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Annular Air Leaks in a liquid hydrogen storage tank

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Abstract. Large liquid hydrogen (LH2) storage tanks are vital infrastructure for NASA, the DOD, and industrial users. Over time, air may leak into the evacuated, perlite filled annular region of these tanks. Once inside, the extremely low temperatures will cause most of the air to freeze. If a significant mass of air is allowed to accumulate, severe damage can result from nominal draining operations. Collection of liquid air on the outer shell may chill it below its ductility range, resulting in fracture. Testing and analysis to quantify the thermal conductivity of perlite that has nitrogen frozen into its interstitial spaces and to determine the void fraction of frozen nitrogen within a perlite/frozen nitrogen mixture is presented. General equations to evaluate methods for removing frozen air, while avoiding fracture, are developed. A hypothetical leak is imposed on an existing tank geometry and a full analysis of that leak is detailed. This analysis includes a thermal model of the tank and a time-to-failure calculation. Approaches to safely remove the frozen air are analyzed, leading to the conclusion that the most feasible approach is to allow the frozen air to melt and to use a water stream to prevent the outer shell from chilling.

1. Introduction

This paper will address methods to safely remove large quantities of frozen air from the annulus of an LH2 storage tank. Our prior work [1] detailed methods of air introduction and long term effects. Testing methods, to determine the thermal conductivity of perlite that has air frozen into its interstitial spaces, was also discussed [1], but data collection and analysis from this testing will be presented here. Further, this paper presents analysis of the void fraction of solid nitrogen within a perlite/frozen nitrogen/vacuum mixture. Equations are developed to determine if air can be safely removed by vacuum pumping or heating. A specific tank geometry with a hypothetical leak is then analyzed. A thermal model of the selected tank (created in SINDA/FLUINT) is presented. The thermal model together with a void fraction estimate, a mass of ingested air, and a specified leak rate can be used to determine the time-to failure of the tank. Time-to-failure describes how long a tank may remain operational with an annular space air leak. When the time-to-failure has elapsed, the annular space will no longer be able to freeze the air, and the tank will enter a run-away failure scenario. Finally, a detailed engineering analysis of air removal techniques determines a water heating solution will allow for the safe removal of air from the annular space.

2. Experimental data collection/analysis

Testing was accomplished to determine the thermal conductivity of perlite that has nitrogen frozen into its interstitial spaces [1]. The experimental details were described in our prior paper, but in summary, we embedded temperature sensors in a vertical column of perlite located in a nitrogen atmosphere on top of cryocooler cold head. Figure 1 shows the various temperature readings during system chill-down (T01 on the bottom working up to T08 on top). Note: T03 is shown as a distribution of points, rather than a line, because this sensor had occasional drop outs throughout testing.

In order to determine the thermal conductivity, steady-state temperatures were obtained. Equal energy flow through each layer of perlite implies $Q = Q_1 = Q_2 = Q_3 = Q_4 = Q_5 = Q_6 = Q_7$. With known temperatures and spacing, the thermal conductivity of each layer can be calculated using equation 1, where k_1 thru k_7 represent the thermal conductivities of the layers between the temperature sensors. Likewise, l_1 thru l_7 represent the distance between the temperature sensors and ΔT_1 thru ΔT_7 represent the differential temperature across each layer.

$$Q = \frac{k_1 \Delta T_1}{l_1} = \frac{k_2 \Delta T_2}{l_2} = \frac{k_3 \Delta T_3}{l_3} = \frac{k_4 \Delta T_4}{l_4} = \frac{k_5 \Delta T_5}{l_5} = \frac{k_6 \Delta T_6}{l_6} = \frac{k_7 \Delta T_7}{l_7} \quad (1)$$

To employee this methodology, it is important to accurately characterize the thermal conductivity of the layers of perlite at the top of the sample. Perlite thermal conductivity is a function of perlite density, temperature, and pressure of the background gas. Empirical data showing the effect of each of these is detailed in the work of Kropschot & Burgess, and Fulk [2] [3]. Adams formulates an analytical model built from published empirical data [4], and Geisler builds off the work of Kaganer to develop a theoretical model [5] [6]. These works combined provide reliable values for thermal conductivity at the test conditions. Equation 1 was then employed and the thermal conductivity of the frozen nitrogen/perlite mixture was calculated to be 28.9 mW/m-K +/- 11%. The uncertainty is due to the limited accuracy of the measurement of the sensor locations.

