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Chilldown and Storage Losses of Large Liquid Hydrogen Storage Dewars*

by

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INTRODUCTION

In the operation of large scale cryogenic facilities, the test planner frequently must rely on long extrapolation from much smaller scale operations. In order to avoid continued use of assumptions which even deviate further from reality as sizes increase it would appear advantageous to attempt to establish the degree of validity of such assumptions as storage dewars increase in size.

This paper will report measurements on the chilldown and steady state boiloff losses of a 55,000 gallon evacuated perlite insulated liquid hydrogen storage dewar at the Nuclear Rocket Development Station in Nevada. Results of these observations are directly applicable to large dewar storage vessels currently being designed, built or being placed into service. These results should assist the designer and planner in estimating the necessary cryogen quantities and may even in some cases aid in evaluating the relative merits of different types of insulation systems available.

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DEWARS

The results reported herein are for the currently existing liquid hydrogen storage system of Test Cell "C" at the Nuclear Rocket Development Station in Nevada. Each of the two spherical dewars has a total capacity of 55,000 gallons including ten percent ullage. Each dewar is insulated with thirty-eight inches of evacuated perlite having a bulk density of 8.5 pounds per cubic foot and a thermal conductivity of $6.0 \times 10^{-4} \frac{\text{Btu}}{\text{ft}^2 \times \text{hr} \times ^\circ\text{R}/\text{ft}}$.

The inner shell is constructed of 0.47-inch thick 304 stainless steel and outer shell is 0.56-inch thick carbon steel.

The dewar is mounted on a load cell system which provides continuous weight indication. In addition, the dewar is equipped with a capacitance type liquid level gauge and an instrumentation rake is located on the vertical axis of the dewar. Mounted on the rake are four carbon resistor point level sensors for calibration of the capacitance gauge, and twenty-four platinum resistance temperature probes to monitor ullage gas and liquid temperatures as a function of height at one foot intervals.

BOILOFF MEASURING APPARATUS

The boiloff measuring apparatus is shown in Fig. 1. The venting hydrogen gas first passes through a thermostatically controlled heat exchanger where it is heated to approximately 140°F. The gas then passes through a variable throat area rotameter where the volumetric flow rate is measured. From here it passes through a control valve which maintains a constant pressure on the dewar.

The gas is then discharged to the atmosphere through a check valve. The gas temperature is measured and recorded upstream of the rotameter with a vapor bulb thermometer. The average temperature variation has been no greater than $\pm 2^{\circ}\text{F}$. The dewar pressure is monitored upstream of the rotameter by a precision test gauge and the average pressure deviation at temperature equilibrium in the dewar has been no greater than ± 0.02 psi.

The rotameter used to measure flow rates was calibrated with hydrogen gas and the commercially supplied calibration was found to differ from this calibration by less than one percent in the range over which it was used.

DISCUSSION

Estimates of the quantity of liquid cryogen required to chill a dewar to operating temperature require accounting for cooling the inner shell, support rod system, interconnecting piping and insulation to equilibrium temperatures. In addition to the above liquid requirements, there exists a cryogen loss associated with heat gain from the dewar surroundings. This heat gain is nonexistent when the dewar is warm (before beginning the initial chilldown) but upon filling of the dewar slowly increases as temperature equilibrium is approached until finally at temperature equilibrium it is the cause of the steady state boiloff.

The liquid requirement for inner shell chilldown is usually calculated conservatively with the assumption of only latent heat of vaporization providing refrigeration. Only if initial liquid

input (and boiling) are so vigorous that liquid is entrained in the boiloff gases can more than this amount of liquid be used. Hence this quantity has been referred to as a "maximum" coolant requirement.⁽¹⁾ Chilling slowly (with good opportunity for the boiloff gases to receive heat from the portion of the tank later to be covered with liquid as the level increases) results in a much smaller liquid coolant requirement. Indeed if the vapor can always be vented at the temperature of the last metal it contacts within the dewar a minimum coolant requirement results and specific liquid requirements for the maximum and minimum have been calculated by Jacobs.⁽¹⁾ In the case of cooling stainless steel to liquid hydrogen temperature the maximum is five times the minimum requirement. For dewar chilldown one might expect close to the maximum consumption, however, the data presented below do not bear out this expectation.

For the dewar under consideration the weight of support rods is less than one percent of the inner shell weight and therefore they are neglected. The weight of interconnecting piping is also small (about 4 percent of the inner shell weight) however, about 1/3 of this weight is within the inner shell and hence is included in the inner shell weight.

