A Passive Ventilation Device for Hydrogen Control

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A Passive Ventilation Device for Hydrogen Control

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Introduction

Pump pit tanks are employed at the Savannah River Site to facilitate the transfer of radioactive liquid waste between generation locations and waste tanks and among waste tanks. A heel of radioactive liquid waste remains in the pump pit tank following a transfer. Hydrogen is generated in the liquid as a result of radiolysis. The tanks are equipped with an active forced convection ventilation system in order to ensure that the hydrogen concentration in the tank vapor space remains at an acceptably low level. However, the active ventilation system is subject to several failure modes and is periodically taken out of service. As a defense-in-depth measure, a passive ventilation device (PVD) has been designed and deployed which will prevent the hydrogen concentration in the tank vapor space from reaching the lower flammability limit (LFL) in the event the ventilation system is unavailable.

The PVD operates on the principal of natural convection. A hydrogen-air mixture in the tank vapor space would have a lower density than that in the environment exterior to the tank and hence a natural convection driving force would be available. Any temperature difference between the tank vapor space and exterior environment would lead to even larger driving forces. The natural convective driving force is simply the product of the density difference, effective stack height, and the gravitational acceleration constant. A pressure drop will occur across the device due to the flow of air into the tank and the flow of gas out of the tank, and the flow rate established through the device is that required to balance the two differential pressure terms. The calculations assume unidirectional flow in each path, although bidirectional flow could occur in the lower resistance path and yield increased flow rates relative to the calculated values.

The device provides separate inlet and outlet paths through a single tank penetration by employing a central pipe contained within an annulus. The termination points of the two paths are separated so as to prevent mixing of the inlet and outlet streams and subsequent reduction in the natural convective driving force.

Device Description
A schematic of the PVD as deployed in a pump pit tank is shown in Figure 1. The tank penetration is a 6” diameter Schedule 40 pipe which extends approximately 6” above the tank wall and slightly into the tank vapor space. The center section of the PVD is comprised of 3” diameter Schedule 40 pipe. The center pipe section is extended away from the annular section so as to prevent mixing of the inlet and outlet streams and subsequent reduction in the natural convective driving force. The elevation change from the centerline of the top pipe section to the bottom of the pipe is 26”.

![Figure 1 Schematic of Passive Ventilation Device Inserted in Tank Penetration.](image)

The nominal pump pit tank diameter and height are 12' and 8.5', respectively. The internal volume of a tank is 6800 gallons and the operating limit on the maximum liquid volume is 5900 gallons. The tanks are located in below-grade cells which have an internal volume of approximately 5900 ft³.

**Hydrogen Evolution Rate**

The PVD was designed to ventilate hydrogen produced via radiolysis under steady-state conditions. The hydrogen generation rate for this case can be expressed as:
\[ Q_{H2} = G_{H2} \cdot q_v \cdot V_1 \]  

where:  
\( Q_{H2} \) = Hydrogen production rate,  
\( G_{H2} \) = Hydrogen production G-value (molecules \( H_2 \) per 100 eV absorbed),  
\( q_v \) = Volumetric heat generation rate, and  
\( V_1 \) = Liquid waste volume.

The solutions of specific interest in this evaluation contain nitrates at concentrations above 1.0 M with a maximum volumetric heat generation rate of 10.8 Btu/hour/gallon. These solutions result in a predominately \( \beta/\gamma \) radiation field.

The G-value for a predominately \( \beta/\gamma \) radiation field in water is approximately 0.45\(^1\). Nitrates inhibit radiolytic hydrogen production, as do a number of other species. At a nitrate concentration of 1.0 M, the G value drops to 0.12\(^1\) (26\% of that with a zero nitrate concentration). The production rate in an \( \alpha \) radiation field would be approximately a factor of 2 to 4 larger than that for a \( \beta/\gamma \) radiation field\(^2\) (Bibler 1992).