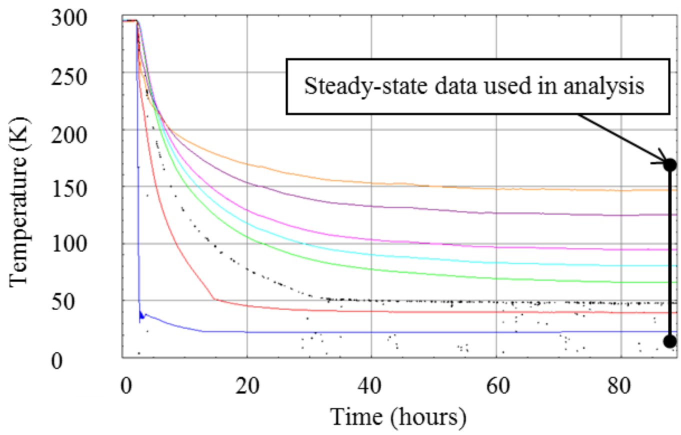

Figure 1. T01 thru T08 shown top to bottom in run 2

3. Void Fraction of frozen nitrogen/perlite mixture

A mesoscopic numerical tool employing a lattice Boltzmann algorithm was used to calculate the effective thermal conductivity of a mixture of materials [7]. The thermal conductivity of clean perlite at STP is approximately 6 mW/m-K [8], and its void fraction is 79% [9]. The thermal conductivity of 550 kg/m^3 solid nitrogen crystals is 250 mW/m-K [10]. Using these values, with experimentally determined combined thermal conductivity of 28.9 mW/m-K, the mesoscopic numerical tool, using the lattice Boltzmann algorithm predicts that approximately 18.5% of the space is composed of frozen nitrogen crystals.

4. Equation Development

A series of equations were developed to allow for determination of critical inputs into the solution analysis. Equation 2 can be used to determine the quantity of air that has frozen into an annular space. Equation 3 shows how long it would take to remove that air using vacuum pumps. A determination of the current leak rate can be made using equation 4. When LH2 is saturated at 1 atmosphere and the boiloff rate is known in gallons per day, equation 5 will yield the heat leak into the tank in kW. Equation 6 can be used to determine the shortest amount of time (conservative) it would take for all of the ingested air ice to melt. Lastly, equation 7 will reveal how much power must be added to the tank wall to prevent the liquid air from chilling the outer wall temperature down below a specified temperature (loss ductility temperature of wall material).

$$N = \frac{100\, P_r\, V}{A\, T\, R} \tag{2}$$

$$t_e = \frac{N}{E} \tag{3}$$

$$r = \frac{M\, N}{\rho_{air}\, t_a} \tag{4}$$

$$H = 0.001384\, B \tag{5}$$

$$t_l = \frac{\Delta H_{fus}\, M\, N}{k\, \Delta T\, ({}^{SA}/_{l}) + H_n} \tag{6}$$

$$P = \frac{M\, N\, \Delta H_{vap} - cp\, m_s\, \Delta T_w}{t_l} \tag{7}$$

(P_r) annular pressure rise
(A) percentage of air that is helium and neon
(R) universal gas constant
(E) evacuation rate when annular pressure is <133 Pa
(k) thermal conductivity of the insulation at standard temp/press
(N) number of moles of air that have been ingested into an annulus
(t_l) time required to liquefy the frozen air
(SA) surface area of the outer tank wall
(cp) heat capacity of the tank wall material
(t_e) time required to evacuate a given amount of air
(H_n) heat leak of the tank under nominal conditions
(ΔT_w) allowable temperature change in the tank wall
(ΔT) difference between the temperature of the inner tank and the outer tank walls
(P) power required to keep the tank wall above a specified temperature
(V) volume of the annulus
(T) gas temperature
(M) molar mass of air
(t_a) air accumulation time
(H) tank heat leak
(ΔH_{vap}) heat of vaporization
(ΔH_{fus}) heat of fusion of air
(l) width of the annulus
(m_s) mass of tank wall
(B) boil off rate
(r) leak rate
(ρ_{air}) density of air

5. Hypothetical Problem/Solution

NASA's Kennedy Space Center (KSC) has two 3,218 m^3 (850,000 gallon) LH_2 storage spheres at Launch Complex 39 (LC-39), which were built in the 1960s, and were used in support of both the Apollo and the Space Shuttle Programs. At least one of these is intended for use in future human space flight programs. They are each comprised of an 18.7 m (61.5 ft.) diameter 1.75 cm (0.688 in) thick stainless steel inner sphere suspended inside a 21.6 m (70 ft.) diameter, 2.95 cm (1.16 in) thick carbon steel outer sphere (jacket) [11]. The 1,642 m^3 (58,000 $ft.^3$) annular vacuum space contains inner sphere supports as well as liquid and gas lines, and is filled with insulating perlite powder.

