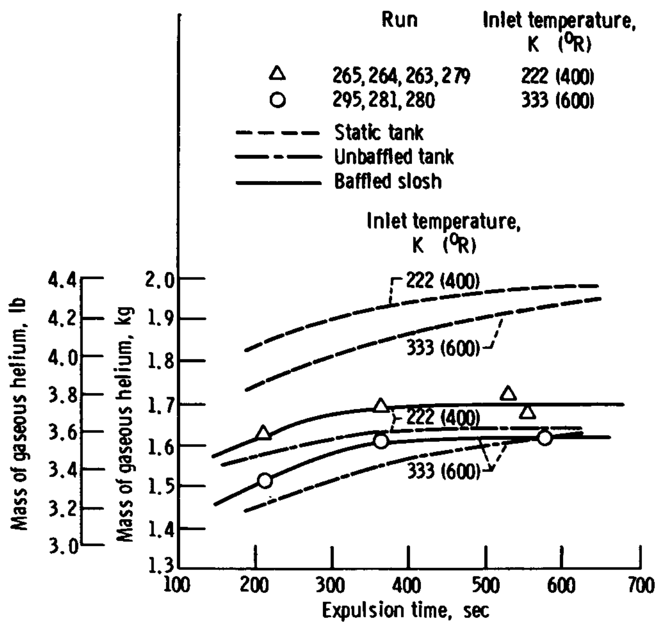


Figure 53. - Mass required during baffled slosh expulsion using GHe pressurant as a function of expulsion time. Tank pressure, 34.47×10^4 newtons per square meter (50 psia).

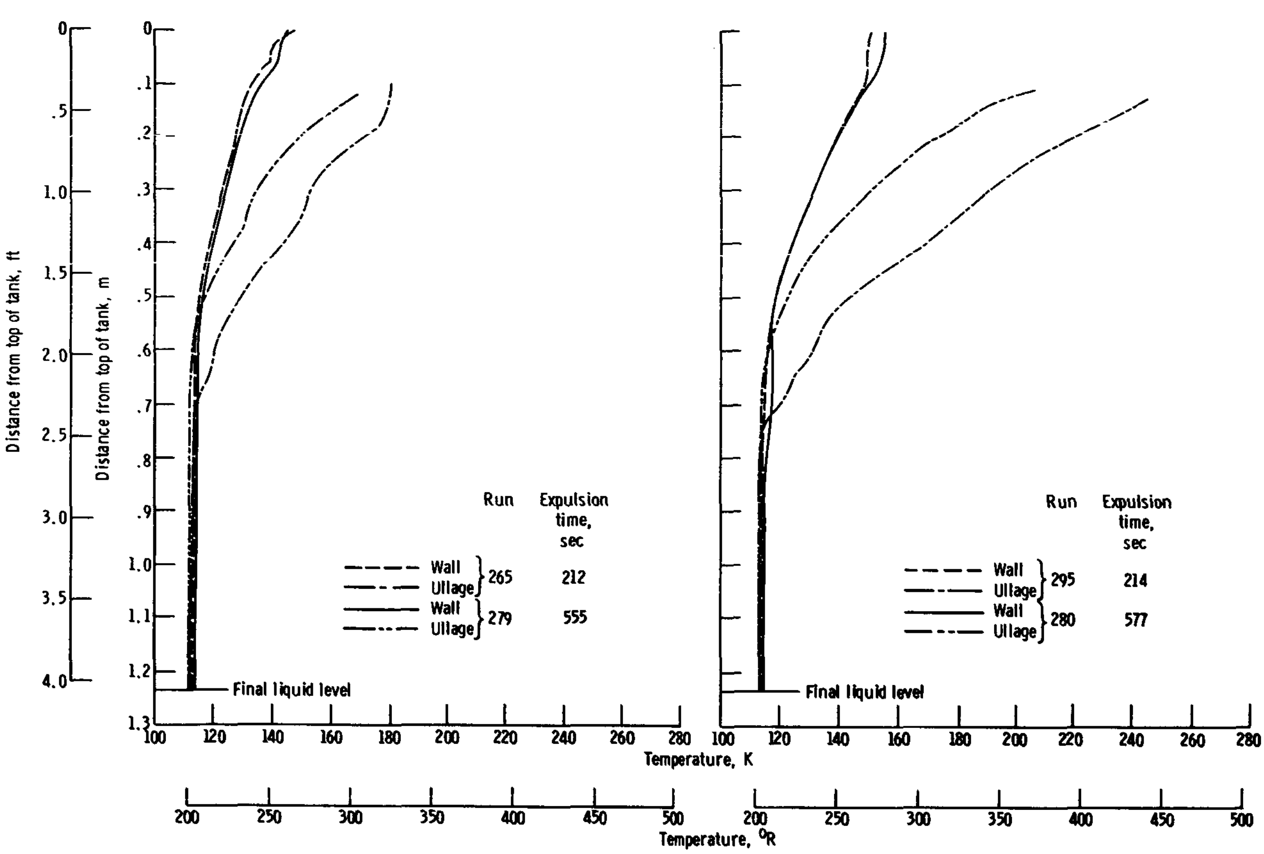
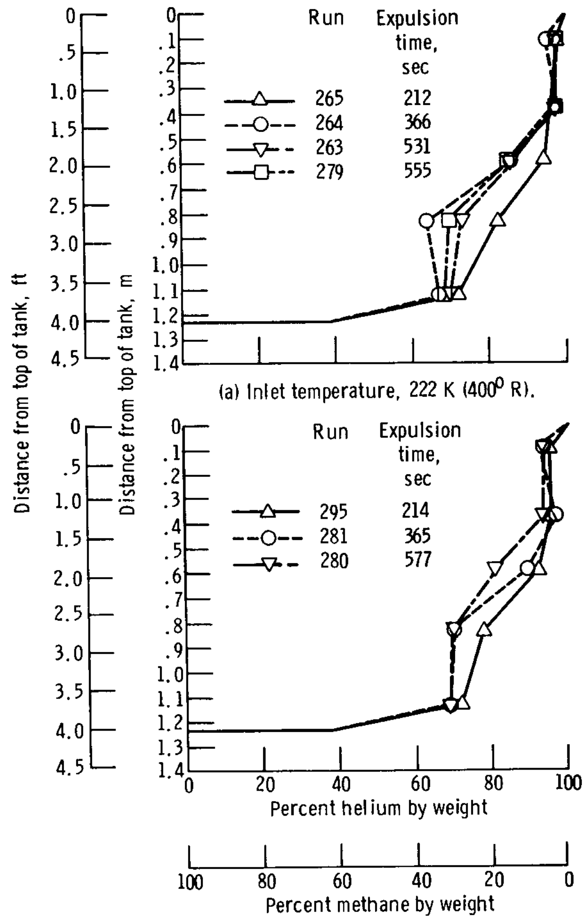


Figure 54. - Experimental gas and wall temperatures at end of baffled slosh expulsions using GHe pressurant. Tank pressure, 34.47×10^4 newtons per square meter (50 psia).

Figure 55 displays the ullage gas concentration curves for both sets of GHe runs. These data show significant percentages of GCH_4 present throughout the ullage volume. However, these concentrations are slightly less than observed for similar runs made without baffles. Using this data, both the mass of GCH_4 in the ullage and the amount of GHe dissolved in the LCH_4 propellant were calculated. Table V lists the mass of methane evaporated during these expulsions. The results show slightly less evaporation for these baffled slosh runs compared to the bare tank slosh expulsions. The trend of increasing evaporation with increasing expulsion time is present.

Figure 56 displays the amount of GHe dissolved in the LCH_4 propellant. The quantities are displayed in a percentile manner relative to the total amount of pressurant added during the complete pressurization cycle. As in the case of the bare tank slosh runs, the authors consider the data in figure 56 accurate only within ±3 ordinate units. As a result of this uncertainty, the authors did not consider any heat contribution to the liquid by the dissolved GHe.

Figure 57 shows the distribution of the total energy added to the tank via both the incoming GHe and the environment. The major heat sink is the ullage gas $\Delta U_{U,X}$. The



(a) Inlet temperature, 222 K (400° R).

(b) Inlet temperature, 333 K (600° R).

Figure 55. - End of expulsion ullage gas concentrations for baffled slosh expulsion using GHe pressurant. Tank pressure, 34.47×10^4 newtons per square meter (50 psia).

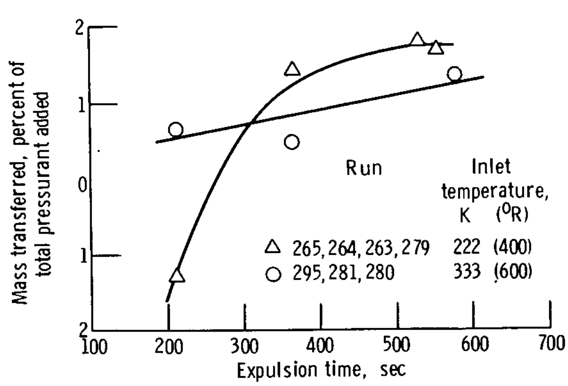
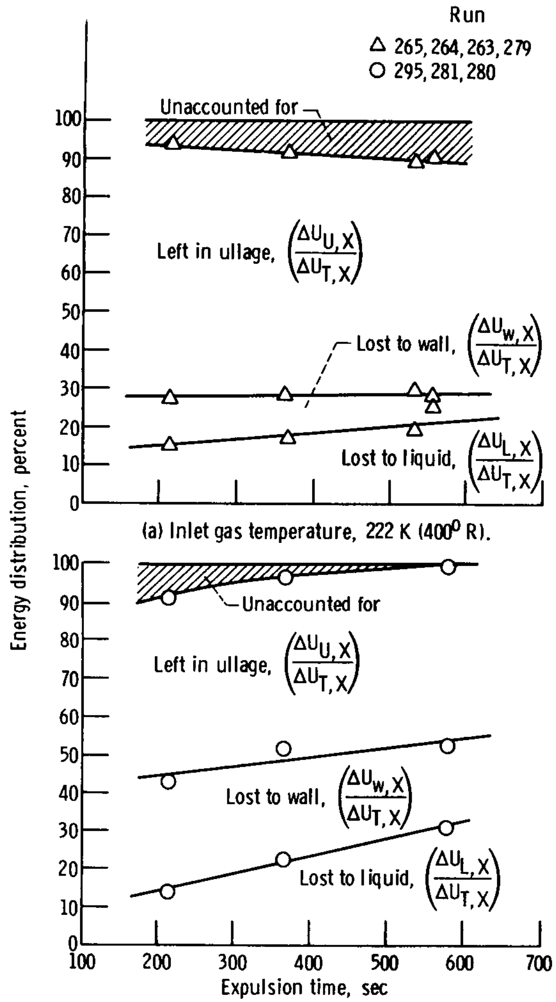


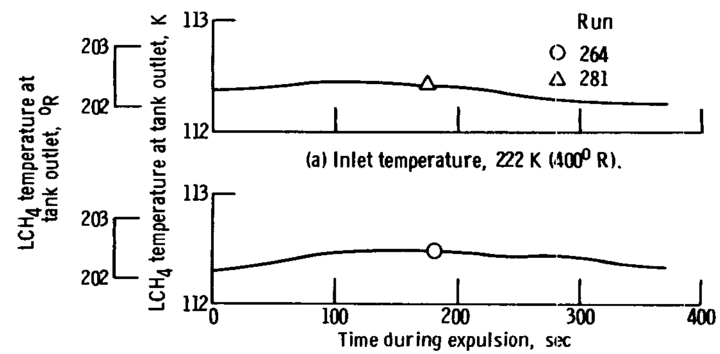
Figure 56. - Percent of GHe, dissolved in propellant, of total pressurant added during each complete baffled slosh run as a function of expulsion time. Tank pressure, 34.47×10^4 newtons per square meter (50 psia).



(a) Inlet gas temperature, 222 K (400° R).

(b) Inlet gas temperature, 333 K (600° R).

Figure 57. - Energy distribution for expulsion period for baffled slosh tests using GHe pressurant as a function of expulsion time. Tank pressure, 34.47×10^4 newtons per square meter (50 psia).



(a) Inlet temperature, 222 K (400° R).

(b) Inlet temperature, 333 K (600° R).

Figure 58. - Time history of LCH_4 outflow temperature during baffled slosh runs using GHe pressurant. Tank pressure, 34.47×10^4 newtons per square meter (50 psia).

amount of heat left in the ullage for the baffled slosh runs was almost identical with the data observed for the bare tank slosh runs. The reduced wall washing caused by the presence of the baffles was considered to have resulted in more of a heat gain by the tank wall $\Delta U_{W,X}$, and a reduction of the quantity lost to the liquid propellant $\Delta U_{L,X}$, when compared to the unbaffled slosh tests.

Figure 58 is a typical time history of the LCH_4 outflow temperature for both a 222 K (400° R) and a 333 K (600° R) expulsion. The same trends relative to the histories during the unbaffled slosh runs are present. Also, as in the unbaffled slosh runs, tank pressure fluctuations can only account at most for a variation of 0.03 K (0.06° R) for these baffled slosh expulsions and hence were again ruled out as a possible cause for the trend in the temperature histories shown here. The increase in liquid temperature relatively early in the expulsion indicates that mixing in the LCH_4 extends significantly down into the propellant. The histories begin to show a dropoff about halfway through. This implies that liquid cooling, because of methane evaporation, is occurring. If the work term $P \Delta V$ of approximately 515×10^{3} joules (488 Btu) and half the environmental heating term are subtracted from the liquid energy term $\Delta U_{L,X}$, the result is again generally negative. This implies that the cooling effect on the propellant of the evaporating methane is generally greater than the heat gained because of wall washing and heat addition from the pressurant gas. The net change in temperature of the propellant is small as was the case for both the static tank and unbaffled slosh runs.

Variable Amplitude Slosh With and Without Baffles

General. - Since the effect of slosh excitation on the mass requirements for GCH_4 pressurant is so large, it was decided to determine the effects of slosh excitation at conditions other than the very severe one imposed during the slosh expulsions covered in previous sections. The main test parameters for the following runs were inlet gas temperature, slosh input frequency, and slosh input amplitude. Complete tank expulsions were made, both with and without baffles, using only GCH_4 pressurant. Expulsion time was held to a nominal value of 389 seconds which corresponded approximately to the midrange point for all previous tests. The inlet gas temperatures were the nominal values of 222 K (400° R) and 333 K (600° R). Two different slosh input frequency schedules were employed. The first corresponded to the natural frequency of the liquid remaining in an unbaffled tank (i.e., same conditions as used in previous sections) and the second was a constant input frequency of 0.716 hertz. The 0.716-hertz value corresponds to the natural frequency of an unbaffled tank one-half full. Slosh amplitude ranged from 0.0 to ±2.23 centimeters (0.0 to ±0.88 in.) for the series of runs. Once imposed, however, the slosh amplitude was kept constant throughout a complete expulsion. Slosh amplitude was also linearly ramped for these runs from 0.0 centimeter (0.0 in.) to the desired run value during approximately a 60-second time period.

The main test parameters, as well as the mass and energy balances for the three major groups of data, appear in tables VII and VIII.

Unbaffled tank. - The quantity of GCH_4 required for the expulsion period is shown in figure 59 for the two different inlet temperatures and the two different slosh input frequency profiles. It is quite evident from the curves that there is a definite inflection point below which slosh effects on pressurant requirements are small and above which they are appreciable. This inflection point is taken as ±0.51 centimeter (±0.20 in.) of amplitude. The jump in pressurant requirements is much more sharply defined for the natural frequency profile slosh input runs than for the 0.716-hertz excitations. There is a less pronounced rate of rise in the pressurant requirements for the 0.716-hertz expulsions. This is expected inasmuch as resonance effects occur during only part of these runs.