A G-value of 0.12 corresponds to a specific hydrogen production rate of \( 1.1 \times 10^{-5} \) scfh \( H_2 \) per gallon of waste per Btu/hr./gallon. At the maximum volumetric heat generation rate of the waste solution (10.8 Btu/hour/gallon), this gives a volumetric hydrogen generation rate of \( 1.2 \times 10^{-4} \) scfh/gallon. Using the maximum liquid waste volume (5900 gallons), the resulting maximum hydrogen production rate would be 0.7 scfh. A zero nitrate concentration with this heat load and volume would yield a production rate approaching 3 scfh and a significant contribution from alpha radiation could increase the rate to as much as 6 scfh. Hydrogen production rates up to 6 scfh were evaluated, although expected production rates are in the ranges of 0.1 scfh or less.

It should be noted that this evaluation assumes that the rate of hydrogen evolution into the tank vapor space is equal to the rate of hydrogen production within the waste. This is, in general, a conservative assumption since no credit is taken for mass transfer effects and holdup of hydrogen within the waste generating material. However, this assumption restricts the application of these results to cases in which the waste is quiescent. Waste disturbing activities (i.e. startup of a transfer pump or other device which agitates the waste) could lead to a sudden release of hydrogen stored within the waste. Such a release could produce tank vapor space hydrogen concentrations in excess of that based on the methodology employed here.

**Natural Convection Flow Rate**

The pressure differential established across the passive ventilation device due to the density difference between the tank vapor space and cell (i.e. the buoyancy force or natural convection driving force) can be written as:

\[ \Delta P_{nc} = g \cdot \Delta z \cdot \Delta \rho \]  

where:  
\( \Delta P_{nc} \) = Natural convection (buoyancy) driving force,  
\( g \) = Gravitational acceleration,
\[ \Delta z = \text{Elevation change}, \quad \Delta \rho = \text{Density difference}. \]

Using the ideal gas law, the density difference can be written as:

\[ \Delta \rho = \frac{P}{R} \left( \frac{\sum y_{cj} MW_{cj}}{T_c} - \frac{\sum y_{vj} MW_{vj}}{T_v} \right) \tag{3} \]

where:
- \( P \) = Pressure (absolute),
- \( R \) = Universal gas constant,
- \( y_{cj} \) = Concentration (mole fraction) of jth gas species in the cell,
- \( MW_{cj} \) = Molecular weight of the jth gas species in the cell,
- \( T_c \) = Temperature of the gas in the cell (absolute),
- \( y_{vj} \) = Concentration (mole fraction) of jth gas species in the tank vapor space,
- \( MW_{vj} \) = Molecular weight of the jth gas species in the tank vapor space, and
- \( T_v \) = Temperature of the gas in the tank vapor space (absolute).

The equilibrium concentrations of the various gas species are governed by their evolution rates or vapor pressures and by the tank ventilation rate.

The flow rate developed through the passive ventilation device due to an imposed pressure differential can be written as:

\[ \Delta P = \frac{\rho}{2} \left[ \sum f_j \left( \frac{L_j + (L_e / D) j \cdot D_{hj}}{D_{hj} \cdot A_j^2} \right) + \left( \frac{K_j}{A_j^2} \right) \right] \cdot Q_j^2 \tag{4} \]

where:
- \( \Delta P \) = Imposed pressure differential,
- \( \rho \) = Density,
- \( f_j \) = Friction factor for jth flow path segment,
- \( L_j \) = Length for jth flow path segment,
- \( D_{hj} \) = Hydraulic diameter for jth flow path segment (= \( 4 \cdot A_f / P_w \)),
- \( A_f \) = Flow area for jth flow path segment,
- \( P_w \) = Wetted perimeter jth flow path segment,
- \( L_e/D \) = Effective length to diameter ratio (loss term) jth flow path segment,
- \( K_j \) = Form loss coefficient for jth flow path segment, and
- \( Q_j \) = Volumetric flow rate for jth flow path segment.

The flow rate developed due to a given natural convection driving force (i.e. a given \( \Delta z \cdot \Delta \rho \) value) can be found by setting eqns. (2) and (4) equal (via the Bernoulli equation). This is an iterative procedure due to the effect of the tank vapor space hydrogen concentration, and a numerical solution was implemented. In applying these expressions, it was implicitly assumed that unidirectional flow exists within a given flow path, the impact of gas released from the vessel contents is negligible, and that the inlet and outlet flows have the same properties (i.e. density.
differences are neglected in the flow balance). This set of assumptions is judged to be conservative.