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The following hypothetical scenario is set forth for this analysis. One of KSC's LH_2 vessels is operational and its annular pressure has increase by 2.7 Pa (20 millitorr) over the last 2 years and 2 months. All attempts to identify the location of the leak have failed, and operational demands require the vessel to remain in service. The annular pressure has increased to approximately 24 Pa (180 millitorr) in total. All of the pressure increase was confirmed to be trace Helium and Neon from air via RGA. Additionally, the boiloff rate has increased from a nominal value of 300 gallons per day to 2,100 gallons per day.

The program being supported by the leaking tank needs to know how long they can continue operations without risking a run-a-way scenario in the tank. In order to determine this, a thermal model of the tank is developed in order to describe the extent to which air may freeze within the annulus. That, coupled with mass estimates of ingested air, void fraction estimates of air ice formation, and the estimate leak rate will provide an estimated time-to-failure.

A thermal model of a half full, nominal condition, LC-39 LH_2 storage tank was created using Thermal Desktop in [1] and is shown on the left side of figure 2. Results from the model of a tank which has leaked enough air to increase the annular pressure to 24 Pa (180 millitorr) are shown on the right side of figure 2. This model uses the experimentally determined thermal conductivity of perlite/frozen nitrogen mixture as an input, and consequently, the freezable zone expands to approximately 22.6 cm (8.9 in) in thickness or 7.8% of the total annular volume.

The model provides maximum boundaries for the location of the air-ice under varying conditions. As air leaks in, there is a pressure increase due to residual helium (5.24 ppm) and neon (18.18 ppm) that will work to shrink the freezable zone, and there is a reverse effect from the increase in thermal conductivity due to the condensation of air. The net effect of these two opposing mechanisms is to increase the freezable zone until approximately 26.7 Pa (200 millitorr). Above that pressure the increase in thermal conductivity due to residual gases causes the freezable zone to recede.

The maximum extent of the freezable zone is important because once the available volume is filled, there will be nowhere for additional leaking air to freeze, which will cause the pressure to climb at a much higher rate. When the pressure increases above the triple point for oxygen (assuming no eutectic effect), warming will cause the frozen oxygen to melt. The tank may then enter a run-away scenario in which rapid liquefaction of the frozen air may result in outer sphere cracks. The freezable zone begins to recede after 26.7 Pa (200 millitorr) of pressure is reached.

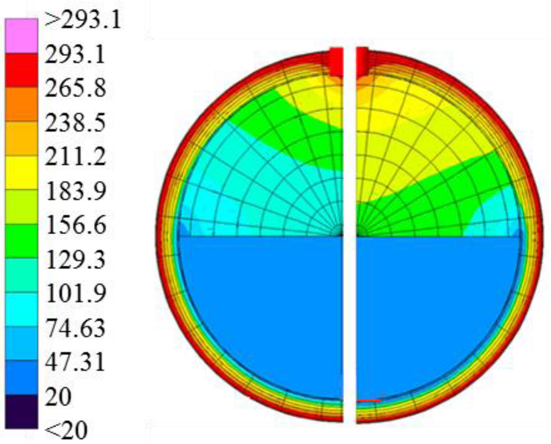

Figure 2. Thermal model (50% full): 10 millitorr (left) 180 millitorr w/air-ice (right)

In order to determine the time-to-failure, the thermal model is used to determine the maximum portion of the annulus that may freeze air. A zone extending 22.6 cm (8.9 in) from the inner tank wall is cold enough to hold air in the frozen form when the annular pressure is 24 Pa (180 millitorr). If the storage tank is full, that results in a volume of approximately 225 m^3 (7,950 ft^3). The fraction of solid nitrogen crystals within that space is approximately 18.5%, which means up to 42 m^3 (1,500 ft^3) of nitrogen can be frozen in the perlite around the inner tank. Because the density of solid nitrogen is 550 kg/m^3, the annular space may hold at most, 23,000 kg of solid nitrogen. That much nitrogen, frozen from air, would result in an annular pressure rise to 31 Pa (230 millitorr) due to residual helium and neon that remain in the gaseous state. Assuming a constant leak rate of approximately 55 sccs (calculated using equation 4), it will take approximately 3.6 years to leak enough air into the tank to increase the pressure from 180 millitorr to 230 millitorr.