In the section Slosh Expulsions, Unbaffled Tank, the authors implied that the heat absorbed by the liquid propellant is controlled essentially by the amount of wall washing and the amount of splashing occurring in the tank. Transferring this absorbed heat into the bulk propellant is a function of mixing in the liquid. The curves in figure 59 show that a combination of both amplitude and a resonant point, or near resonant point, are

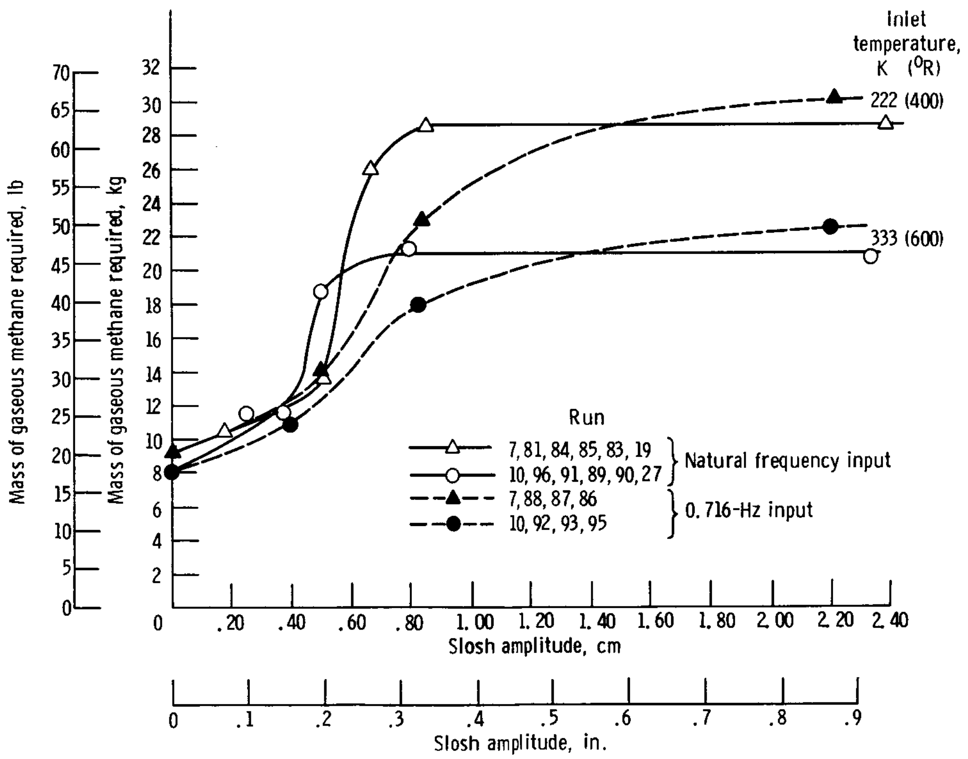


Figure 59. - Mass of GCH_4 pressurant required during unbaffled slosh expulsions for range of slosh amplitudes. Tank pressure, 34.47×10^4 newtons per square meter (50 psia); expulsion time, 389 seconds.

both needed to cause large increases in the quantities of required pressurant gas.

Figure 60 is a time history of the GCH_4 pressurant flow rate for three runs in the immediate vicinity of the inflection point for the 333 K (600° R) natural frequency profile runs. The flow rates shown are typical in trends, but slightly lower in absolute magnitude, than runs made at 222 K (400° R) inlet temperature. Each curve reaches its maximum very shortly after the steady-state slosh amplitude is reached (60 sec after the start of expulsion). It should also be noted that, as slosh amplitude increases, the pressurant flow rate required after the initial peak also increases and exists for a longer period of time. Based on this comparison, the authors postulate that the small slosh amplitude of ±0.51 centimeter (±0.20 in.) is evidently sufficient to break the stratification force in the liquid propellant and cause pronounced mixing to occur. This postulation is substantiated by figure 61 which displays the time histories of the liquid methane at the tank outlet for both the 222 K (400° R) and the 333 K (600° R) natural frequency ex-

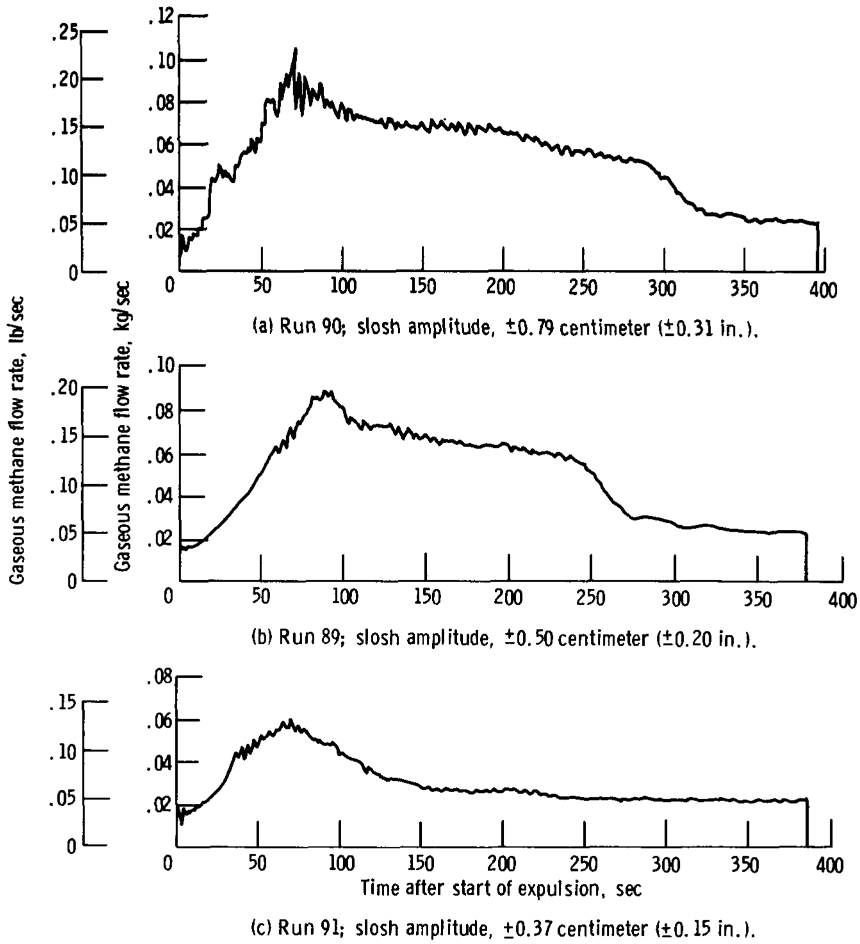
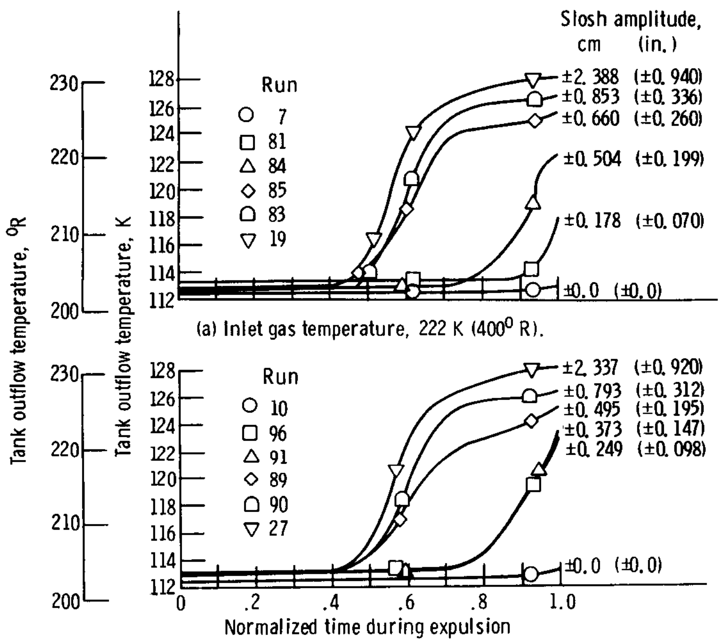


Figure 60. - Time histories of GCH_4 pressurant flow rates during unbaffled slosh expulsions. Tank pressure, 34.47×10^4 newtons per square meter (50 psia); inlet temperature, 333 K (600° R); natural slosh frequency input; runs 90, 89, and 91.



(b) Inlet gas temperature, 333 K (600° R).

Figure 61. - Temperature of liquid methane at tank outlet as a function of normalized time during expulsion for unbaffled slosh expulsions over range of slosh amplitudes. Tank pressure, 34.47×10^4 newtons per square meter (50 psia); natural slosh frequency input.

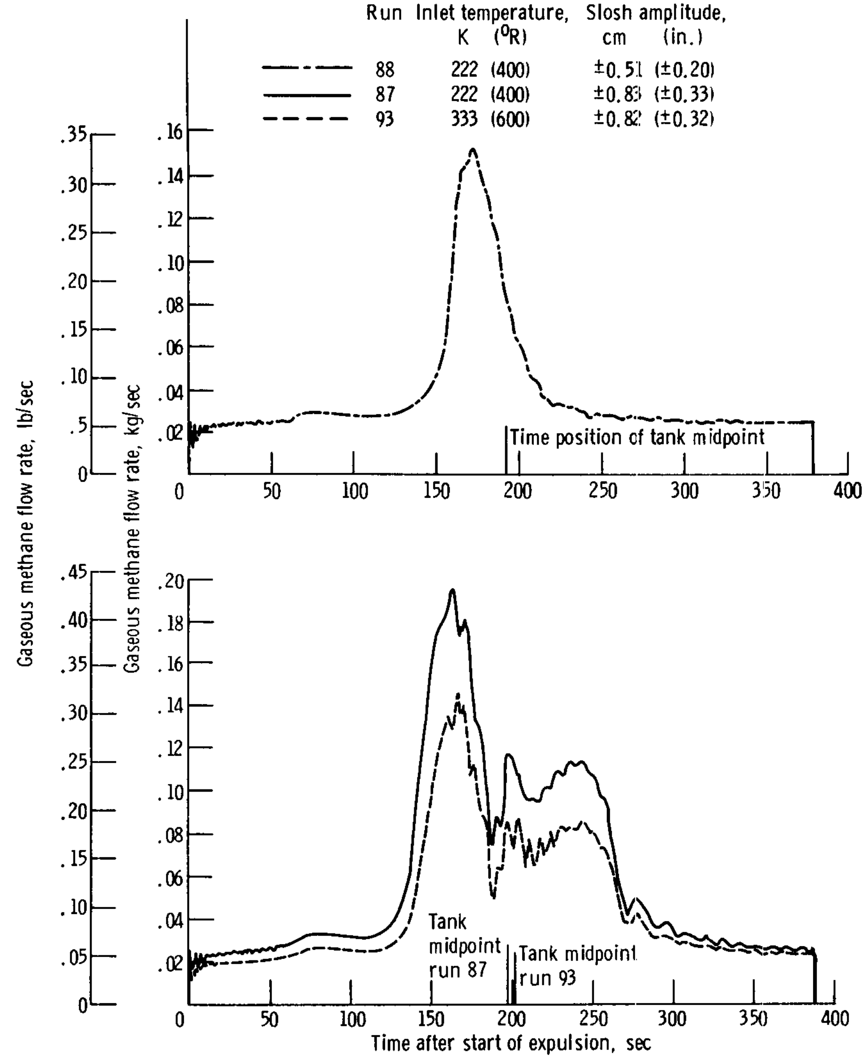


Figure 62. - Time histories of GCH_4 pressurant flow rates during unbaffled slosh expulsions. Tank pressure, 34.47×10^4 newtons per square meter (50 psia); 0.716-hertz slosh frequency input.

pulsions. Both sets of data show pronounced liquid heating occurring for runs having a slosh amplitude greater than ±0.51 centimeter (±0.20 in.).

Figure 62 displays the pressurant mass flow rates for three of the slosh runs made using a 0.716-hertz input. Run 88 (amplitude of ±0.51 cm or ±0.20 in.) and 87 (amplitude of ±0.83 cm or ±0.33 in.) are shown for a 222 K (400° R) inlet temperature. The main difference in the profiles of this type of run, relative to the natural frequency profile expulsion, is the pronounced flow increase when the liquid surface nears the center of the tank where the constant imposed frequency matches the natural frequency of the liquid remaining in the unbaffled tank. The gas flow peaks occur near the center of the tank over the expulsion time range. Comparison of runs 88 and 87 shows that, as the slosh amplitude increases, the pressurant flow rate starts rising earlier and stays up longer.

Also plotted in figure 62 is the flow rate for a 333 K (600° R) expulsion made at the same amplitude as the 222 K (400° R) temperature run 87. The flow characteristics for the 333 K (600° R) runs are identical in form with those made at the lower temperature. They differ only in that the absolute magnitude is lower.

Figure 63 displays the time histories of the liquid methane at the tank outlet for both the 222 K (400° R) and the 333 K (600° R) 0.716-hertz expulsions. As in the case of the natural frequency expulsions, these runs also show pronounced liquid heating at slosh

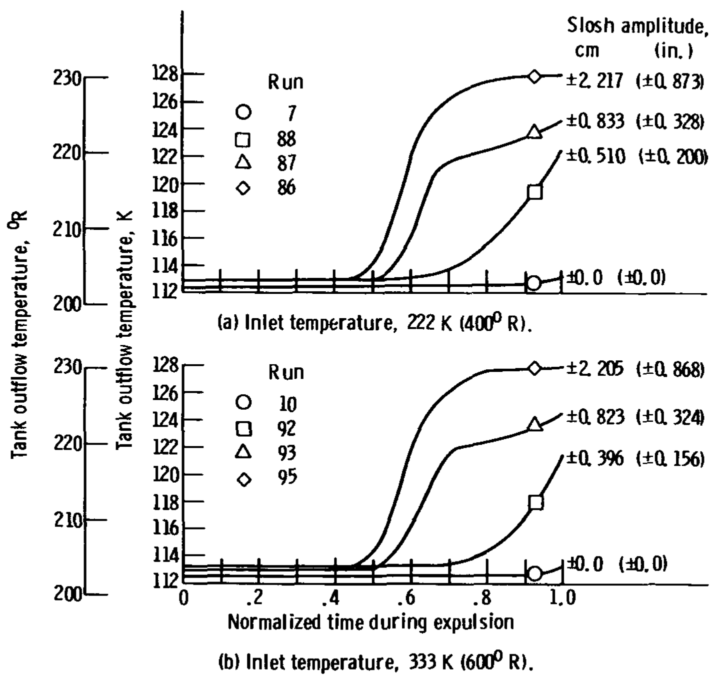


Figure 63. - Temperature of liquid methane at tank outlet as a function of normalized time during expulsion for unbaffled slosh expulsions over range of slosh amplitudes. Tank pressure, 34.47x10^4 newtons per square meter (50 psia); 0.716-hertz slosh frequency inputs.

amplitudes greater than ±0.51 centimeter (±0.20 in.).

Baffled tank. - This group was run using only 222 K (400° R) GCH_4 pressurant. The three concentric ring baffles are the same units used in the section Slosh Expulsions, Baffled Tank testing and shown in figure 6. Mass requirements are shown in figure 64 as a function of excitation amplitude for both the natural frequency and 0.716-hertz excitation. The mass requirement for the 222 K (400° R) unbaffled tank runs have only been added for reference.

The effect of the baffles was to linearize the pressurant gas requirements over the range of test amplitudes. Relative to the unbaffled tank requirements, the difference shown by the baffled runs is due to the baffles damping resonance effects in the liquid. This fact is also applicable to explaining the relatively small difference observed between the two sets of baffled tank data. As noted in figure 64, considerable spray was visually observed to be occurring when the liquid hit the underside of the baffles at test amplitudes greater than approximately ±1.02 centimeters (±0.4 in.). Evidently, this spray served to cool the ullage gas and thereby increase the amount of condensation at the higher slosh amplitudes. This action resulted in the pressurant gas increase over the unbaffled tank runs for the higher slosh amplitudes. Similarly, the "lack" of splashing at test amplitudes ≤1.02 centimeters (±0.4 in.) was probably the most significant reason for the smaller pressurant gas requirements in this range.