If laminar flow conditions exist, the friction factor can be expressed as:

\[
\frac{f}{\text{Re}} = \frac{64 \cdot \mu}{\rho \cdot V \cdot D_h} = \frac{64 \cdot \mu \cdot A}{\rho \cdot Q \cdot D_h}
\]

where: \( \text{Re} \) = Reynolds number, and \( \mu \) = Absolute viscosity.

If turbulent flow conditions exist, then the friction factor can be approximated using the expression given below, which is an explicit approximation to the Colebrook-White correlation:

\[
f = \left[ 1.14 - 2 \cdot \log_{10} \left( \frac{e}{D} + \frac{21.25}{Re^{0.9}} \right) \right]^{-2}
\]

where: \( e \) = Surface roughness.

The laminar friction factor was employed for Reynolds numbers below 2000, the turbulent friction factor was employed for Reynolds numbers above 4000, and linear interpolation between the 2000 and 4000 values was employed for intermediate Reynolds numbers.

The device form loss coefficients and equivalent length to diameter values were taken from standard literature sources. The passive ventilation device and pump pit penetration surface roughness values were assumed to be 0.01 mm. This value is between those for drawn tubing and commercial steel values; the results of this evaluation are insensitive to assumed roughness in flow regime of interest (laminar or just into turbulent regime).

The applicable value for the elevation change (\( \Delta z \)) is dependent upon the flow direction established in the device. For upflow through the central pipe (the expected behavior), \( \Delta z \) is the difference in elevation between the top of the pipe and bottom of the annular section. For upflow through the annulus, \( \Delta z \) is the difference in elevation between the top of the annular section and bottom of the central pipe. However, these values are approximately equal for the PVD so that it makes essentially no difference which flow direction set is assumed; the minimum \( \Delta z \) was employed for the purposes of this evaluation (16 ").

The calculations assume unidirectional flow in each path, although bidirectional flow could occur in the lower resistance path and yield increased flow rates relative to the calculated values.

**Tank Vapor Space Hydrogen Concentrations**

The LFL for a hydrogen-air mixture (at 25°C and 1 atm.) is 4 vol.%. If the pump pit tank is assumed to be sealed, then the times required to reach the LFL at the expected hydrogen
generation rates (near 0.1 scfh) are in the range of several days or more. However, the required
time can be as low as one hour under bounding conditions. Hence, without the PVD, relatively
quick response times might be required to implement mitigative actions.

Figure 2 illustrates the equilibrium tank vapor space hydrogen concentration with the PVD as a
function of hydrogen production rate up to 6 scfh for no temperature difference, for a 5°C \(\Delta T\)
with 75% relative humidity, and for a 10°C \(\Delta T\) with 75% relative humidity. The cell temperature
was taken to be 20°C for these calculations. The hydrogen concentrations in this figure are given
as a per cent of the LFL.

As noted previously, the maximum hydrogen generation rate for the cases of interest was only
0.7 scfh with expected rates in the range of 0.1 scfh or less. Even at the maximum hydrogen
generation rate (0.7 scfh), the equilibrium hydrogen concentration would only reach 25% of the
LFL even with no temperature difference. The equilibrium hydrogen concentration is below the
LFL at a hydrogen production rate of 6 scfh.

Large hydrogen production rates correspond to large heat loads so that some temperature
difference would be established between the tank vapor space and exterior environment. As
shown in Figure 2, accounting for even a 10°C temperature difference and the corresponding
water vapor concentration decreases the hydrogen concentration by 15 to 30% of the LFL. With
respect to buoyancy driving force, the combined effect of 10°C temperature differential along
with the corresponding water vapor concentrations at a tank vapor space temperature of 30°C is
equivalent to a hydrogen concentration of approximately 5% (125% of the LFL).