The time-to-failure can be extended significantly by periodically evacuating the annular space to maintain a pressure near 2.7 Pa (20 millitorr). In this case, the freezable zone increases to 626 m^3, equating to a maximum of nearly 64,000 kg of frozen air. It would take more than 20 years to leak in that much air at a constant rate of 55 sccs. While evacuation of residual gas is a convenient way to extend a tank's operational status, it would not alleviate the issue entirely. To begin with, structural stress calculations may be required to ensure the inner tank support structure can carry the additional weight of the air. Additionally, when the tank is eventually drained for refurbishment, the likelihood of over-chilling the outer tank wall multiplies due to the increase in the liquid mass to be vaporized. Much more heat input will be required to prevent crack formation in the outer wall.

6. Safe removal analysis

This section discusses the options available to prevent the outer tank wall temperature from dropping below the ductility range in the event that the LH_2 in the tank is completely and rapidly drained shortly after identification of the problem. A partial drain would increase the time-scales resulting in less power input required. The first option discussed is to use pumps to remove the sublimating frozen air, keeping the annular region pressure below the triple point so that no liquid is formed. The second method considered is to allow the frozen air to rapidly melt and apply heat to the outer tank to prevent it from chilling below its ductility temperature.

The 3,218 m^3 (850,000 gallon) LH_2 storage tank at LC-39B was removed from service at the end of the Space Shuttle Program. The tank had been experiencing an abnormally high boiloff, so the annular region was backfilled with GN_2, and investigated. The cause of the high heat leak was confirmed to be a perlite void in the annular region. The perlite void was filled with new perlite and other refurbishment activities ensued [12]. A pump-down log was kept during re-establishment of the annular vacuum, enabling determination of evacuation rates. The evacuation rates were then used to ascertain the amount of time it would take to remove the given mass of air.

The predominant two constituents of air are nitrogen and oxygen. They have triple points of approximately 63 K / 12.5 kPa (94,000 millitorr) and 54 K / 0.15 kPa (1,100 millitorr) respectively. It is therefore necessary to maintain the annular pressure at or below approximately 133.3 Pa (1,000 millitorr) in order to prevent the frozen air from liquefying as it warms. Data from the LC-39B pump down logs show an evacuation rate of 1.5 – 1.7 Pa (11-13 millitorr) per hour when pumping in the 133.3 – 60 Pa (1,000 – 450 millitorr) range. The volume of the annular space is known, and the tank was at ambient temperatures during the evacuation. Using the ideal gas law, the evacuation rate was determined to be approximately 1 mole per hour.

Historically, the evacuated LC-39A and LC-39B tank pressure was 1.3 – 2.7 Pa (10 - 20 millitorr) when the tanks were full of LH_2. Therefore, 2.7 Pa (20 millitorr) will be considered a baseline pressure for the analysis, reducing the pressure requiring removal from the annular space from 24 Pa (180 millitorr) to 21.3 Pa (160 millitorr). Helium and neon account for 5.24 parts per million (PPM) and 18.18 PPM of air respectively (0.002342% combined). The 21.3 Pa (160 millitorr) of He and Ne must then represent a pressure of 911,000 Pa (132 psia) of air under ambient conditions. The volume of annulus is known (1636.74 m^3), and the temperature of the sample is ambient, so the ideal gas law can be employed to determine that 21.3 Pa (160 millitorr) of He and Ne suggest that 612,000 moles of air are present in the annulus. With continuous pumping at a rate of 1 mole per hour, it would take nearly 70 years to evacuate the air and maintain the pressure below 133.3 Pa (1,000 millitorr). That is clearly not practical. Consequently, this option is deemed non-feasible.