Figure 65 is a time history of the pressurant gas flow rates for three of the 333 K (600° R) natural frequency profile slosh runs. The direct effect of the baffles on pressurant gas requirements can be seen quite clearly, more so as test amplitude increases. Considering any one of the histories, the drop in the maximum flow from peak to peak is

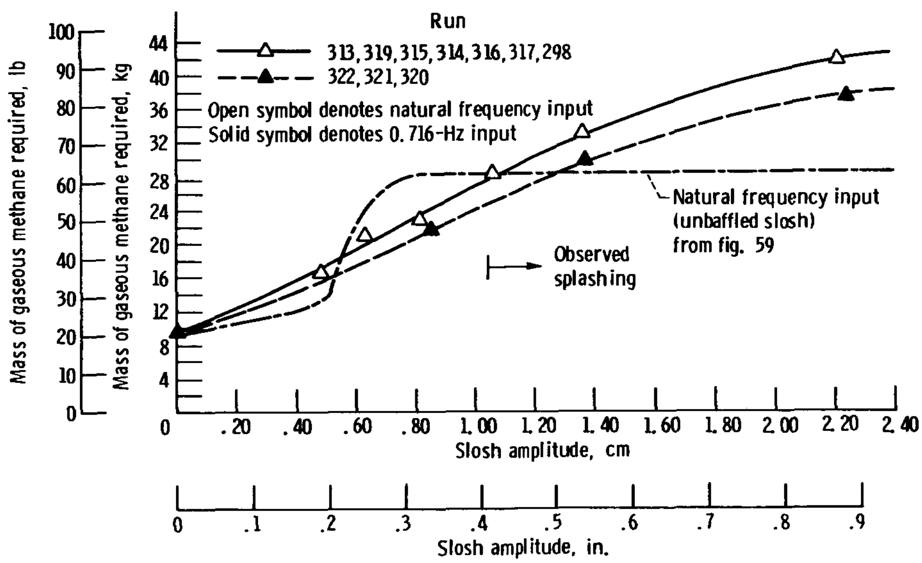
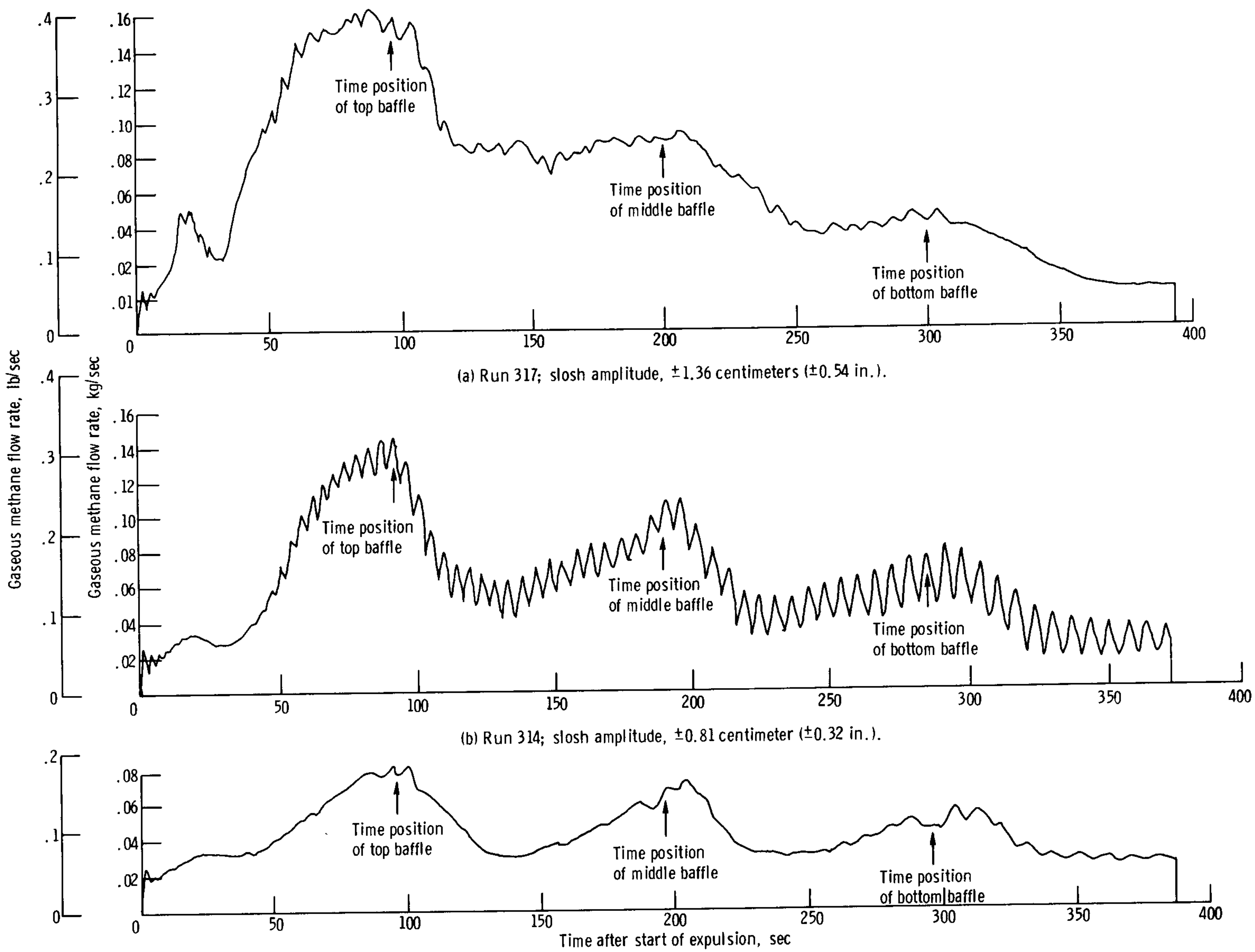


Figure 64. - Mass of GCH_4 pressurant required during baffled slosh expulsions for range of slosh amplitudes. Tank pressure, 34.47×10^4 newtons per square meter (50 psia); inlet temperature, 222 K (400° R); expulsion time, 389 seconds average.



(a) Run 317; slosh amplitude, ±1.36 centimeters (±0.54 in.).

(b) Run 314; slosh amplitude, ±0.81 centimeter (±0.32 in.).

(c) Run 319; slosh amplitude, ±0.483 centimeter (±0.19 in.).

Figure 65. - Time histories of GCH_4 pressurant flow rates during baffled slosh expulsions. Tank pressure, 34.47×10^4 newtons per square meter (50 psia); inlet temperature, 333 K (600^0 R); natural frequency slosh input; runs 317, 314, and 319.

to be expected since the liquid propellant is continuously warming. Near the end of expulsion, the liquid propellant is highly heated and, therefore, ullage gas condensation due to sprayed propellant is negligible.

Figure 66 displays the time histories of the liquid methane at the tank outlet for the 222 K (400° R) natural frequency expulsions. Comparison of these profiles with those in figure 61 reveals considerably more liquid heating for the baffled runs (compared to the unbaffled cases) for slosh amplitudes greater than ±1.052 centimeters (±0.42 in.). This relation has the same trend as that shown in figure 64 for the pressurant gas requirements.

Figure 67 is a time history of pressurant flow rates for two of the 0.716-hertz slosh

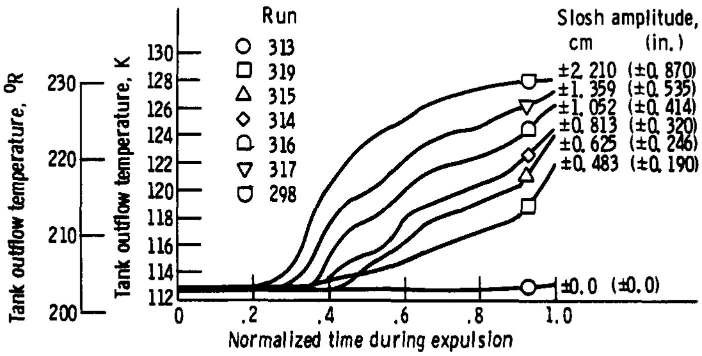
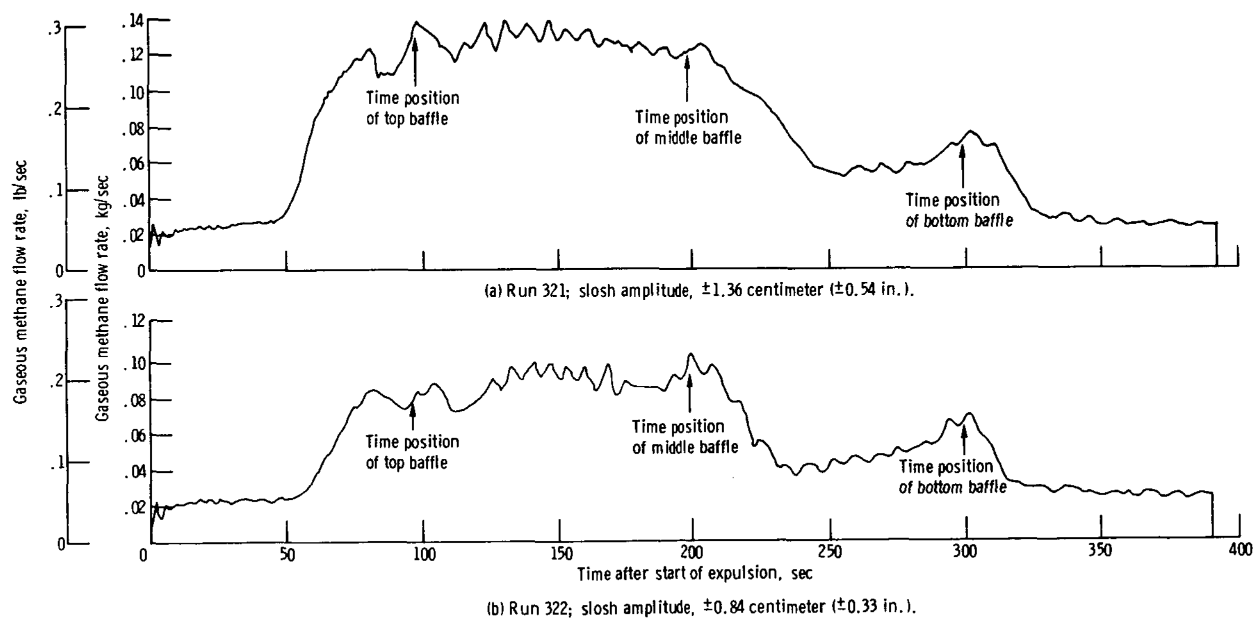
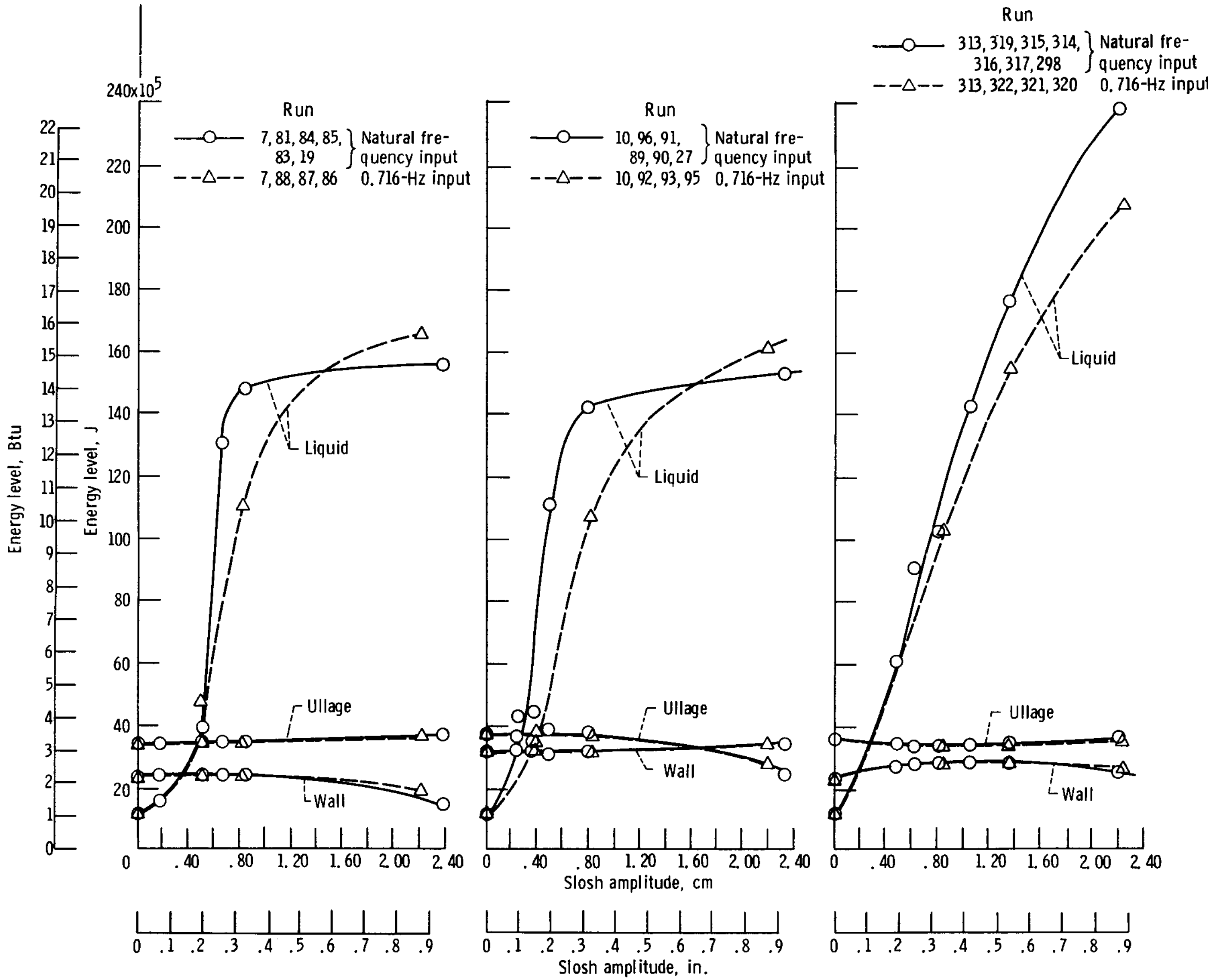


Figure 66. - Temperature of liquid methane at tank outlet as a function of normalized time during expulsion for baffled slosh expulsions over range of slosh amplitudes. Tank pressure, 34.47×10^4 newtons per square meter (50 psia); inlet temperature, 222 K (400° R); natural slosh frequency input.



(b) Run 322; slosh amplitude, ±0.84 centimeter (±0.33 in.).

Figure 67. - Time histories of GCH_4 flow rates during baffled slosh expulsions. Tank pressure, 34.47×10^4 newtons per square meter (50 psia); inlet temperature, 333 K (600° R); 0.716-hertz slosh input frequency; runs 321 and 322.



(a) Unbaffled slosh; inlet temperature, 222 K (400° R).

(b) Unbaffled slosh; inlet temperature, 333 K (600° R).

(c) Slosh with baffles; inlet temperature, 222 K (400° R).

Figure 68. - Energy levels as a function of slosh amplitude using GCH_4 pressurant. Nominal expulsion, 389 seconds. (Amplitude = 0 is no slosh base point.)

runs. After the initial increase, flow requirements for these runs remains relatively constant for a longer period of time than those for the natural frequency runs. The net effect of this action, averaged out over the entire expulsion, is to reduce the total pressurant requirements only slightly.

Figure 68 is a summary figure for all the expulsions made in the section Variable Amplitude Slosh, With and Without Baffles. The main point to be made by this figure is the amount of propellant heating experienced for the range of slosh runs (both natural frequency profile and 0.716 Hz). In all cases, the presence of almost any liquid sloshing gives rise to at least some liquid heating so that the propellant, when delivered into an engine flow system, could obviate good system performance because of cavitation. It is very interesting to note that this statement can be made even when the tank has been baffled to reduce liquid motion.

Partial Tank Expulsions

General. - Twelve partial tank expulsions were made during which only half the liquid propellant in the tank was expelled. The first six of these runs dealt with expulsion of only the upper half of the tank contents. For the remaining six runs the expulsion was started at the 50 percent ullage level and continued until only 5 percent of the methane propellant remained (i.e., 95 percent ullage).

These partial expulsions were made using GCH_4, GHe, and GH_2 pressurants. The test parameter was inlet gas temperature. Each half-tank expulsion was made over a nominal time period of 200 seconds.

The experimentally determined pressurant gas requirements were compared to analytically predicted values. The exact test conditions, as well as the mass and energy balances for all six groups of data, appear in tables IX and X. The mass requirements data are plotted in figure 69.

5 to 50 percent ullage expulsions. - The pressurant required for these runs was slightly less than half the amount needed for comparable full tank expulsions discussed in the section Static Tank Expulsions. As was the case for the complete tank expulsions, agreement between experimental and predicted gas requirements is good. All detailed run characteristics such as pressurant flow rate, liquid outflow temperature, ullage gas and tank wall temperatures, amount of mass transfer, and so forth, will not be discussed since these expulsions are identical to the first half of complete tank runs.