For the previous chilldown the inner shell and its interior piping are assumed to reach 38°R (the dewar operating temperature). Even though the topmost metal might never get this cold, from the standpoint of the integral of $C_p dT$, the error is small and may be neglected.

For the insulation, however, a temperature gradient from ambient to 38°R must be assumed. The distribution chosen can affect the chilldown liquid requirement and equilibration time drastically. Once the quantity of heat to be removed is determined (as calculated from the assumed temperature gradient and specific heat) it is again necessary to postulate the amount of refrigeration obtained from the hydrogen. Since this heat is added slowly it is reasonable to believe that a good portion of the heat will reach the inner shell after it is submerged and therefore only hydrogen vaporization would be expected to contribute refrigeration for this cooling.

Several analytical solutions have been presented for the cooling of the evacuated perlite insulation of a spherical dewar. (2,3,4) With the assumption of a steady state temperature gradient and knowledge of the specific heat of perlite as a function of temperature, the heat to be removed may be calculated by direct integration. This has been done with a conservatively assumed linear temperature gradient. (4)

A calculation describing the chilldown in more detail considers the problem as a slab with initially uniform temperature. At the time zero the inner surface has the temperature chilldown step impressed on it and both inner and outer surfaces are then held at constant temperature. The specific heat and thermal conductivity of perlite are averaged and taken as constant. Therefore, for infinitely large dewars this implies a linear steady state temperature distribution. A simplified

Eq. (1) results

$$\frac{\partial T}{\partial t} = \frac{\bar{k}}{\bar{c}\rho} \frac{\partial^2 T}{\partial r^2} \quad (1)$$

where T is the temperature; t , the time; $\bar{k}$, the average thermal conductivity of perlite; $\bar{c}$, the average specific heat of perlite; ρ , the density of perlite; and r is the radial distance. When the inner and outer surface of the annulus are held at constant temperature and the whole inner surface is assumed to have the same temperature a solution to differential equation is found as in Eq. (2)

$$\frac{q(t)}{q_{ss}} = 1 + 2 \frac{a}{b} \sum_{n=1}^{\infty} \exp \left(- \frac{\bar{k} n^2 \pi^2 t}{\bar{c}\rho L^2} \right) \quad (2)$$

where L is the annulus thickness, $q(t)$ is the instantaneous heat flux, q_{ss} is the steady state heat flux, n is an integer, and a and b are the inner and outer radii of the annular space. Account is taken of the heat transport by radiation through the average thermal conductivity of perlite so these solutions may be expected to be conservative since radiation is the dominant heat transfer mechanism at steady state conditions. (5) The chilldown vs. time for the 55,000 gallon dewar as predicted from this model is shown in Fig. 2. The time constant implicit in Eq. (2) is $t_0 = \bar{c}\rho L^2 / \bar{k} \pi^2$ and for this dewar is $t_0 = 55$ days. Variation in apparent heat flux may be compared with the measured dewar boiloff data and/or the measured loss of liquid in the dewar.

The integral of the heat flux into the dewar added to the inner shell chilldown requirements will give the integrated liquid loss as in Eq. (3)

$$\Delta M_{H_2} = \frac{1}{\ell_v} \left\{ \int_{T_1}^{T_f} m C_{pm} dT + \int_0^{t_f} Q(t) dt \right\} \quad (3)$$

where ΔM_{H_2} is the mass of LH_2 used as a coolant up to time t_f , ℓ_v is the latent heat of vaporization, m is the mass of metal to be cooled, C_{pm} is the specific heat of the metal, T_f is the final temperature and T_1 is the initial temperature. The calculated liquid loss may be compared with the quantity of liquid put into the dewar and that remaining in storage in the dewar at time t_f . If an average gas exit temperature is known the quantity ℓ_v can be replaced with $\ell_v + \Delta h$ where the Δh represents the additional enthalpy carried out of the dewar by the superheating of the boiloff gas.

The second integral of Eq. (3) decreases slowly to the steady state value. This value can be computed using effective thermal conductivities or can be measured directly by monitoring the quantity of boiloff gas. However, both spot checks of the boiloff gas temperature (during steady state operating conditions) as well as mass balance presented in Table I indicate that in order to make accurate estimates of liquid loss during cooldown and to obtain accurate values of the heat gain of a dewar, the exit gas temperature must be measured. For

example if the liquid hydrogen daily loss in a dewar is used to calculate the heat leak on the basis of latent heat alone, an error of a factor of up to 9 could be made.