The LH_2 storage tank has a boiloff rate of approximately 563 kg/day (2,100 gallons/day). The heat of vaporization of LH_2 at 1 atmosphere is 446 kJ/kg, therefore, 251 MJ/day (2.91 kW) must be coming into the system. The heat of fusion of N_2 and O_2 is 25.7 kJ/kg, and 13.9 kJ/kg respectively. Weighting these values by percentage of each in air results in a value of 23.2 kJ/kg for the heat of fusion of air. 612,000 moles of air (calculated above) translates to 17,700 kg of air. In order to establish a minimum time in which the air could melt, the heat leak at standard temperature and pressure (STP) is considered. The thermal conductivity of perlite at STP is 54 mW/m-K [4]. The surface area of the outer tank wall is 1,430 m^2, and the annulus is 1.3 m thick [11]. Therefore, the heat leak into the tank at STP due through the perlite is approximately 16.7 kW. Adding 0.4 kW to account for additional heat leak from flanges, access ports, etc. results in a total worst case heat leak of 17.1 kW at STP. 17.1 kW could melt 17,700 kg of air in approximately 6.7 hours if the heat were used exclusively to convert the frozen air to liquid air. Though this is not the case, a conservatively low time estimate is required to determine the maximum heat input required, so 6.7 hours will be used in subsequent analysis.

The heat of vaporization of air is 201.4 kJ/kg, so it would take 3,570 MJ to vaporize the entire 17,700 kg mass of liquid air. However, the temperature of the outer jacket may be allowed to drop, as long as it remains above the ductility limit of the carbon steel (245 K). A temperature of 275 K is used in the analysis to prevent the formation of frost on the surface, which would act as an insulator. The surface area of the inside of the outer wall that may be contacted by liquid air was calculated to be 374 m^2 (carbon steel volume of 11 m^3) based on assumed dripping of liquid air to the surface. The density of carbon steel is 7,850 kg/m^3 and the heat capacity is 0.49 kJ/kg-K, so the energy required to lower 11 m^3 of outer tank wall from 300 K to 275 K is 1,060 MJ. Subtracting that from the total 3,570 MJ required to vaporize the liquid leaves 2,510 MJ which must be added to the tank in order to vaporize the liquid and keep the outer shell at or above 275 K. Because this liquid may form in as little as 6.7 hours, 376 MJ/hr or 104 kW (distributed over 374 m^2) will be required to keep the outer wall in a safe temperature range during the melting/vaporization process.

Because the outer tank wall is 2.95 cm (1.16 in.) thick, the question remains, if the outside of the outer wall can be kept above the freezing temperature of water, can cold spots below the ductility range of carbon steel still form on the inside of the outer tank wall? In order to answer this question, SINDA/FLUINT was used to model a 16 m^2 section of outer tank wall. The outside of the wall was set at a constant temperature of 275 K. Next, the 104 kW load on the inside of the wall was divided into equivalent 16 m^2 portions (4.5 kW). The 4.5 kW cooling load was then concentrated on the 16 m^2 sample plate (with a constant heat distribution), representing a stream of liquid air contacting a small portion of the inside of the wall. Temperatures on the inside of the wall did not reach 245 K until the load area was reduced to 232 cm^2 (36 $in.^2$). This suggests that while it is possible to have very small areas of the inner surface below the ductility range while the entire outer surface is above the freezing point of water, the likelihood of that happening is very low because all of the liquid would need to be coursing to the inner surface in extremely narrow and focused streams, which is highly unlikely.

Several methods of adding heat were considered. Polyimide heaters bonded directly to the tank wall would provide more than enough heating power, but between 140 – 280 heaters would be required (depending on heater size and set point) in order to distribute the heat over the entire 374 m^2 of tank wall without leaving cold spots between the heaters. Blowing warm air across the surface of the tank with fans would also provide enough heating power. However, wind conditions may counter-act the effects in some locations, other locations may be difficult to reach, and fans would be required at elevation in order to provide the coverage required. Infrared heaters also provide sufficient heating power, but do not meet the necessary Class 1 Division 2 maximum temperature requirements. Consequently, they would need to be placed 7.62 m (25 ft.) away from the tank wall. While they can still provide adequate heating from this distance, there would likely be significant gaps in coverage due to obstructions lying between the heaters and the tank wall. The optimal heating solution is the spraying of water onto the outer tank wall. This method provides adequate heating, causes no increase in hazard, sufficiently covers all areas, and imposes only minimal implementation costs. The following section details the analysis and design for a spray water heating system at LC-39B.