The results of the experimentally determined energy balances are shown in table X. For all three pressurants the heat added via both the incoming gas and the environment is slightly less than half of the same category for complete expulsions. The heat left in the ullage after these partial expulsions, compared to the complete tank runs, was slightly

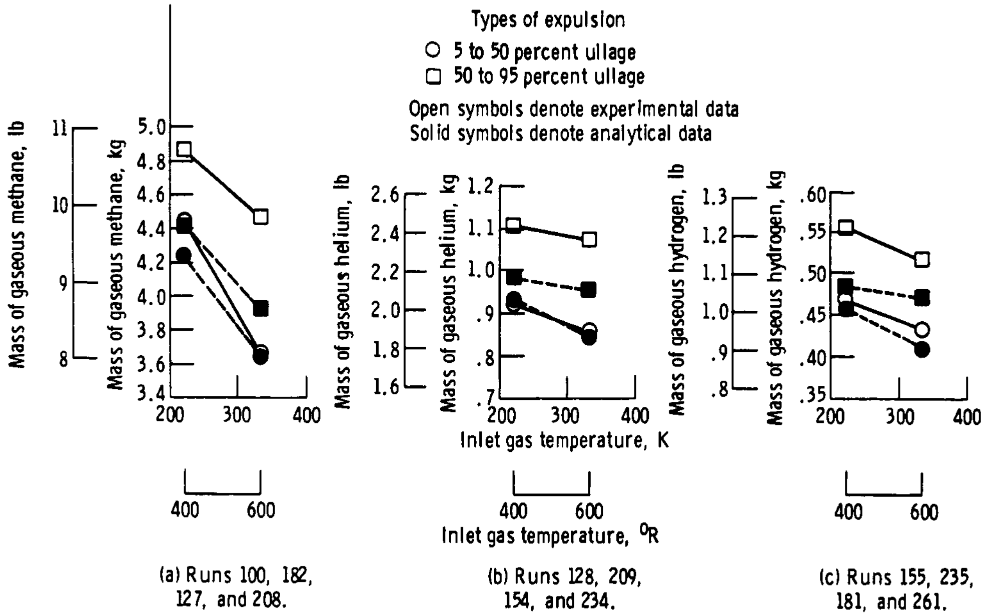


Figure 69. - Mass required for partial static tank expulsions using GCH_4, GHe, and GH_2 pressurants.

less than half for the condensible pressurant and slightly more than half for the noncondensibles. As a general rule, the heat absorbed by the tank wall, and the heat transferred to the liquid propellant, were also slightly less than half of the full expulsion values. The energy gained by the liquid is not highly accurate, however, due to the large surface area of stratified liquid existing at the end of a partial expulsion. The large area makes the calculated energy content very sensitive to temperature immediately below the liquid interface.

50 to 95 percent ullage expulsions. - The pressurant required for these runs was slightly greater than half the amount required for comparable full tank expulsions. The analytically predicted results are also low. The several factors which made it more difficult for the analysis were higher initial ullage energies, a higher ratio of total to added mass, and the condensation which was present in all of these runs. In the cases where GHe and GH_2 were the pressurants, over half of the original methane in the ullage at the beginning of expulsion ended up being condensed. The marked difference in molecular weights between GHe or GH_2 and GCH_4 contributed to the normal stratification at the beginning of expulsion. At the end of the ramp pressurization the partial pressure of methane vapor, because of the higher concentration of GCH_4 near the interface, is greater than the vapor pressure of the interface and hence some of the GCH_4 condenses. This effect is also present during complete expulsions, however, the amount of GCH_4 in a 5 percent ullage is only one tenth of that present in these expulsions.

The results of the experimental energy balance are shown in table X. For all three pressurants the heat added via both the incoming gas and the environment is greater than half of the same values corresponding to a complete tank expulsion. The energy left in the ullage was slightly greater using GCH_4, and slightly less when using GHe and GH_2, than half of the same values corresponding to a complete tank expulsion. As a general rule the heat absorbed by the tank wall, and that transferred to the liquid, were slightly greater than that required during half of the full expulsion values.

SUMMARY OF RESULTS

Pressurized expulsion tests were conducted to determine the effect of various physical parameters on the pressurant gas requirements during the expulsion of liquid methane (LCH_4) from a 1.52-meter- (5-ft-) diameter spherical tank. Methane, helium, hydrogen, and nitrogen were used as pressurant gases. The necessary quantities of these gases to expel 90 percent of the LCH_4 propellant (an average of 651 kg or 1435 lb) were studied as a function of expulsion time at a nominal operating pressure of 34.47×10^4 newtons per square meter (50 psia) using nominal inlet gas temperatures of 222 and 333 K (400° and 600° R). Also studied were the effects on methane, helium, and hydrogen pressurant requirements of various slosh excitation frequencies, and amplitudes, both with and without slosh suppressing baffles in the tank.

Several partial tank expulsion runs were also made. The first six of these runs dealt with expulsion of only the upper half of the tank contents. For the remaining six runs, the expulsion was started at the 50 percent ullage level and continued until only 5 percent of the methane propellant remained.

The experimental results for the static tank tests (i.e., nonslosh) were compared with predicted results obtained from an analytical program previously developed at Lewis Research Center. The following general results were found.

Static Tank Expulsions

1. With GCH_4 pressurant, a significant amount of condensation takes place. The quantities of GCH_4 required to expel the LCH_4 propellant were between 7.0 and 10.1 kilograms (15.5 and 22.2 lb) for an expulsion time range of 231 to 638 seconds. The amounts of pressurant condensed were between 1.9 and 3.2 kilograms (4.3 and 7.0 lb); these quantities represent between 28 and 33 percent of the pressurant added during expulsion.

2. Gaseous nitrogen is unacceptable as a pressurant because of its high solubility in liquid methane. The quantities of GN_2 required to expel the LCH_4 propellant were between 20.7 and 32.9 kilograms (45.7 and 72.5 lb) for an expulsion time range of 232 to 568 seconds. The amounts of pressurant dissolved were between 12.7 and 23.8 kil-

ograms (28 to 52.5 lb); these quantities represent between 61 and 73 percent of the pressurant added during expulsion.

3. With the noncondensable pressurants, GHe and GH_2, neither inlet gas temperature nor expulsion time had a large effect on gas requirements. The quantities of GHe required during expulsion were between 1.76 and 1.98 kilograms (3.88 and 4.36 lb) for an expulsion time range of 223 to 622 seconds. The GH_2 requirements were between 0.85 and 1.00 kilograms (1.88 and 2.20 lb) for a time range of 219 to 567 seconds. The maximum change in pressurant gas requirements due to both inlet gas temperature and expulsion time was only 17.7 percent and occurred with hydrogen. The amounts of noncondensable pressurant dissolved in the LCH_4 propellant were small, being a maximum of 0.10 kilogram (0.21 lb) of GHe and 0.05 kilogram (0.101 lb) of GH_2.

4. The comparison between the analytical predictions and the experimental results for helium, hydrogen, and methane pressurants were good. The predictions for nitrogen pressurant were meaningless because of its large solubility.

Slosh Expulsions at Natural Frequency and ±2.23-Centimeters (±0.88-in.) Amplitude With and Without Baffles

1. Using GCH_4, pressurant mass requirements for unbaffled slosh expulsions are greatly increased over those required for a static tank. The increase was a factor of between 2.7 and 3.1.

2. Using GCH_4, the requirements for baffled slosh expulsions were increased by a factor of between 3.9 to 4.6 over those required for a static tank. (N.B. The addition of baffles increased gas requirements for this condensable pressurant.)

3. Using GCH_4, significantly larger amounts of condensation were observed. The increase was a factor of 5.7 to 7.6 in the case without baffles and 9.9 to 12.3 for the case with baffles.

4. Both with and without baffles, using GCH_4 pressurant, severe liquid heating was observed. The greatest effect was observed for the tank with baffles. At least 50 percent of the liquid showed some heating for the unbaffled tank (37 percent or more was within 5.5 K (10° R) of being saturated). At least 70 percent of the liquid showed heating for the baffled configuration (59 percent or more was within 5.5 K (10° R) of being saturated).

5. The GCH_4 flow rate is not constant throughout a given expulsion as it was for the static tank cases. A large peak was required at the beginning of each slosh expulsion with a succeeding dropoff in pressurant flow requirements as the expulsion continued.

6. The difference in GCH_4 requirements for the 222 and 333 K (400° and 600° R) inlet temperatures can be directly correlated with inlet temperature.

7. Using the noncondensable pressurants, GHe and GH_2, the pressurant requirements were reduced by a factor of 0.05 to 0.16 (5 to 16 percent) in the case without baffles.

8. Using the noncondensable pressurant GHe, the pressurant requirements were reduced by a factor of 0.13 to 0.14 (13 to 14 percent) in the case with baffles. (Note that the requirements for the baffled tank expulsions were between the requirements for the static tank and those for the unbaffled tank.)

9. Using the noncondensable pressurants, GHe and GH_2, considerable evaporation of LCH_4 propellant took place during the expulsion period. This evaporation reduces the noncondensable pressurant requirement.

10. For the noncondensable pressurant, GH_2, solution into the LCH_4 propellant caused some propellant heating.

Slosh Expulsions With Variable Amplitude and Frequency Excitation

With and Without Baffles

In this section, f_n denotes a slosh frequency input profile which corresponds, at all times, with the natural frequency of the liquid remaining in an unbaffled tank and f_o denotes a constant slosh frequency input equal to the natural frequency of the tank when half full of propellant.

1. For the unbaffled case, there is a definite excitation amplitude below which slosh effects are small and above which they are large. This amplitude was essentially the same for both f_n and f_o frequency profiles and was approximately ±0.5 centimeter (±0.2 in.).

2. The addition of antislosh baffles generally increased GCH_4 pressurant requirements over the range of test amplitudes. The addition of antislosh baffles resulted in greater GCH_4 pressurant requirements than for the unbaffled tanks at slosh amplitudes greater than ±1.13 centimeters (±0.5 in.).

3. The addition of antislosh baffles resulted in a linear relation between GCH_4 pressurant requirements for complete expulsions and slosh amplitude.

4. The GCH_4 flow rate was not constant through any of the expulsions over the range of test amplitudes. A large peak was required at the beginning of each f_n slosh expulsion; a large peak was encountered approximately halfway through each of the f_o slosh expulsions.

5. Because of compensating heat transfer mechanisms, the total GCH_4 pressurant requirement is only slightly less for the f_o slosh expulsions compared to the f_n runs.

Partial Expulsions, Static Tank

1. Gaseous methane, helium, and hydrogen requirements for the 5 to 50 percent ullage expulsions were slightly less than half of the requirements necessary for complete tank expulsions.

2. The comparison between analytical predictions and the experimental results for the 5 to 50 percent ullage expulsions was good.

3. Gaseous methane, helium, and hydrogen requirements for the 50 to 95 percent ullage expulsions were slightly greater than half of the requirements necessary for a complete tank expulsion.

4. Gaseous methane condensation was observed in all 50 to 95 percent ullage expulsions.

5. Analytical predictions for the 50 to 95 percent ullage expulsions were less than the experimental requirements for all three pressurants. Methane condensation from the ullage was the reason.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, November 27, 1973,
502-24.

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TABLE I. - MASS BALANCE FOR STATIC TANK EXPULSIONS

(a) SI units

								Ramp			Hold				Expulsion								
Run	Type of pressurant	Tank pressure, N/m^2	Mass of LCH_4 expelled, kg	Inlet gas temperature, K	Ramp time, sec	Hold time, sec	Expulsion time, sec	Initial ullage mass, $M_{i,r}$, kg	Mass added during ramp, $M_{G,r}$, kg	Mass transferred during ramp, $M_{t,r}$, kg	Ullage mass after ramp, $M_{i,h}$, kg	Mass of added pressurant specie in ullage at end of ramp, kg	Mass added during hold, $M_{G,h}$, kg	Mass transferred during hold, $M_{t,h}$, kg	Ullage mass after hold, $M_{i,e}$, kg	Mass of added pressurant specie in ullage at end of hold, kg	Mass added during expulsion, $M_{G,e}$, kg	Mass transferred during expulsion, $M_{t,e}$, kg	Final ullage mass, $M_{f,e}$, kg	Mass of added pressurant specie in ullage at end of expulsion, kg	Increase in added specie in ullage during expulsion, kg	Predicted pressurant required during expulsion, $M_{G,e,P}$, kg	Predicted mass transferred during expulsion, $M_{t,e,P}$, kg
8	GCH_4	33.9×10^4	650	226	33.0	24.1	230.7	0.158	0.578	0.369	0.367	-----	0.181	0.135	0.413	-----	8.522	2.477	6.458	-----	-----	8.029	2.300
7		33.6	647	227	33.8	23.0	404.9	.155	.593	.390	.358	-----	.167	.122	.403	-----	9.184	2.780	6.807	-----	-----	8.396	
6		34.1	644	226	32.7	24.4	632.8	.148	.639	.447	.340	-----	.209	.150	.399	-----	10.056	3.196	7.259	-----	-----	8.754	
11		33.9	650	338	33.2	24.1	233.5	.174	.625	.515	.284	-----	.212	.156	.340	-----	7.027	1.946	5.421	-----	-----	6.904	
10		33.7	645	344	33.4	24.0	410.0	.153	.503	.361	.295	-----	.180	.131	.344	-----	8.028	2.463	5.909	-----	-----	7.425	
9		33.5	642	339	33.9	23.2	637.6	.157	.535	.382	.310	-----	.169	.113	.366	-----	8.935	2.909	6.392	-----	-----	7.820	
37	GHe	34.0	646	229	31.9	25.8	223.4	.142	.112	.105	.149	0.086	.028	.010	.167	0.098	1.850	[a].131	2.148	1.969	1.871	1.792	-----
36		34.0	639	226	31.9	25.7	389.2	.153	.124	.135	.142	.092	.038	[a].006	.186	.120	1.934	[a].177	2.297	2.064	1.944	1.871	-----
33		34.0	633	231	32.1	24.7	622.3	.152	.130	.112	.170	.096	.038	.011	.197	.112	1.977	[a].296	2.470	2.050	1.938	1.939	-----
42		34.1	646	324	32.1	25.2	223.7	.152	.108	.113	.147	.082	.029	.012	.164	.093	1.758	[a].061	1.983	1.863	1.770	1.653	-----
41		34.1	642	331	30.8	26.8	390.3	.152	.113	.118	.147	.082	.030	.013	.164	.093	1.857	[a].206	2.227	1.995	1.902	1.792	-----
40		34.1	633	311	30.9	26.2	598.5	.151	.116	.119	.148	.083	.039	[a].009	.196	.109	1.936	[a].159	2.291	2.025	1.916	1.862	-----
63	GH_2	33.9	643	223	31.9	25.4	219.3	.150	.064	.119	.095	.049	.016	[a].003	.114	.061	.921	[a].078	1.113	.978	.917	.874	-----
62		33.9	638	226	31.9	26.0	372.8	.152	.065	.126	.091	.048	.017	[a].009	.117	.060	.963	[a].123	1.203	1.016	.956	.908	-----
61		33.9	635	224	31.7	26.0	561.7	.152	.066	.118	.100	.052	.015	[a].001	.116	.060	.998	[a].153	1.267	1.033	.973	.939	-----
68		34.1	647	338	30.7	26.4	221.6	.146	.055	.113	.088	.044	.014	.004	.098	.050	.853	[a].097	1.048	.907	.857	.785	-----
66		34.0	644	333	31.0	26.1	377.3	.147	.054	.112	.089	.044	.014	.008	.095	.049	.918	[a].141	1.154	.963	.914	.854	-----
69		34.1	642	334	31.2	26.7	566.1	.154	.056	.118	.091	.046	.014	.006	.099	.051	.956	[a].196	1.251	1.009	.958	.899	-----
65		34.1	640	332	30.6	27.4	567.4	.139	.058	.102	.095	.047	.016	.008	.103	.053	.968	[a].166	1.237	1.004	.951	.907	-----
98	GN_2	34.1	659	335	30.8	26.7	232.2	.164	.867	.575	.456	.319	.904	.877	.483	.423	20.725	12.703	8.505	8.368	7.945	-----	-----
99		34.1	655	335	30.3	27.1	377.7	.152	.881	.589	.444	.347	.807	.769	.482	.432	27.054	18.600	8.936	8.785	8.353	-----	-----
97		34.1	660	337	30.8	26.8	567.9	.154	.891	.604	.441	.326	.877	.843	.475	.423	32.864	23.792	9.547	9.329	8.906	-----	-----

[a]Evaporated. (All other values are condensed.)