RESULTS

In Table I are presented the results of calculations made to estimate chilldown quantities of liquid hydrogen as well as results of field measurements. Two dewar chilldowns were carried out; one was a slow fill in which a quantity of approximately 8000 gallons was delivered to the dewar which then stood for one week. Then a second 8000 gallons was added and again the dewar was allowed to stand for one week. The dewar was then filled. The other fill was a faster fill in which the dewar was filled in one week. As can be seen the slow chill was much more efficient using only about $\frac{1}{2}$ the quantity of liquid hydrogen. Also in neither case was the actual requirement as great as the maximum predicted. Unfortunately it is not possible to distinguish between shell and insulation chilldown. However, it would seem safe to say that neither shell nor insulation chill is requiring anywhere near the calculated amount. Therefore, the assumption of latent heat only is too conservative for shell cooldown and the linear temperature gradient is too conservative in the case of the insulation chill.

For the approach to steady state conditions, evaporation rates on the 55,000 gallon dewar were measured for a period covering from three to five weeks after liquid hydrogen entered the ambient

temperature dewar. The average daily evaporation loss varied from 0.24 percent at three weeks to 0.22 percent at five weeks. A previous boiloff measurement taken after 5 months equilibration with dewar level and weight instrumentation gives a steady state loss of 0.18 percent per day. The experimental data are shown in Fig. 2 together with results from the calculations as described above.

The heat balance of the dewar after temperature equilibrium obtains can be estimated. Using the measured gas exit temperature and liquid level change to calculate enthalpy change and mass loss we find $\Delta h + \ell_v = 385 \text{ Btu/lb}$ and $\Delta M = 54 \text{ lb/day}$. Hence the total heat flux is 870 Btu/hr.

Calculations of expected heat leak are made for the support rod structure, the manway and instrument port inner shell connections, and the perlite filled evacuated annular space. Average conductivities are used as well as perlite conditions as specified above. The contributions are summarized in Table II.

The distribution of heat input to liquid and gas can be estimated and as will be seen from the dominance of the manway heat leak, the ullage gas will receive the major part of the heat input. This is in contrast to missile tankage where the liquid-wetted surface receives the major heat input.

The boiloff quantity from computed heat leaks is somewhat less than that measured (0.10 percent is indicated rather than 0.18 percent). Also the computed gas heating is lower than observed by about the same

ratio. This might be indicative of inadequacy of direct scaling of the insulating value of perlite with thickness. Since a significant part of the heat transport across the perlite insulation is by radiation⁽⁵⁾ such scaling cannot strictly be done.

A suppressed evaporation rate was observed just prior to the time that temperature equilibrium in the liquid was attained. This warrants further discussion. When the test apparatus was placed into service on the dewars it was necessary to raise the pressure two to three psi thus subcooling the liquid hydrogen in the dewars. It was then necessary to wait, usually two to three days, for the liquid to reach a higher boiling point before the normal evaporation rate could be measured. During this period a suppressed evaporation rate was observed which was somewhat erratic, but in general was approximately one third the normal evaporation rate. This would seem to indicate that the heat input to the dewars promoted the formation of a layer of warm liquid on top of the subcooled liquid. Such a warm layer formation has been observed during a self pressurization experiment with this dewar.⁽⁶⁾

CONCLUSIONS

The time history of the boiloff gas quantity has been measured and compared with the total measured liquid input for a 55,000 gallon LH₂ storage dewar. These measurements have shown that this vacuum perlite insulated dewar chills more quickly and requires less liquid hydrogen for chilldown than is generally calculated from theory. The measured steady state heat flux is less by a factor of 2 than conservative calculations would predict.

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Table I.

Cooldown of 50,000 Gallon Dewar

<u>Item</u>	<u>One Week</u>	<u>Three Weeks</u>	<u>Assumption</u>
Calculated shell cooldown	6500 lb	6500 lb	Latent heat only
Calculated insulation	<u>1660</u>	<u>3880</u>	Latent heat only and linear temperature gradient
Calculated total cooldown	8160	10380	
Actual requirement	4980	2400	

Table II.

Computed Heat Leak

Support rod structure:	$Q_s = 10 \text{ Btu/hr}$
Manway and rake heat flux:	$Q_m = 290 \text{ Btu/hr}$
Perlite ($\bar{k} = .006 \text{ mW/cm}^\circ\text{K}$)	$Q_p = 230 \text{ Btu/hr}$
Total	530 Btu/hr

Figure 2. Computed and Measured Dewar Boiloff as a Function of Time