7. Water heating analysis/design

In order to determine the potential effectiveness of spraying water, it is first necessary to determine the amount of water that would be required to achieve adequate heating. The minimum temperature acceptable for the storage sphere's outer wall is 275 K. Assuming the ambient water temperature is 300 K, the water may be chilled by a maximum of 25 K when contacting the outer tank wall. The specific heat of water is approximately 4.19 kJ/kg-K. The specific heat multiplied by the temperature change shows that it would take 105 kJ to reduce 1 kg of water by 25 K. As previously determined, 376 MJ/hour must be added to the tank to keep the wall temperature from dropping below 275 K. 376 MJ/hour divided by 105 kJ/kg shows that 3,600 kg of water must be sprayed on the tank every hour if all of the water is chilled to 275 K. Using the density of water (1000 kg/m^3) and converting units yields 16 gallons per minute of water must be continuously applied to the tank for the entire 6.7 hours in order to keep the wall temperature above 275 K. 16 gallons per minute represents a minimum value because it assumes all of the water is chilled to the maximum extent. If, instead, it is assumed that the water is only chilled by 1 Kelvin when applied to the cold tank, the same methodology results in a water flow rate requirement of 400 gallons per minute. Many factors will affect how much the water will chill when contacting the outer wall, but the flow rate of 400 gallons per minute represents an adequate upper bound.

Next, it is necessary to evaluate the existing water capability on-site at the LH_2 tank. Drawings detailing the existing water deluge system at launch pad LC-39 B show 10 risers surrounding the LH_2 sphere, each spaced 36 degrees apart from the tank's center-line [13]. Each riser has 3 water flow nozzles, (1) 10 feet from grade, (1) 30 feet from grade, and (1) 50 feet 10 inches from grade. The top nozzle extends 13 feet 10 inches above the equator of the tank. Additionally, there are 4 nozzles located below the tank and are directed up to contact the very bottom of the tank. In total, there are 34 nozzles with flow rates of 94 – 240 gallons per minute. There is no way to activate only a portion of nozzles, so activating the system will release water at a flow rate of 5,580 gallons per minute and that water will completely cover the potentially effected zone. This water is drawn from (2) 1.4 million gallon water reservoirs. If both reservoirs are filled to capacity prior to operations, water may flow continuously for up to 8.3 hours.

Activating the water deluge system will release 5,580 gallons per minute of water, but no more than 400 gallons per minute is required to keep the outer tank wall adequately warm. In order to reduce the flowrate, the existing nozzles could be replaced with new, lower flow rate nozzles, but that would require procurement and labor. Alternatively, the 8 inch manual butterfly valve that acts as a system shut-off valve could be modulated as required to reduce the flow on the tank while visually verifying no ice builds up on the outer tank wall. This option would require no procurements or system modifications, but could become labor intensive if the tank's warming process is prolonged. The recommended solution is to partially open the shut-off valve so that full flow is not achieved, while ensuring appropriate water contact with the outer tank wall surface (remaining cognizant of potential cavitation at the valve). Then, the remotely operated 8 inch butterfly valve should be cycled opened and closed from the control room to ensure no ice forms on the surface of the tank. This solution requires no system modifications, and only has minor labor impacts.

8. Summary and Conclusions

Liquid hydrogen tanks that develop air leaks into the annular space can put users into a very difficult position. If significant quantities of air have been ingested into the annulus, attempts to drain and repair the tank can have detrimental effects. The purpose of this work is to characterize some of the physical changes that occur within the system due to an air leak, and to determine the best way to safely remove the ingested air. The thermal conductivity and void fraction of the frozen nitrogen/perlite mixture was determined through testing and analysis. Generalized equations were developed to allow any LH_2 tank operator to evaluate the severity of the situation and determine the heating requirements to prevent severe damage of the storage tank. A specific leak scenario was then proposed and evaluated. A thermal model of the proposed tank was developed and used to estimate the length of time the tank could remain operational with the proposed leak. Methods to safely remove the air were evaluated, and the most practical approach for the proposed case was determined to be the use of an in-place water deluge system. The specific case solution can be applied to either of the LC-39 LH_2 tanks at KSC, and the generalized equations developed in the theory section can be used to evaluate any other leaking LH_2 tank.

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