TABLE I. - Concluded. MASS BALANCE FOR STATIC TANK EXPULSIONS

(b) U.S. customary units

Ramp — Hold — Expulsion

Run	Type of pressurant	Tank pressure, psia	Mass of LCH_4 expelled, lb	Inlet gas temperature, ^oR	Ramp time, sec	Hold time, sec	Expulsion time, sec	Initial ullage mass, $M_{i,r}$, lb	Mass added during ramp, $M_{G,r}$, lb	Mass transferred during ramp, $M_{t,r}$, lb	Ullage mass after ramp, $M_{i,h}$, lb	Mass of added pressurant specie in ullage at end of ramp, lb	Mass added during hold, $M_{G,h}$, lb	Mass transferred during hold, $M_{t,h}$, lb	Ullage mass after hold, $M_{i,e}$, lb	Mass of added pressurant specie in ullage at end of hold, lb	Mass added during expulsion, $M_{G,e}$, lb	Mass transferred during expulsion, $M_{t,e}$, lb	Final ullage mass, $M_{f,e}$, lb	Mass of added pressurant specie in ullage at end of expulsion, lb	Increase in added specie in ullage during expulsion, lb	Predicted pressurant required during expulsion, $M_{G,e,P}$, lb	Predicted mass transferred during expulsion, $M_{t,e,P}$, lb
8	GCH_4	49.2	1433	407	33.0	24.1	230.7	0.349	1.274	0.814	0.809	-----	0.398	0.296	0.911	-----	18.787	5.461	14.237	-----	-----	17.70	5.07
7		48.7	1426	409	33.8	23.0	404.9	.342	1.308	.860	.190	-----	.369	.271	.888	-----	20.246	6.127	15.007	-----	-----	18.51	
6		49.5	1420	407	32.7	24.4	632.8	.327	1.408	.986	.749	-----	.461	.330	.880	-----	22.169	7.016	16.033	-----	-----	19.30	
11		49.2	1433	608	33.2	24.1	233.5	.384	1.378	1.135	.627	-----	.468	.345	.750	-----	15.491	4.290	11.951	-----	-----	15.22	
10		48.9	1422	619	33.4	24.0	410.0	.337	1.109	.796	.650	-----	.397	.289	.758	-----	17.698	5.429	13.027	-----	-----	16.37	
9		48.6	1415	610	33.9	23.2	637.6	.346	1.179	.842	.683	-----	.373	.249	.807	-----	19.699	6.415	14.091	-----	-----	17.24	
37	GHe	49.3	1424	412	31.9	25.8	223.4	.312	.246	.229	.329	0.190	.062	.022	.369	0.216	4.078	[a].289	4.736	4.340	4.124	3.950	----
36		49.3	1409	407	31.9	25.7	389.2	.337	.273	.298	.312	.203	.083	[a].014	.409	.264	4.264	[a].392	5.065	4.551	4.287	4.125	----
33		49.3	1396	416	32.1	24.7	622.3	.336	.287	.248	.375	.211	.084	.024	.435	.247	4.359	[a].652	5.446	4.519	4.272	4.275	----
42		49.5	1424	583	32.1	25.2	223.7	.336	.239	.250	.325	.180	.064	.027	.362	.204	3.875	[a].134	4.371	4.107	3.903	3.645	----
41		49.5	1415	596	30.8	26.8	390.3	.336	.249	.261	.324	.180	.066	.028	.362	.206	4.094	[a].454	4.910	4.399	4.193	3.951	----
40		49.5	1396	560	30.9	26.2	598.5	.333	.256	.262	.327	.183	.085	[a].019	.431	.240	4.267	[a].352	5.050	4.465	4.225	4.105	----
63	GH_2	49.2	1418	401	31.9	25.4	219.3	.330	.141	.262	.210	.109	.036	[a].006	.252	.134	2.031	[a].170	2.453	2.157	2.023	1.926	----
62		49.2	1407	407	31.9	26.0	372.8	.334	.144	.277	.201	.106	.038	[a].018	.257	.133	2.123	[a].273	2.653	2.239	2.106	2.002	----
61		49.2	1400	403	31.7	26.0	561.7	.335	.146	.261	.220	.114	.033	[a].002	.255	.132	2.201	[a].338	2.794	2.278	2.146	2.070	----
68		49.5	1426	608	30.7	26.4	221.6	.321	.122	.248	.195	.098	.031	.010	.216	.110	1.881	[a].213	2.310	1.999	1.889	1.731	----
66		49.3	1420	599	31.0	26.1	377.3	.325	.119	.247	.197	.098	.031	.019	.209	.108	2.023	[a].312	2.544	2.122	2.014	1.883	----
69		49.5	1415	601	31.2	26.7	566.1	.339	.123	.261	.201	.101	.031	.013	.219	.112	2.108	[a].432	2.759	2.225	2.113	1.982	----
65		49.5	1411	598	30.6	27.4	567.4	.307	.128	.226	.209	.104	.035	.016	.228	.116	2.135	[a].365	2.728	2.213	2.097	2.000	----
98	GN_2	49.5	1453	603	30.8	26.7	232.2	.361	1.911	1.267	1.005	.704	1.998	1.933	1.065	.932	45.690	28.005	18.750	18.449	17.517	-----	----
99		49.5	1444	603	30.3	27.1	377.7	.334	1.942	1.298	.978	.766	1.778	1.694	1.062	.952	59.643	41.004	19.701	19.363	18.416	-----	----
97		49.5	1455	607	30.8	26.8	567.9	.340	1.964	1.332	.972	.719	1.933	1.857	1.048	.932	72.451	52.451	21.048	20.567	19.635	-----	----

[a]Evaporated. (All other values are condensed.)

TABLE II. - ENERGY BALANCE FOR STATIC TANK EXPULSIONS

(a) SI units

Run	Type of pressurant	Inlet gas temperature, K	Expulsion time, sec	Total energy added, ΔU_T, J		Energy gained by tank wall during expulsion, J		Energy gained by ullage, $\Delta U_{U,X}$, J	Energy gained by liquid during expulsion, J	
				Energy added by pressurant gas during expulsion (experimental)	Energy added by environment during expulsion (experimental)	Experimental $\Delta U_{w,X}$	Predicted $\Delta U_{w,P}$		Experimental $\Delta U_{L,X}$	Predicted $\Delta U_{L,P}$
8	GCH_4	226	230.7	635.0×10^4	15.8×10^4	195.4×10^4	197.0×10^4	328.5×10^4	94.4×10^4	[a]69.9×10^4
7	↓	227	404.9	688.1	27.7	233.6	228.8	338.0	108.4	[a]76.5
6	↓	226	632.8	750.2	43.3	261.1	257.9	354.3	115.9	[a]87.0
11	↓	338	233.5	779.5	16.0	275.3	306.2	300.9	86.6	[a]67.9
10	↓	344	410.0	813.3	28.2	363.2	377.0	313.8	108.6	[a]75.6
9	↓	339	637.6	892.0	43.7	414.5	420.4	325.8	129.7	[a]84.8
37	GHe	229	223.4	239.4	15.3	76.6	92.9	83.6	71.3	[b]59.4
36	↓	226	389.2	229.3	26.7	90.8	112.1	85.2	55.5	[b]64.6
33	↓	231	622.3	239.2	42.6	108.5	134.9	91.4	64.2	[b]72.6
42	↓	324	223.7	298.7	15.3	130.4	159.7	81.7	62.7	[b]59.6
41	↓	331	390.3	320.7	26.7	162.5	199.7	85.9	60.7	[b]65.3
40	↓	311	598.5	314.7	41.0	171.6	215.3	85.8	71.3	[b]72.0
63	GH_2	223	219.3	289.3	15.0	90.1	101.7	134.2	66.4	[b]58.7
62	↓	226	372.8	306.2	25.5	112.0	128.2	136.7	70.4	[b]63.8
61	↓	224	561.7	315.7	38.5	125.6	144.2	138.9	69.9	[b]70.3
68	↓	338	221.6	406.8	15.2	180.5	205.4	135.0	72.9	[b]59.6
66	↓	333	377.3	431.8	25.8	210.9	244.8	137.9	62.9	[b]64.6
69	↓	334	566.1	450.2	38.8	252.2	287.4	141.1	71.2	[b]71.4
65	↓	332	567.4	453.5	38.9	242.2	284.4	140.1	72.4	[b]71.2
98	GN_2	335	232.2	1038.9	15.9	244.5	-----	251.1	473.6	-----
99	↓	335	377.7	1357.4	25.9	348.1	-----	258.2	673.4	-----
97	↓	337	567.9	1653.2	38.9	450.5	-----	268.6	893.4	-----

[a]$P\,\Delta V + (1/2)Q_{\text{added by environment}} + M_{cond}(U_{SL})_{112\text{ K}}$.

[b]$P\,\Delta V + (1/2)Q_{\text{added by environment}}$.

TABLE II. - Concluded. ENERGY BALANCE FOR STATIC TANK EXPULSIONS

(b) U.S. customary units

Run	Type of pressurant	Inlet gas temperature, ^{o}R	Expulsion time, sec	Total energy added, ΔU_T, Btu		Energy gained by tank wall during expulsion, Btu		Energy gained by ullage, $\Delta U_{U,X}$, Btu	Energy gained by liquid during expulsion, Btu	
				Energy added by pressurant gas during expulsion (experimental)	Energy added by environment during expulsion (experimental)	Experimental $\Delta U_{w,X}$	Predicted $\Delta U_{w,P}$		Experimental $\Delta U_{L,X}$	Predicted $\Delta U_{L,P}$
8	GCH_4	407	230.7	6023	150	1853	1868	3116	895	[a]663
7	↓	409	404.9	6526	263	2216	2170	3206	1028	[a]726
6	↓	407	632.8	7115	411	2476	2446	3360	1099	[a]325
11	↓	608	233.5	7393	152	2611	2904	2854	821	[a]644
10	↓	619	410.0	7714	267	3446	3576	2976	1030	[a]717
9	↓	610	637.6	8460	414	3931	3987	3090	1230	[a]304
37	GHe	412	223.4	2271	145	727	881	793	676	[b]563
36	↓	407	389.2	2175	253	861	1063	808	526	[b]613
33	↓	416	622.3	2269	404	1029	1279	867	609	[b]689
42	↓	583	223.7	2833	145	1237	1515	775	595	[b]565
41	↓	596	390.3	3042	253	1541	1894	815	576	[b]619
40	↓	560	598.5	2985	389	1628	2042	814	676	[b]683
63	GH_2	401	219.3	2744	142	855	965	1273	630	[b]557
62	↓	407	372.8	2904	242	1062	1216	1297	668	[b]605
61	↓	403	561.7	2994	365	1191	1368	1317	663	[b]667
68	↓	608	221.6	3858	144	1712	1948	1280	691	[b]565
66	↓	599	377.3	4095	245	2000	2322	1308	597	[b]613
69	↓	601	566.1	4270	368	2392	2726	1338	675	[b]677
65	↓	598	567.4	4301	369	2297	2697	1329	687	[b]676
98	GN_2	603	232.2	9853	151	2319	----	2382	4492	----
99	↓	603	377.7	12874	246	3302	----	2449	6387	----
97	↓	607	567.9	15680	369	4273	----	2548	8473	----

[a] $P\ \Delta V/777.6 + (1/2)Q_{\text{added by environment}} + M_{cond}(U_{SL})_{202^{o}\ R}$.

[b] $P\ \Delta V/777.6 + (1/2)Q_{\text{added by environment}}$.

TABLE III. - MASS BALANCE FOR SLOSH CONDITIONS WITHOUT BAFFLES

(a) SI units

								Ramp					Hold				Expulsion				
Run[a]	Type of pressurant	Tank pressure, N/m^2	Mass of LCH_4 expelled, kg	Inlet gas temperature, K	Ramp time, sec	Hold time, sec	Expulsion time, sec	Initial ullage mass, $M_{i,r}$, kg	Mass added during ramp, $M_{G,r}$, kg	Mass transferred during ramp, $M_{t,r}$, kg	Ullage mass after ramp, $M_{i,h}$, kg	Mass of added pressurant specie in ullage at end of ramp, kg	Mass added during hold, $M_{G,h}$, kg	Mass transferred during hold, $M_{t,h}$, kg	Ullage mass after hold, $M_{i,e}$, kg	Mass of added pressurant specie in ullage at end of hold, kg	Mass added during expulsion, $M_{G,e}$, kg	Mass transferred during expulsion, $M_{t,e}$, kg	Final ullage mass, $M_{f,e}$, kg	Mass of added pressurant specie in ullage at end of expulsion, kg	Increase in added specie in ullage during expulsion, kg
21	GCH_4	33.4×10^4	660	230	33.7	22.8	297.5	0.152	0.688	0.485	0.355	-----	0.203	0.145	0.413	-----	26.676	19.092	7.997	-----	-----
19		33.4	662	230	34.0	23.4	371.8	.155	.678	.479	.354	-----	.196	.136	.414	-----	28.475	21.226	7.663	-----	-----
16		33.9	660	231	33.7	24.4	442.7	.155	.610	.400	.365	-----	.181	.126	.420	-----	29.604	22.545	7.479	-----	-----
12		33.9	664	231	33.4	23.2	674.4	.149	.651	.464	.336	-----	.198	.143	.391	-----	31.617	23.771	8.237	-----	-----
29		33.4	652	349	33.7	24.0	296.3	.149	.503	.353	.299	-----	.157	.109	.347	-----	19.082	11.918	7.511	-----	-----
27		33.6	652	347	34.0	24.1	360.9	.155	.532	.373	.314	-----	.168	.116	.367	-----	20.639	14.362	6.644	-----	-----
25		33.6	659	344	33.9	23.7	438.9	.147	.582	.433	.296	-----	.176	.132	.340	-----	22.470	16.249	6.561	-----	-----
23		33.2	650	342	34.2	23.0	657.7	.156	.560	.421	.295	-----	.168	.115	.348	-----	23.003	15.367	7.984	-----	-----
45	GHe	34.0×10^4	635	226	31.7	25.9	217.4	.154	.132	.133	.153	0.104	.039	.014	.178	0.122	1.582	[b]1.715	3.475	1.761	1.639
44		34.0	640	226	31.4	25.6	398.8	.154	.134	.140	.148	.101	.038	.009	.177	.121	1.631	[b]1.921	3.729	1.755	1.634
43		34.0	632	228	31.7	25.3	591.9	.169	.139	.144	.164	.111	.039	.018	.185	.126	1.639	[b]2.071	3.895	1.751	1.625
48		33.9	639	333	32.4	24.8	218.8	.146	.119	.125	.140	.086	.032	.005	.167	.102	1.465	[b]1.706	3.338	1.625	1.523
47		33.9	640	318	32.3	26.0	383.4	.150	.124	.129	.145	.092	.037	.006	.176	.112	1.557	[b]1.909	3.642	1.694	1.582
46		33.9	638	311	32.2	25.3	608.7	.149	.121	.118	.152	.092	.038	.024	.166	.106	1.623	[b]1.893	3.682	1.729	1.623
78	GH_2	34.0×10^4	646	224	30.8	26.8	223.2	.147	.063	.127	.083	.044	.014	.004	.093	.050	.886	[b]1.641	2.620	.881	.831
77		33.9	640	223	30.8	26.6	300.0	.152	.064	.125	.091	.048	.015	.005	.101	.054	.897	[b]1.696	2.694	.889	.835
76		33.9	643	224	31.1	26.2	374.7	.150	.064	.111	.103	.046	.015	.004	.114	.051	.928	[b]1.979	3.021	.861	.810
75		33.9	636	225	30.7	27.2	561.1	.166	.065	.114	.117	.050	.015	.009	.123	.054	.934	[b]2.020	3.077	.858	.804
74		34.1	646	340	30.9	26.3	228.8	.149	.054	.110	.093	.042	.014	.006	.101	.047	.794	[b]1.735	2.630	.796	.749
73		34.1	643	339	30.1	27.1	302.5	.155	.054	.130	.079	.037	.014	.006	.087	.042	.812	[b]1.906	2.805	.793	.751
72		34.1	642	340	30.1	27.3	372.1	.148	.058	.111	.095	.043	.016	.010	.101	.047	.842	[b]2.007	2.950	.810	.763
71		34.1	637	339	31.0	26.9	563.6	.138	.055	.106	.087	.039	.015	.003	.099	.045	.872	[b]1.959	2.930	.826	.781

[a]All runs were made under natural frequency slosh input and a slosh amplitude of ±2.23 cm (±0.13 cm).