Note that doubling the hydrogen production rate does not double the hydrogen concentration
since the natural convective driving force, and hence flow rate, increase with hydrogen
concentration. As can be seen in Figure 2, tripling the hydrogen production rate only doubles the
hydrogen concentration for the case where temperature differences and water vapor are not
credited.
In performing this evaluation, it was assumed that the exterior cell environment did not contain hydrogen. Assuming that the cell is sealed, then the time required for the hydrogen concentration to reach the LFL would be several months at expected hydrogen generation rates (near 0.1 scfh); however, the required time falls to only a few days at bounding hydrogen generation rates (6 scfh). Hence, the assumption of a zero cell hydrogen concentration may be invalid for long periods of operation without the ventilation system. It is actually expected that the hydrogen would migrate out of the cell due to natural convective flow through the cell covers; however, this has not been definitively shown at this time. To account for this, as a first approximation, the cell hydrogen concentration for a given hydrogen production rate and time period can be added directly to that for the tank (i.e. that calculated for the tank with the passive ventilation device based on a zero cell hydrogen concentration). For example, if the cell concentration were 0.2%H₂ and that for the tank was calculated to be 1%H₂ based on a zero cell concentration, then the tank concentration would be taken to be 1.2%H₂.

PVD Optimization
Several passive ventilation device modifications could be made to enhance its performance. One such change would be to increase the diameter of the inner pipe so that the hydraulic resistance of the two flow paths (inner pipe and outer annulus) are similar. In the current design, the resistance of the inner pipe is much larger than that of the outer annulus. The hydraulic resistance of Schedule 40 piping 3” to 5” in diameter were evaluated to examine this effect. The hydraulic resistance of the total flow path decreases by almost a factor of 2 as the diameter is increased from 3” to 4”. The 4” diameter corresponds to the point at which the resistances of the inner pipe and outer annulus are roughly equal. The required pressure drop at 100 cfm drops by almost a factor of 2 as the diameter is increased from 3” to 4”. Increasing the inner pipe diameter also increases the flow rate at which the turbulent regime is entered. At a hydrogen production rate of 6 scfh (the largest evaluated), this increase in diameter would decrease the calculated tank hydrogen concentration from 90 to 72% of the LFL for the case where temperature differences and water vapor are not credited.

Increasing the height of the inner pipe and extending the outer annulus above the pump pit tank would increase the effective elevation change ($z$); the natural convective driving force is proportional to $\bullet z$. Doubling $z$ (from 16 to 32") would decrease the calculated tank hydrogen concentration at 6 scfh from 90 to 69% of the LFL for the case where temperature differences and water vapor are not credited. Both doubling $z$ and increasing the inner pipe diameter from 3 to 4” would decrease the calculated tank hydrogen concentration at 6 scfh from 90 to 55% (slightly less than the sum of the two separate effects).

**Conclusions**

The capacity of the passive ventilation device to control the vapor space hydrogen concentration in a pump pit tank is dependent upon the hydrogen production rate in the tank and the conditions in the cell. The hydrogen production rate was treated parametrically within this evaluation with rates up to 6 scfh considered, although expected rates are in the range of 0.1 scfh or less. The results provided here assume that the cell hydrogen concentration is zero. Hydrogen will buildup within the cell if it is not ventilated, so that this assumption would not be protected. To account for this, the tank vapor space concentration can be estimated by adding the cell concentration to the tank concentration calculated assuming no hydrogen in the cell. Hydrogen may migrate out of the cell, so this approach is overly conservative; however, an evaluation of hydrogen loss from the cell has not been performed at this time.

Assuming a zero hydrogen concentration in the cell, the passive ventilation device would be capable of maintaining the hydrogen concentration in the pump pit tank below the LFL for all hydrogen production rates considered even if there was no temperature difference between the tank vapor space and cell. At a 0.7 scfh hydrogen production rate, which is larger than that actually expected, the calculated hydrogen concentration is only 25% of the LFL. At the upper end of the range evaluated, 6 scfh, the calculated hydrogen concentration is 90% of the LFL. Accounting for even small temperature differences significantly lowers the calculated hydrogen concentration, and large hydrogen production rates would be accompanied by significant temperature differences.
Sample results were provided to illustrate the impact of 1) optimizing the inner pipe diameter to minimize the device hydraulic resistance, and 2) increasing the effective elevation change available through the device. Significant reductions in the calculated hydrogen concentrations can be achieved by either design modification.

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