[b]Evaporated. (All other values are condensed.)

TABLE III. - Concluded. MASS BALANCE FOR SLOSH CONDITIONS WITHOUT BAFFLES

(b) U. S. customary units

								Ramp			Hold				Expulsion						
Run[a]	Type of pressurant	Tank pressure, psia	Mass of LCH_4 expelled, lb	Inlet gas temperature, ^oR	Ramp time, sec	Hold time, sec	Expulsion time, sec	Initial ullage mass, $M_{l,r}$, lb	Mass added during ramp, $M_{G,r}$, lb	Mass transferred during ramp, $M_{t,r}$, lb	Ullage mass after ramp, $M_{l,h}$, lb	Mass of added pressurant specie in ullage at end of ramp, lb	Mass added during hold, $M_{G,h}$, lb	Mass transferred during hold, $M_{t,h}$, lb	Ullage mass after hold, $M_{l,e}$, lb	Mass of added pressurant specie in ullage at end of hold, lb	Mass added during expulsion, $M_{G,e}$, lb	Mass transferred during expulsion, $M_{t,e}$, lb	Final ullage mass, $M_{f,e}$, lb	Mass of added pressurant specie in ullage at end of expulsion, lb	Increase in added specie in ullage during expulsion, lb
21	GCH_4	48.4	1455	414	33.7	22.8	297.5	0.335	1.517	1.070	0.782	-----	0.447	0.319	0.910	-----	58.810	42.090	17.630	-----	-----
19		48.4	1459	414	34.0	23.4	371.8	.342	1.495	1.056	.781	-----	.431	.299	.913	-----	62.775	46.794	16.894	-----	-----
16		49.2	1455	416	33.7	24.4	442.7	.341	1.344	.880	.805	-----	.398	.277	.926	-----	65.264	49.703	16.487	-----	-----
12		49.2	1464	416	33.4	23.2	674.4	.328	1.436	1.023	.741	-----	.437	.315	.863	-----	69.702	52.406	18.159	-----	-----
29		48.4	1437	628	33.7	24.0	296.3	.329	1.108	.777	.660	-----	.347	.242	.765	-----	42.069	26.276	16.558	-----	-----
27		48.7	1437	625	34.0	24.1	360.9	.341	1.172	.820	.693	-----	.370	.256	.808	-----	45.500	31.660	14.648	-----	-----
25		48.7	1453	619	33.9	23.7	438.9	.325	1.283	.956	.652	-----	.388	.289	.750	-----	49.537	35.823	14.464	-----	-----
23		48.2	1433	616	34.2	23.0	657.7	.345	1.235	.929	.651	-----	.370	.254	.767	-----	50.713	33.878	17.602	-----	-----
45	GHe	49.3	1400	407	31.7	25.9	217.4	.340	.291	.293	.338	0.230	.085	.030	.393	0.268	3.487	[b]3.782	7.662	3.882	3.614
44		49.3	1410	407	31.4	25.6	398.8	.340	.296	.309	.327	.223	.084	.021	.390	.267	3.596	[b]4.234	8.220	3.870	3.603
43		49.3	1393	410	31.7	25.3	591.9	.373	.306	.318	.361	.244	.086	.039	.408	.278	3.614	[b]4.565	8.587	3.861	3.583
48		49.2	1409	599	32.4	24.8	218.8	.321	.262	.275	.308	.189	.070	.010	.368	.225	3.229	[b]3.762	7.359	3.583	3.358
47		49.2	1411	572	32.3	26.0	383.4	.330	.273	.284	.319	.203	.081	.013	.387	.247	3.433	[b]4.210	8.030	3.735	3.488
46		49.2	1407	560	32.2	25.3	608.7	.328	.267	.259	.336	.203	.083	.054	.365	.234	3.577	[b]4.175	8.117	3.812	3.578
78	GH_2	49.3	1424	403	30.8	26.8	223.2	.325	.139	.280	.184	.098	.031	.009	.206	.110	1.954	[b]3.617	5.777	1.943	1.833
77		49.2	1411	401	30.8	26.6	300.0	.334	.141	.274	.201	.106	.032	.011	.222	.118	1.977	[b]3.745	5.944	1.960	1.842
76		49.2	1418	403	31.1	26.2	374.7	.331	.140	.244	.227	.101	.032	.007	.252	.113	2.046	[b]4.362	6.660	1.899	1.786
75		49.2	1402	405	30.7	27.2	561.1	.367	.143	.252	.258	.111	.032	.018	.272	.119	2.058	[b]4.454	6.784	1.891	1.772
74		49.5	1424	612	30.9	26.3	228.8	.328	.120	.244	.204	.092	.031	.012	.223	.103	1.751	[b]3.824	5.798	1.754	1.651
73		49.5	1418	610	30.1	27.1	302.5	.341	.118	.285	.174	.081	.031	.014	.191	.092	1.791	[b]4.202	6.184	1.749	1.657
72		49.5	1415	612	30.1	27.3	372.1	.327	.127	.245	.209	.094	.035	.022	.222	.104	1.856	[b]4.426	6.504	1.786	1.682
71		49.5	1404	610	31.0	26.9	563.6	.305	.121	.235	.191	.087	.034	.007	.218	.100	1.923	[b]4.319	6.460	1.820	1.720

[a]All runs were made under natural frequency slosh input and a slosh amplitude of ±0.88 in. (±0.05 in.).

[b]Evaporated. (All other values are condensed.)

TABLE IV. - ENERGY BALANCE FOR SLOSH CONDITIONS WITHOUT BAFFLES

(a) SI units

Run	Type of pressurant	Inlet gas temperature, K	Expulsion time, sec	Total energy added, ΔU_T, J		Energy gained by tank wall during expulsion, $\Delta U_{W,X}$, J	Energy gained by ullage, $\Delta U_{U,X}$, J	Energy gained by liquid during expulsion, $\Delta U_{L,X}$, J	Energy due to work term plus half of energy added by environment, J
				Energy added by pressurant gas during expulsion (experimental)	Energy added by environment during expulsion (experimental)				
21	GCH_4	230	297.5	2018×10^4	[a]23.8×10^4	130.4×10^4	372.0×10^4	1469×10^4	--------
19		230	371.8	2152	25.5	143.5	363.9	1551	--------
16		231	442.7	2244	30.3	163.6	358.1	1640	--------
12		231	674.4	2400	46.2	124.1	383.3	1822	--------
29		349	296.3	1946	20.3	153.2	360.4	1424	--------
27		347	360.9	2101	24.7	234.7	334.3	1525	--------
25		344	438.9	2277	30.1	287.6	333.6	1666	--------
23		342	657.7	2319	45.1	184.8	373.6	1781	--------
45	GHe	226	217.4	187.9	14.9	6.0	140.2	54.3	58.8×10^4
44		226	398.8	193.4	27.3	8.2	149.5	51.5	65.0
43		228	591.9	196.3	40.5	17.5	155.4	54.7	71.4
48		333	218.8	255.7	15.0	37.0	140.0	81.9	59.0
47		318	383.4	258.4	26.3	45.0	148.3	83.1	64.4
46		311	608.7	263.9	41.7	43.0	148.9	105.9	72.2
78	GH_2	224	223.2	279.4	15.3	17.1	188.8	[b]71.7	59.7
77		223	300.0	282.5	20.6	12.2	190.6	[b]74.1	62.0
76		224	374.7	293.5	25.7	14.4	201.4	[b]85.1	64.6
75		225	561.1	295.5	38.4	-3.0	202.5	[b]104.0	70.7
74		340	228.8	381.4	15.7	59.9	189.6	[b]130.8	59.9
73		339	302.5	389.4	20.7	65.0	196.8	[b]133.1	62.8
72		340	372.1	403.9	25.5	69.2	200.4	[b]148.6	64.8
71		339	563.6	417.0	38.6	43.2	199.5	[b]207.6	71.3

[a]Includes 3.4×10^4 J from television lights.

[b]Includes $\left(M_{GH_2,D}\right)\left(h_{GH_2}\right)_{112\ K,\ 34.47\times10^4\ N/m^2}$ (i.e., data reduction equation + Mh_{GH_2}).

TABLE IV. - Concluded. ENERGY BALANCE FOR SLOSH CONDITIONS WITHOUT BAFFLES

(b) U. S. customary units

Run	Type of pressurant	Inlet gas temperature, ^oR	Expulsion time, sec	Total energy added, ΔU_T, Btu		Energy gained by tank wall during expulsion, $\Delta U_{w,X}$, Btu	Energy gained by ullage, $\Delta U_{U,X}$, Btu	Energy gained by liquid during expulsion, $\Delta U_{L,X}$, Btu	Energy due to work term plus half of energy added by environment, Btu
				Energy added by pressurant gas during expulsion (experimental)	Energy added by environment during expulsion (experimental)				
21	GCH_4	414	297.5	19 138	[a]225.7	1237	3528	13 935	-----
19		414	371.8	20 415	241.9	1361	3451	14 706	-----
16		416	442.7	21 285	287.4	1552	3396	15 558	-----
12		416	674.4	22 759	438.2	1177	3635	17 277	-----
29		628	296.3	18 454	192.5	1453	3418	13 506	-----
27		625	360.9	19 923	234.3	2226	3171	14 466	-----
25		619	438.9	21 594	285.5	2728	3164	15 804	-----
23		616	657.7	21 996	427.8	1753	3543	16 891	-----
45	GHe	407	217.4	1782	141.3	57.3	1330	515.0	557.3
44		407	398.8	1834	258.9	78.1	1418	488.8	616.1
43		410	591.9	1862	384.1	165.9	1474	518.8	677.3
48		599	218.8	2425	142.3	350.8	1328	777.1	559.4
47		572	383.4	2451	249.4	427.2	1407	788.0	610.4
46		560	608.7	2503	395.5	408.0	1412	1004	685.2
78	GH_2	403	223.2	2650	145.1	161.8	1791	[b]680.0	566.3
77		401	300.0	2679	195.4	115.8	1808	[b]702.8	588.2
76		403	374.7	2784	243.8	136.3	1910	[b]807.1	612.4
75		405	561.1	2803	364.2	-28.9	1921	[b]986.3	670.4
74		612	228.8	3617	148.9	568.5	1798	[b]1241	567.8
73		610	302.5	3693	196.3	616.8	1867	[b]1262	595.9
72		612	372.1	3831	241.9	656.7	1901	[b]1409	614.3
71		610	563.6	3955	366.1	409.5	1892	[b]1969	676.4

[a]Includes 32.3 Btu from television lights.

[b]Includes $\left(M_{GH_2,D}\right)\left(h_{GH_2}\right)_{202^o R,\ 50\ psia}$ $\left(\text{i.e., data reduction equation} + Mh_{GH_2}\right)$.

TABLE V. - MASS BALANCE FOR SLOSH CONDITIONS WITH BAFFLES

(a) SI units

								Ramp				Hold			Expulsion					
Run[a]	Type of pressurant	Tank pressure, N/m^2	Mass of LCH_4 expelled, kg	Inlet gas temperature, K	Ramp time, sec	Hold time, sec	Expulsion time, sec	Initial ullage mass, $M_{i,r}$, kg	Mass added during ramp, $M_{G,r}$, kg	Mass transferred during ramp, $M_{t,r}$, kg	Ullage mass after ramp, $M_{i,h}$, kg	Mass of added pressurant specie in ullage at end of ramp, kg	Mass added during hold, $M_{G,h}$, kg	Mass transferred during hold, $M_{t,h}$, kg	Ullage mass after hold, $M_{i,e}$, kg	Mass of added pressurant specie in ullage at end of hold, kg	Mass added during expulsion, $M_{G,e}$, kg	Mass transferred during expulsion, $M_{t,e}$, kg	Final ullage mass, $M_{f,e}$, kg	Mass of added pressurant specie in ullage at end of expulsion, kg	Increase in added specie in ullage during expulsion, kg
298	GCH_4	34.0×10^4	674	229	33.0	23.5	402.5	0.155	0.776	0.560	0.371	-----	0.178	0.143	0.406	-----	41.633	34.505	7.564	-----	-----
299		34.0	690	214	33.2	24.1	486.5	.154	.645	.427	.372	-----	.154	.124	.402	-----	44.113	36.813	7.702	-----	-----
296		34.0	663	229	33.0	25.3	616.5	.161	.779	.561	.379	-----	.207	.173	.413	-----	45.120	37.424	8.109	-----	-----
324		33.9	666	338	32.6	24.7	395.6	.158	.648	.521	.285	-----	.215	.166	.334	-----	30.604	24.273	6.665	-----	-----
338		33.9	667	332	32.5	24.5	474.9	.157	.667	.535	.289	-----	.242	.191	.340	-----	32.692	26.058	6.975	-----	-----
323		33.9	660	338	32.6	24.6	597.8	.155	.564	.429	.290	-----	.198	.155	.333	-----	34.307	27.159	7.481	-----	-----
265	GHe	33.8×10^4	636	219	32.4	25.4	211.6	.145	.124	.118	.151	0.093	.020	.005	.166	0.103	1.625	[b]1.577	3.368	1.792	1.689
264		33.7	637	219	31.6	26.1	366.4	.145	.124	.114	.155	.096	.020	.007	.168	.105	1.690	[b]1.622	3.480	1.808	1.703
263		33.9	645	217	32.4	25.1	530.6	.150	.133	.128	.155	.096	.022	.010	.167	.104	1.718	[b]1.646	3.531	1.840	1.736
279		33.8	636	222	32.8	24.1	555.1	.143	.126	.111	.158	.103	.020	.002	.176	.108	1.673	[b]1.841	3.690	1.789	1.681
295		34.1	644	342	31.6	25.5	214.3	.157	.112	.129	.140	.087	.023	.003	.160	.098	1.515	[b]1.664	3.339	1.640	1.542
281		34.0	642	336	31.1	26.1	364.9	.157	.116	.133	.140	.088	.023	.004	.159	.097	1.607	[b]1.667	3.433	1.736	1.639
280		34.1	640	328	31.7	25.5	576.6	.150	.114	.126	.138	.086	.023	.005	.156	.096	1.615	[b]1.893	3.664	1.728	1.632

[a]All runs were made under natural frequency slosh input and a slosh amplitude of ±2.23 cm (±0.13 cm).

[b]Evaporated. (All other values are condensed.)

TABLE V. - Concluded. MASS BALANCE FOR SLOSH CONDITIONS WITH BAFFLES

(b) U.S. customary units

								Ramp					Hold				Expulsion				
Run[a]	Type of pressurant	Tank pressure, psia	Mass of LCH_4 expelled, lb	Inlet gas temperature, ^oR	Ramp time, sec	Hold time, sec	Expulsion time, sec	Initial ullage mass, $M_{i,r}$, lb	Mass added during ramp, $M_{G,r}$, lb	Mass transferred during ramp, $M_{t,r}$, lb	Ullage mass after ramp, $M_{i,h}$, lb	Mass of added pressurant specie in ullage at end of ramp, lb	Mass added during hold, $M_{G,h}$, lb	Mass transferred during hold, $M_{t,h}$, lb	Ullage mass after hold, $M_{i,e}$, lb	Mass of added pressurant specie in ullage at end of hold, lb	Mass added during expulsion, $M_{G,e}$, lb	Mass transferred during expulsion, $M_{t,e}$, lb	Final ullage mass, $M_{f,e}$, lb	Mass of added pressurant specie in ullage at end of expulsion, lb	Increase in added specie in ullage during expulsion, lb
298	GCH_4	49.3	1486	412	33.0	23.5	402.5	0.341	1.711	1.233	0.819	-----	0.392	0.317	0.894	-----	91.850	76.069	16.675	-----	-----
299	↓	49.3	1521	385	33.2	24.1	486.5	.340	1.421	.940	.821	-----	.339	.273	.887	-----	97.251	81.158	16.980	-----	-----
296		49.3	1462	412	33.0	25.3	616.5	.356	1.717	1.237	.835	-----	.457	.382	.910	-----	99.471	82.505	17.876	-----	-----
324		49.2	1468	608	32.6	24.7	395.6	.349	1.429	1.149	.629	-----	.473	.366	.736	-----	67.470	53.512	14.694	-----	-----
338		49.2	1470	598	32.5	24.5	474.9	.346	1.471	1.179	.638	-----	.534	.422	.750	-----	72.072	57.446	15.376	-----	-----
323		49.2	1455	608	32.6	24.6	597.8	.342	1.244	.946	.640	-----	.437	.342	.735	-----	75.633	59.876	16.492	-----	-----
265	GHe	49.0	1402	394	32.4	25.4	211.6	.319	.273	.259	.333	0.206	.045	.013	.365	0.227	3.582	[b]3.477	7.424	3.951	3.724
264	↓	48.9	1404	394	31.6	26.1	366.4	.320	.274	.252	.342	.211	.043	.015	.370	.231	3.725	[b]3.576	7.671	3.985	3.754
263		49.2	1422	391	32.4	25.1	530.6	.330	.294	.283	.341	.211	.048	.020	.369	.230	3.788	[b]3.627	7.784	4.057	3.827
279		49.0	1402	400	32.8	24.1	555.1	.315	.278	.245	.348	.227	.045	.004	.389	.238	3.689	[b]4.058	8.136	3.945	3.707
295		49.5	1420	616	31.6	25.5	214.3	.346	.247	.285	.308	.192	.051	.006	.353	.215	3.341	[b]3.668	7.362	3.615	3.400
281		49.3	1415	605	31.1	26.1	364.9	.347	.255	.293	.309	.193	.050	.008	.351	.215	3.542	[b]3.675	7.568	3.828	3.613
280		49.5	1411	590	31.7	25.5	576.6	.331	.251	.278	.304	.190	.050	.009	.345	.211	3.560	[b]4.173	8.078	3.809	3.598

[a]All runs were made under natural frequency slosh input and a slosh amplitude of ±0.88 in. (±0.05 in.).
[b]Evaporated. (All other values are condensed.)

TABLE VI. - ENERGY BALANCE FOR SLOSH CONDITIONS WITH BAFFLES

(a) SI units

Run	Type of pressurant	Inlet gas temperature, K	Expulsion time, sec	Total energy added, ΔU_T, J		Energy gained by tank wall during expulsion, $\Delta U_{w,X}$, J	Energy gained by ullage, $\Delta U_{U,X}$, J	Energy gained by liquid during expulsion, $\Delta U_{L,X}$, J	Energy due to work term plus half of energy added by environment, J
				Energy added by pressurant gas during expulsion (experimental)	Energy added by environment during expulsion (experimental)				
298	GCH_4	229	402.5	3040×10^4	27.6×10^4	250.1×10^4	362.5×10^4	2381×10^4	--------
299	↓	214	486.5	3187	33.3	236.5	366.7	2593	--------
296	↓	229	616.5	3289	42.3	237.4	378.6	2586	--------
324	↓	338	395.6	3043	27.1	364.3	337.7	2294	--------
338	↓	332	474.9	3215	32.5	392.7	346.7	2458	--------
323	↓	338	597.8	3396	40.9	378.4	361.9	2614	--------
265	GHe	219	211.6	187.3	14.5	24.8	134.9	29.6	58.8×10^4
264	↓	219	366.4	193.9	25.1	25.4	138.3	36.6	64.0
263	↓	217	530.6	195.8	36.3	23.6	139.4	44.8	70.0
279	↓	222	555.1	195.5	38.0	7.6	146.2	59.0	70.4
295	↓	342	214.3	271.3	14.7	82.4	140.2	38.9	59.5
281	↓	336	364.9	282.4	25.0	87.3	140.0	70.0	64.4
280	↓	328	576.6	276.8	39.5	68.1	148.9	97.3	71.9

TABLE VI. - Concluded. ENERGY BALANCE FOR SLOSH CONDITIONS WITH BAFFLES

(b) U.S. customary units

Run	Type of pressurant	Inlet gas temperature, ^{o}R	Expulsion time, sec	Total energy added, ΔU_T, Btu		Energy gained by tank wall during expulsion, $\Delta U_{w,X}$, Btu	Energy gained by ullage, $\Delta U_{U,X}$, Btu	Energy gained by liquid during expulsion, $\Delta U_{L,X}$, Btu	Energy due to work term plus half of energy added by environment, Btu
				Energy added by pressurant gas during expulsion (experimental)	Energy added by environment during expulsion (experimental)				
298	GCH_4	412	402.5	28 834	261.8	2372	3438	22 585	-----
299		385	486.5	30 227	315.8	2243	3478	24 594	-----
296		412	616.5	31 198	401.2	2252	3591	24 527	-----
324		608	395.6	28 865	257.0	3455	3203	21 762	-----
338		598	474.9	30 494	308.2	3725	3288	23 309	-----
323		608	597.8	32 214	387.9	3589	3432	24 788	-----
265	GHe	394	211.6	1776	137.5	235	1279	280.7	557.2
264		394	366.4	1839	238.1	240.5	1312	347.0	606.5
263		391	530.6	1857	344.3	224.3	1322	424.5	662.6
279		400	555.1	1854	360.4	71.7	1387	559.4	666.5
295		616	214.3	2573	139.4	781.4	1330	369.3	563.1
281		605	364.9	2678	237.1	827.7	1328	664.0	609.9
280		590	576.6	2625	374.6	646.1	1412	922.4	680.7

TABLE VII. - MASS BALANCE FOR SLOSH CONDITIONS WITH AND WITHOUT BAFFLES, VARIABLE FREQUENCY AND AMPLITUDE

(a) SI units

Run	Type of pressurant	Frequency profile	Amplitude, cm	Tank pressure, N/m^2	Mass of LCH_4 expelled, kg	Inlet gas temperature, K	Ramp time, sec	Hold time, sec	Expulsion time, sec	Ramp: Initial ullage mass, $M_{i,r}$, kg	Ramp: Mass added during ramp, $M_{G,r}$, kg	Ramp: Mass transferred during ramp, $M_{t,r}$, kg	Ramp/Hold: Ullage mass after ramp, $M_{i,h}$, kg	Hold: Mass added during hold, $M_{G,h}$, kg	Hold: Mass transferred during hold, $M_{t,h}$, kg	Hold/Expulsion: Ullage mass after hold, $M_{i,e}$, kg	Expulsion: Mass added during expulsion, $M_{G,e}$, kg	Expulsion: Mass transferred during expulsion, $M_{t,e}$, kg	Expulsion: Final ullage mass, $M_{f,e}$, kg
Without baffles (nominal inlet temperature, 222 K)																			
7	GCH_4	------	0.000	33.6×10^4	647	227	33.8	23.0	404.9	0.155	0.593	0.390	0.358	0.167	0.122	0.403	9.184	2.780	6.807
81	↓	Natural	.178	34.1	646	223	31.5	25.8	374.0	.177	.843	.634	.386	.352	.303	.435	10.411	3.950	6.896
84	↓	↓	.504	34.2	669	221	31.0	26.2	377.8	.153	.631	.429	.355	.235	.187	.403	13.466	6.863	7.006
85	↓	↓	.660	34.2	664	222	30.8	26.0	390.2	.154	.580	.376	.358	.221	.179	.400	25.923	19.565	6.758
83	↓	↓	.853	34.2	654	221	30.8	26.9	393.3	.151	.687	.512	.326	.273	.225	.374	28.511	21.970	6.915
19	↓	↓	2.388	33.4	662	230	34.0	23.4	371.8	.155	.678	.479	.354	.196	.136	.414	28.475	21.226	7.663
88	↓	0.716 Hz	.510	34.2	656	222	30.5	27.4	378.2	.154	.585	.374	.365	.204	.167	.402	14.470	7.983	6.889
87	↓	↓	.833	34.1	660	220	30.7	27.3	388.2	.153	.585	.381	.358	.229	.181	.406	22.932	16.585	6.753
86	↓	↓	2.217	34.2	671	223	30.8	26.4	399.8	.154	.648	.446	.356	.240	.194	.402	30.051	22.977	7.476
Without baffles (nominal inlet temperature, 333 K)																			
10	GCH_4	------	0.000	33.7×10^4	645	344	33.4	24.0	410.0	0.153	0.503	0.361	0.295	0.180	0.131	0.344	8.028	2.463	5.909
96	↓	Natural	.249	34.1	653	339	30.8	26.6	386.8	.152	.640	.533	.259	.255	.201	.313	11.426	5.626	6.113
91	↓	↓	.373	34.1	653	338	30.4	27.5	386.2	.153	.399	.245	.307	.181	.149	.339	11.407	5.737	6.009
89	↓	↓	.495	34.1	654	338	30.8	26.4	381.9	.166	.605	.473	.298	.277	.233	.342	18.646	13.357	5.631
90	↓	↓	.793	34.1	660	337	31.0	26.0	396.9	.151	.492	.357	.286	.215	.173	.328	21.238	15.890	5.676
27	↓	↓	2.337	33.6	652	347	34.0	24.1	360.9	.155	.532	.373	.314	.168	.115	.367	20.639	14.362	6.644
92	↓	0.716 Hz	.396	34.1	653	338	30.3	27.7	385.9	.153	.612	.512	.253	.257	.206	.304	10.800	5.327	5.777
93	↓	↓	.820	34.1	662	332	30.2	27.6	394.6	.161	.590	.486	.265	.250	.180	.335	17.870	12.616	5.589
95	↓	↓	2.205	34.1	663	338	30.4	27.1	402.8	.157	.634	.523	.268	.255	.200	.323	22.236	15.957	6.602
With baffles																			
313	GCH_4	------	0.000	33.9×10^4	645	220	32.9	24.6	363.8	0.153	0.590	0.364	0.379	0.153	0.119	0.413	9.266	2.455	7.224
319	↓	Natural	.483	33.8	660	220	32.8	25.3	386.5	.157	.819	.616	.360	.231	.185	.406	16.393	10.010	6.789
315	↓	↓	.625	33.4	656	219	32.0	25.0	389.7	.150	.583	.361	.372	.168	.131	.409	20.803	14.688	6.523
314	↓	↓	.813	34.0	655	220	32.3	25.3	374.1	.171	.924	.706	.389	.269	.228	.430	22.645	16.399	6.676
316	↓	↓	1.052	33.9	665	218	31.9	25.7	390.2	.160	.829	.612	.377	.283	.251	.409	28.284	21.951	6.742
317	↓	↓	1.359	33.9	666	220	32.1	25.7	393.3	.161	.795	.585	.371	.248	.204	.415	33.084	26.560	6.939
298	↓	↓	2.210	34.0	663	229	33.0	23.5	402.5	.155	.776	.660	.371	.178	.143	.406	41.663	34.505	7.564
322	↓	0.716 Hz	.841	33.9	668	219	33.0	24.2	390.6	.161	.826	.616	.371	.231	.193	.409	21.601	15.379	6.631
321	↓	↓	1.364	33.8	669	220	33.0	24.2	390.9	.155	.831	.617	.369	.235	.193	.411	29.614	23.373	6.652
320	↓	↓	2.240	33.8	673	216	32.8	24.6	400.8	.161	.820	.614	.367	.248	.182	.433	37.298	30.678	7.053

TABLE VII. - Concluded. MASS BALANCE FOR SLOSH CONDITIONS WITH AND WITHOUT BAFFLES, VARIABLE FREQUENCY AND AMPLITUDE

(b) U.S. customary units

										Ramp	Ramp	Ramp	Ramp / Hold	Hold	Hold	Hold / Expulsion	Expulsion	Expulsion	Expulsion
Run	Type of pressurant	Frequency profile	Amplitude, in.	Tank pressure, psia	Mass of LCH_4 expelled, lb	Inlet gas temperature, ^oR	Ramp time, sec	Hold time, sec	Expulsion time, sec	Initial ullage mass, $M_{i,r}$, lb	Mass added during ramp, $M_{G,r}$, lb	Mass transferred during ramp, $M_{t,r}$, lb	Ullage mass after ramp, $M_{i,h}$, lb	Mass added during hold, $M_{G,h}$, lb	Mass transferred during hold, $M_{t,h}$, lb	Ullage mass after hold, $M_{i,e}$, lb	Mass added during expulsion, $M_{G,e}$, lb	Mass transferred during expulsion, $M_{t,e}$, lb	Final ullage mass, $M_{f,e}$, lb
Without baffles (nominal inlet temperature, 400° R)																			
7	GCH_4	------	0.000	48.7	1426	409	33.8	23.0	404.9	0.342	1.308	0.860	0.790	0.369	0.271	0.888	20.246	6.127	15.007
81		Natural	.070	49.5	1424	401	31.5	25.8	374.0	.391	1.858	1.399	.850	.776	.668	.958	22.953	8.709	15.202
84			.199	49.6	1475	398	31.0	26.2	377.8	.338	1.392	.947	.783	.519	.414	.888	29.686	15.129	15.445
85			.260	49.6	1464	400	30.8	26.0	390.2	.339	1.279	.828	.790	.487	.396	.881	57.150	43.133	14.898
83			.336	49.6	1442	398	30.8	26.9	393.3	.333	1.514	1.129	.718	.601	.494	.825	62.854	48.434	15.245
19			.940	48.4	1459	414	34.0	23.4	371.8	.342	1.495	1.056	.781	.431	.299	.913	62.775	46.794	16.894
88		0.716 Hz	.200	49.6	1446	400	30.5	27.4	378.2	.340	1.289	.824	.805	.449	.368	.886	31.900	17.598	15.188
87			.328	49.5	1455	396	30.7	27.3	388.2	.338	1.290	.839	.789	.504	.397	.896	50.556	36.565	14.887
86			.873	49.6	1479	401	30.8	26.4	399.8	.340	1.428	.983	.785	.528	.426	.887	66.249	50.655	16.481
Without baffles (nominal inlet temperature, 600° R)																			
10	GCH_4	------	0.000	48.9	1422	619	33.4	24.0	410.0	0.337	1.109	0.796	0.650	0.397	0.289	0.758	17.698	5.429	13.027
96		Natural	.098	49.5	1440	610	30.8	26.6	386.8	.336	1.410	1.174	.572	.563	.446	.689	25.190	12.403	13.476
91			.147	49.5	1440	608	30.4	27.5	386.2	.337	.879	.540	.676	.400	.328	.748	25.148	12.648	13.248
89			.195	49.5	1442	608	30.8	26.4	381.9	.365	1.334	1.014	.658	.610	.513	.755	41.106	29.446	12.415
90			.312	49.5	1455	607	31.0	26.0	396.9	.332	1.085	.787	.630	.475	.381	.724	46.820	35.031	12.513
27			.920	48.7	1437	625	34.0	24.1	360.9	.341	1.172	.820	.693	.370	.255	.808	45.500	31.660	14.648
92		0.716 Hz	.156	49.5	1440	608	30.3	27.7	385.9	.337	1.350	1.129	.558	.566	.453	.671	23.810	11.745	12.736
93			.324	49.5	1459	598	30.2	27.6	394.6	.355	1.300	1.071	.584	.552	.398	.738	39.397	27.814	12.321
95			.868	49.5	1462	608	30.4	27.1	402.8	.347	1.398	1.154	.591	.563	.443	.711	49.022	35.178	14.555
With baffles																			
313	GCH_4	------	0.000	49.2	1422	396	32.9	24.6	363.8	0.338	1.301	0.803	0.836	0.338	0.264	0.910	20.405	5.390	15.925
319		Natural	.190	49.0	1455	396	32.8	25.3	386.5	.347	1.805	1.358	.794	.510	.408	.896	36.140	22.069	14.967
315			.246	48.4	1446	394	32.0	25.0	389.7	.330	1.285	.794	.821	.370	.290	.901	45.861	32.381	14.381
314			.320	49.3	1444	396	32.3	25.3	374.1	.378	2.037	1.558	.857	.594	.502	.949	49.922	36.154	14.717
316			.414	49.2	1466	392	31.9	25.7	390.2	.353	1.827	1.349	.831	.624	.553	.902	62.355	48.394	14.863
317			.535	49.2	1468	396	32.1	25.7	393.3	.356	1.752	1.291	.817	.547	.449	.915	72.937	58.554	15.298
298			.870	49.3	1462	412	33.0	23.5	402.5	.341	1.711	1.233	.819	.392	.317	.894	91.850	76.069	16.675
322		0.716 Hz	.331	49.2	1473	394	33.0	24.2	390.6	.356	1.820	1.359	.819	.510	.428	.901	47.622	33.905	14.618
321			.537	49.0	1475	396	33.0	24.2	390.9	.341	1.832	1.360	.813	.517	.424	.906	65.286	51.526	14.666
320			.882	49.0	1484	389	32.8	24.6	400.8	.356	1.807	1.356	.808	.547	.401	.954	82.227	67.633	15.548

TABLE VIII. - ENERGY BALANCE FOR SLOSH CONDITIONS WITH AND WITHOUT BAFFLES, VARIABLE FREQUENCY AND AMPLITUDE

(a) SI units

Run	Type of pressurant	Inlet gas temperature, K	Expulsion time, sec	Total energy added, ΔU_T, J: Energy added by pressurant gas during expulsion (experimental)	Total energy added, ΔU_T, J: Energy added by environment during expulsion (experimental)	Energy gained by tank wall during expulsion, $\Delta U_{w,X}$, J	Energy gained by ullage, $\Delta U_{U,X}$, J	Energy gained by liquid during expulsion, $\Delta U_{L,X}$, J
Without baffles (nominal inlet temperature, 222 K)								
7	GCH_4	227	404.9	688.1×10^4	27.7×10^4	233.6×10^4	338.0×10^4	108.4×10^4
81	↓	223	374.0	769.3	25.6	238.2	341.3	158.5
84	↓	221	377.8	994.1	25.9	235.6	346.6	389.6
85	↓	222	390.2	1914	26.7	238.8	339.3	1300
83	↓	221	393.3	2099	26.9	245.5	345.4	1475
19	↓	230	371.8	2152	25.5	143.5	363.9	1551
88	↓	222	378.2	1069	25.9	236.4	343.2	473.0
87	↓	220	388.2	1683	26.6	237.1	338.8	1098
86	↓	223	399.8	2223	27.4	187.8	360.8	1651
Without baffles (nominal inlet temperature, 333 K)								
10	GCH_4	344	410.0	813.3×10^4	28.1×10^4	363.3×10^4	313.8×10^4	108.6×10^4
96	↓	339	386.8	1139	26.5	364.9	323.3	423.6
91	↓	338	386.2	1132	26.5	335.4	318.8	439.5
89	↓	338	381.9	1860	26.2	380.7	307.1	1101
90	↓	337	396.9	2111	27.2	374.7	309.6	1415
27	↓	347	360.9	2101	24.7	234.7	334.3	1525
92	↓	338	385.9	1075	26.4	372.1	313.7	345.9
93	↓	332	394.6	1756	27.0	363.1	307.2	1065
95	↓	338	402.8	2219	27.6	271.2	337.3	1063
With baffles								
313	GCH_4	220	363.8	680.4×10^4	24.9×10^4	220.4×10^4	351.8×10^4	113.9×10^4
319	↓	220	386.5	1204	26.5	264.5	338.7	604.9
315	↓	219	389.7	1528	26.7	272.5	328.7	905.9
314	↓	220	374.1	1668	25.6	277.1	334.3	1027
316	↓	218	390.2	2061	26.7	280.7	337.2	1418
317	↓	220	393.3	2425	26.9	277.0	343.1	1758
298	↓	229	402.5	3040	27.6	250.1	362.5	2381
322	↓	219	390.6	1584	26.8	274.3	333.7	1018
321	↓	220	390.9	2172	26.8	276.3	334.2	1541
320	↓	216	400.8	2707	27.5	258.3	345.6	2061

TABLE VIII. - Concluded. ENERGY BALANCE FOR SLOSH CONDITIONS WITH AND WITHOUT BAFFLES,

VARIABLE FREQUENCY AND AMPLITUDE

(b) U.S. customary units

Run	Type of pressurant	Inlet gas temperature, ^oR	Expulsion time, sec	Total energy added, ΔU_T, Btu		Energy gained by tank wall during expulsion, $\Delta U_{w,X}$, Btu	Energy gained by ullage, $\Delta U_{U,X}$, Btu	Energy gained by liquid during expulsion, $\Delta U_{L,X}$, Btu
				Energy added by pressurant gas during expulsion (experimental)	Energy added by environment during expulsion (experimental)			
Without baffles (nominal inlet temperature, 400^o R)								
7	GCH_4	409	404.9	6 526	263	2216	3206	1 028
81	↓	401	374.0	7 296	242.8	2259	3237	1 503
84		398	377.8	9 429	245.6	2235	3287	3 695
85		400	390.2	18 154	253.2	2265	3218	12 329
83		398	393.3	19 908	255.1	2328	3276	13 990
19		414	371.8	20 415	241.9	1361	3451	14 706
88		400	378.2	10 138	245.6	2242	3255	4 487
87		396	388.2	15 962	252.3	2249	3213	10 415
86		401	399.8	21 088	259.9	1781	3422	15 659
Without baffles (nominal inlet temperature, 600^o R)								
10	GCH_4	619	410.0	7 714	267	3446	2976	1 030
96	↓	610	386.8	10 801	251.3	3461	3066	4 018
91		608	386.2	10 736	251.3	3181	3024	4 168
89		608	381.9	17 641	248.5	3611	2913	10 444
90		607	396.9	20 025	258.0	3554	2936	13 424
27		625	360.9	19 923	234.3	2226	3171	14 466
92		608	385.9	10 192	250.4	3529	2975	3 281
93		598	394.6	16 653	256.1	3444	2914	10 101
95		608	402.8	21 047	261.8	2572	3199	15 203
With baffles								
313	GCH_4	396	363.8	6 453	236.2	2090	3337	1 080
319	↓	396	386.5	11 416	251.3	2509	3212	5 737
315		394	389.7	14 488	253.2	2585	3118	8 592
314		396	374.1	15 817	242.8	2628	3171	9 691
316		392	390.2	19 550	253.2	2662	3198	13 449
317		396	393.3	22 996	255.1	2627	3254	16 675
298		412	402.5	28 834	261.8	2372	3438	22 585
322		394	390.6	15 023	254.2	2602	3165	9 654
321		396	390.9	20 599	254.2	2621	3170	14 615
320		389	400.8	25 678	260.8	2450	3278	19 548

TABLE IX. - MASS BALANCE FOR PARTIAL EXPULSIONS

(a) SI units

Run	Type of pressurant	Tank pressure, N/m^2	Mass of LCH_4 expelled, kg	Inlet gas temperature, K	Ramp time, sec	Hold time, sec	Expulsion time, sec	Ramp: Initial ullage mass, $M_{i,r}$, kg	Ramp: Mass added during ramp, $M_{G,r}$, kg	Ramp: Mass transferred during ramp, $M_{t,r}$, kg	Ramp/Hold: Ullage mass after ramp, $M_{i,h}$, kg	Hold: Mass of added pressurant specie in ullage at end of ramp, kg	Hold: Mass added during hold, $M_{G,h}$, kg	Hold: Mass transferred during hold, $M_{t,h}$, kg	Hold/Expulsion: Ullage mass after hold, $M_{i,e}$, kg	Expulsion: Mass of added pressurant specie in ullage at end of hold, kg	Expulsion: Mass added during expulsion, $M_{G,e}$, kg	Expulsion: Mass transferred during expulsion, $M_{t,e}$, kg	Expulsion: Final ullage mass, $M_{f,e}$, kg	Expulsion: Mass of added pressurant specie in ullage at end of expulsion, kg	Expulsion: Increase in added specie in ullage during expulsion, kg	Predicted pressurant required during expulsion, $M_{G,e,P}$, kg
5 to 50 Percent ullage expulsions																						
100	GCH_4	34.1×10^4	321	222	30.7	25.0	188.7	0.154	0.771	0.517	0.408	-----	0.318	0.258	0.468	-----	4.431	1.222	3.677	-----	-----	4.232
182	GCH_4	34.1	315	344	30.9	26.6	182.8	.160	.631	.511	.281	-----	.257	.193	.345	-----	3.653	.930	3.068	-----	-----	3.647
128	GHe	34.1	320	230	30.8	27.5	187.0	.164	.130	.146	.148	0.100	.027	.015	.160	0.110	.922	[a].193	1.275	1.041	0.931	.928
209	GHe	33.9	315	347	31.0	26.2	181.8	.152	.113	.132	.133	.088	.023	.015	.141	.097	.850	[a].213	1.204	.982	.885	.841
155	GH_2	34.1	321	219	30.1	26.7	187.0	.171	.067	.137	.101	.053	.014	.005	.110	.057	.468	[a].169	.747	.515	.458	.458
235	GH_2	33.8	329	349	31.1	28.5	189.5	.151	.059	.162	.048	.048	.012	.008	.052	.052	.433	[a].234	.719	.488	.436	.412
50 to 95 Percent ullage expulsions																						
127	GCH_4	34.1×10^4	322	223	31.6	21.1	189.0	1.654	2.259	0.620	3.293	-----	0.735	0.612	3.416	-----	4.860	1.205	7.071	-----	-----	4.423
208	GCH_4	33.9	321	336	31.1	22.5	185.2	1.579	1.744	.534	2.789	-----	.586	.706	2.668	-----	4.459	1.060	6.067	-----	-----	3.919
154	GHe	34.1	321	222	29.8	25.9	184.0	1.620	.537	.318	1.839	0.513	.182	.554	1.467	0.733	1.108	.388	2.187	1.818	1.085	.984
234	GHe	33.9	319	336	31.8	21.5	184.6	1.585	.467	.691	1.361	.571	.162	.152	1.371	.645	1.072	.239	2.204	1.684	1.039	.953
181	GH_2	34.1	313	217	31.4	21.9	184.3	1.692	.282	.552	1.422	.298	.078	.374	1.126	.370	.555	.293	1.388	.899	.529	.484
261	GH_2	33.8	324	342	31.6	26.3	185.9	1.588	.225	.510	1.303	.249	.086	.314	1.075	.308	.517	.281	1.311	.831	.523	.472

[a]Evaporated. (All other values are condensed.)

TABLE IX. - Concluded. MASS BALANCE FOR PARTIAL EXPULSIONS

(b) U.S. customary units

								Ramp			Ramp / Hold	Hold			Hold / Expulsion	Expulsion					
Run	Type of pressurant	Tank pressure, psia	Mass of LCH_4 expelled, lb	Inlet gas temperature, ^{o}R	Ramp time, sec	Hold time, sec	Expulsion time, sec	Initial ullage mass, $M_{i,r}$, lb	Mass added during ramp, $M_{G,r}$, lb	Mass transferred during ramp, $M_{t,r}$, lb	Ullage mass after ramp, $M_{i,h}$, lb	Mass of added pressurant specie in ullage at end of ramp, lb	Mass added during hold, $M_{G,h}$, lb	Mass transferred during hold, $M_{t,h}$, lb	Ullage mass after hold, $M_{i,e}$, lb	Mass of added pressurant specie in ullage at end of hold, lb	Mass added during expulsion, $M_{G,e}$, lb	Mass transferred during expulsion, $M_{t,e}$, lb	Final ullage mass, $M_{f,e}$, lb	Mass of added pressurant specie in ullage at end of expulsion, lb	Increase in added specie in ullage during expulsion, lb	Predicted pressurant required during expulsion, $M_{G,e,P}$, lb
5 to 50 Percent ullage expulsions																					
100	GCH_4	49.5	708	400	30.7	25.0	188.7	0.339	1.699	1.139	0.899	-----	0.701	0.568	1.032	-----	9.768	2.693	8.107	-----	-----	9.33
182	GCH_4	49.5	694	619	30.9	26.6	182.8	.353	1.392	1.126	.619	-----	.566	.425	.760	-----	8.054	2.050	6.764	-----	-----	8.04
128	GHe	49.5	705	414	30.8	27.5	187.0	.361	.287	.321	.327	0.221	.059	.034	.352	0.242	2.032	[a].426	2.810	2.296	2.054	2.045
209	GHe	49.2	694	625	31.0	26.2	181.8	.334	.250	.291	.293	.194	.051	.033	.311	.213	1.873	[a].471	2.655	2.164	1.951	1.855
155	GH_2	49.5	708	394	30.1	26.7	187.0	.376	.148	.301	.223	.116	.031	.012	.242	.125	1.032	[a].372	1.646	1.136	1.011	1.010
235	GH_2	49.0	725	628	31.1	28.5	189.5	.332	.129	.356	.105	.105	.027	.017	.114	.114	.955	[a].517	1.586	1.076	.962	.909
50 to 95 Percent ullage expulsions																					
127	GCH_4	49.5	710	401	31.6	21.1	189.0	3.647	4.981	1.368	7.260	-----	1.620	1.349	7.531	-----	10.714	2.656	15.589	-----	-----	9.75
208	GCH_4	49.2	708	605	31.1	22.5	185.2	3.482	3.844	1.178	6.148	-----	1.291	1.558	5.881	-----	9.830	2.335	13.376	-----	-----	8.64
154	GHe	49.5	708	400	29.8	25.9	184.0	3.571	1.183	.699	4.055	1.131	.401	1.221	3.235	1.616	2.443	.857	4.821	4.008	2.392	2.17
234	GHe	49.2	703	605	31.8	21.5	184.6	3.495	1.029	1.523	3.001	1.259	.357	.335	3.023	1.423	2.364	.527	4.860	3.712	2.289	2.10
181	GH_2	49.5	690	391	31.4	21.9	184.3	3.731	.622	1.218	3.135	.656	.171	.824	2.482	.815	1.223	.645	3.060	1.981	1.166	1.068
261	GH_2	49.0	714	616	31.6	26.3	185.9	3.501	.497	1.125	2.873	.549	.190	.692	2.371	.680	1.140	.620	2.891	1.832	1.152	1.040

[a]Evaporated. (All other values are condensed.)

TABLE X. - ENERGY BALANCE FOR PARTIAL EXPULSIONS

(a) SI units

Run	Type of pressurant	Inlet gas temperature, K	Expulsion time, sec	Total energy added, ΔU_T, J		Energy gained by tank wall during expulsion, $\Delta U_{w,X}$, J	Energy gained by ullage, $\Delta U_{U,X}$, J	Energy gained by liquid during expulsion, $\Delta U_{L,X}$, J
				Energy added by pressurant gas during expulsion (experimental)	Energy added by environment during expulsion (experimental)			
5 to 50 Percent ullage expulsions								
100	GCH_4	222	188.7	328.0×10^4	12.93×10^4	102.0×10^4	170.0×10^4	70.94×10^4
182	GCH_4	344	182.8	368.9	12.52	152.5	154.8	39.93
128	GHe	230	187.0	111.4	12.81	42.52	46.95	28.72
209	GHe	347	181.8	154.4	12.45	75.33	46.04	27.25
155	GH_2	219	187.0	144.2	12.81	49.39	72.70	22.57
235	GH_2	349	189.5	213.4	12.98	105.3	75.13	23.45
50 to 95 Percent ullage expulsions								
127	GCH_4	223	189.0	360.6×10^4	12.95×10^4	123.6×10^4	181.7×10^4	59.61×10^4
208	GCH_4	336	185.2	445.6	12.69	204.2	174.5	45.80
154	GHe	222	184.0	129.2	12.60	66.34	24.29	45.74
234	GHe	336	184.6	188.8	12.65	122.5	29.74	39.64
181	GH_2	217	184.3	169.4	12.63	73.98	56.61	46.00
261	GH_2	342	185.9	248.8	12.73	164.4	56.43	35.95

TABLE X. - Concluded. ENERGY BALANCE FOR PARTIAL EXPULSIONS

(b) U.S. customary units

Run	Type of pressurant	Inlet gas temperature, ^oR	Expulsion time, sec	Total energy added, ΔU_T, Btu		Energy gained by tank wall during expulsion, $\Delta U_{w,X}$, Btu	Energy gained by ullage, $\Delta U_{U,X}$, Btu	Energy gained by liquid during expulsion, $\Delta U_{L,X}$, Btu
				Energy added by pressurant during expulsion (experimental)	Energy added by environment during expulsion (experimental)			
5 to 50 Percent ullage expulsions								
100	GCH_4	400	188.7	3111	122.6	967.5	1612	672.8
182	GCH_4	619	182.8	3499	118.7	1446	1468	378.7
128	GHe	414	187.0	1057	121.5	403.3	445.3	272.4
209	GHe	625	181.8	1464	118.1	714.5	436.7	258.5
155	GH_2	394	187.0	1368	121.5	468.4	689.5	214.1
235	GH_2	628	189.5	2024	123.1	998.9	712.6	222.4
50 to 95 Percent ullage expulsions								
127	GCH_4	401	189.0	3420	122.8	1172	1723	565.4
208	GCH_4	605	185.2	4226	120.4	1937	1655	434.4
154	GHe	400	184.0	1225	119.5	629.2	230.4	433.8
234	GHe	605	184.6	1791	120.0	1162	282.1	376.0
181	GH_2	391	184.3	1607	119.8	701.7	536.9	436.3
261	GH_2	616	185.9	2360	120.7	1559	535.2	341.0

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