FLAMMABLE GAS DIFFUSION THROUGH SINGLE-SHELL TANK DOMES

J. E. Meacham
CH2M HILL Hanford Group, Inc.
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Abstract: This report quantified potential hydrogen diffusion through Hanford Site Single-Shell tank (SST) domes if the SSTs were hypothetically sealed airtight. Results showed that diffusion would keep headspace flammable gas concentrations below the lower flammability limit in the 241-AX and 241-SX SSTs.

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EXECUTIVE SUMMARY

The amount of hydrogen that could diffuse through the domes of the Hanford Site Single-Shell tanks (SSTs) if they were hypothetically sealed airtight was quantified. The report examined whether diffusion alone would be sufficient to keep hydrogen concentrations below the lower flammability limit (LFL).

Several steps were necessary to quantify potential diffusion. Reports and drawings were examined to identify potential diffusional barriers. Effective diffusivities for the barriers were estimated and a diffusion resistance term calculated. The amount of hydrogen that could diffuse through the dome and keep steady-state hydrogen concentrations below the LFL was then calculated.

Calculations show that the AX and SX-Farm SSTs do not require ventilation of any kind to keep flammable gas concentrations below the LFL. Hydrogen diffusion alone would be sufficient to keep headspace concentrations well below the LFL.

The A, B, BX, BY, S, T, TX, TY, and U SST domes all have an asphaltic membrane covering that would reduce gaseous diffusion. About 7.9 liters of hydrogen per day in the 100 series SSTs would put equilibrium hydrogen concentrations near the LFL if the only means of dissipating hydrogen were diffusion. The 200 Series SSTs domes have a relatively smaller diffusional surface area and about 0.26 liters of hydrogen per day would put equilibrium concentrations near the LFL.

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TERMS

cm	centimeter
cm^2	square centimeter
cm^3	cubic centimeter
ft	feet
ft^2	square feet
HGR	hydrogen generation rate
in.	inches
LFL	lower flammability limit
psi	pounds per square inch
sec	second
SST	single-shell tank

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1.0 INTRODUCTION

1.1 PURPOSE AND SCOPE

The purpose of this document is to quantify the amount of hydrogen that could diffuse through the domes of the Hanford Site Single-Shell tanks (SSTs) if they were hypothetically sealed airtight. Diffusion is assumed to be the only mechanism available to reduce flammable gas concentrations. The scope of this report is limited to the 149 SSTs.

1.2 BACKGROUND

Hydrogen is produced in Hanford Site SSTs by thermal-chemical reactions and radiolysis in the waste and by corrosion of the steel liner. *Steady-State Flammable Gas Release Rate Calculation and Lower Flammability Level Evaluation for Hanford Tank Waste* (Hu and Barker 2003) calculated the time to reach the lower flammability limit (LFL) if ventilation were not available to dissipate flammable gases. Ventilation was the only mechanism credited for removing flammable gasses; however, previous examinations of concrete waste transfer-associated structures (*Flammable Gas Diffusion from Waste Transfer Associated Structures*, Meacham et al. 2003) showed that sufficient flammable gas would diffuse through the transfer structure walls to keep headspace concentrations below the LFL. This report examines whether diffusion alone would be sufficient to keep hydrogen concentrations below the LFL.

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2.0 ASSUMPTIONS

Several assumptions were made in performing the calculations in this report. Some parameters and effects do not lend themselves to easy quantification; therefore, conservative assumptions were necessary to quantitatively assess diffusion.

2.1 BAROMETRIC BREATHING

Flammable gas losses through ventilation were neglected. SSTs were assumed sealed airtight and remain airtight while flammable gasses slowly accumulate. In reality, the enclosure would be ventilated through atmospheric breathing caused by atmospheric pressure fluctuations. An assumption of no barometric breathing is conservative because assessments show that barometric breathing alone could keep flammable gas concentrations below the LFL in most tanks (Hu and Barker 2003).

2.2 CONCRETE COATINGS

The asphaltic membrane water proofing covering most of the SSTs is assumed not to have degraded. Asphaltic membrane roofs degrade from mechanical damage (e.g., wind), ultraviolet radiation, heat, and oxidation. Although the first two mechanisms can be ruled out for the SST domes, the domes have been exposed to high temperatures from years of waste processing and oxygen which can diffuse through the soil and concrete. It was not possible to estimate the effects of high temperatures and oxidation on asphaltic membrane effective diffusivity, and this remains an unquantified conservatism.

2.3 FLAMMABLE GAS GENERATION

Flammable gases other than hydrogen are produced at a lesser rate by the waste, including ammonia and methane. These gases would contribute to flammability; however, the contribution would be relatively small and falls within the bounds of uncertainty in the analyses presented here.

2.4 WELL MIXED HEADSPACE

The atmosphere within the SST headspace is well mixed. Various mixing processes in the headspace (e.g., convection and molecular diffusion) cause hydrogen to be uniformly mixed throughout the dome (*Homogeneity of Passively Ventilated Waste Tanks*, Huckaby et al. 1997). This is realistic and, therefore, does not lead to conservatism or nonconservatism in the analysis.

2.5 TANK DOME SURFACE AREA

The SST dome radius of curvature varies with height causing the dome to have an elliptical shape. For example, the A, AX and SX farm tanks have an inside radius of curvature of 95 ft at the crown of the dome. This radius does not change for a vertical distance of 1.19 ft. At this point the inside radius of curvature becomes 60 ft for the next 6.11 vertical ft. The radius of curvature then changes to 10 ft for the next 3.52 vertical ft. The final radius of curvature is 2.21 ft for the next 1.18 vertical ft to where the dome meets the side wall. The distance from the crown of the dome to the side wall is about 12 vertical ft. The calculations assume that the domes are circulator over this 12 vertical ft, a slightly conservative assumption.

3.0 ANALYTICAL METHODOLOGY

Physical models are used to describe the generation and retention of hydrogen in the hypothetically sealed SSTs. Important physical parameters and their ranges are discussed in Chapter 4.0. Phenomena of gas diffusion are well investigated and the model is built using these well-defined principles.

3.1 APPROACH

The approach used to estimate hydrogen diffusion through a SST dome is summarized as follows:

1. Estimate the effective diffusivity for hydrogen through concrete, asphaltic membrane, mortar/gunite, and soil (as appropriate).

2. Calculate a diffusion resistance term for each of the barriers listed in 1 above.

3. Sum the resistances for the respective diffusion barriers.

4. Calculate the amount of hydrogen that could diffuse through the dome and keep steady-state hydrogen concentrations below the LFL.

3.2 MODEL

Hydrogen (and other decomposition gases) would begin to build in concentration in the headspace of a sealed SST. Assuming a constant hydrogen generation rate, the concentration in the headspace would increase until the system reached steady state and the diffusion outflow equaled the hydrogen generation rate (HGR):

$$\text{HGR} = \text{Out Diffusion Rate} \tag{3-1}$$

Where HGR = hydrogen generation rate, moles/day

The hydrogen out diffusion rate may be calculated from the sum of fluxes (mole/cm^2-sec) multiplied by the surface areas for each applicable flux:

$$\text{Out Diffusion Rate} = \sum^{i} Q_i A_i \tag{3-2}$$

Where Q_i = hydrogen flux for area i, mole/cm^2-sec
A_i = normal area for ith surface, cm^2

The diffusion flux is

$$Q = \frac{D_e \Delta C}{\Delta X} \tag{3-3}$$

Where Q = diffusion flux, mole/cm^2-sec
D_e = effective diffusivity, cm^2/sec
ΔC = concentration difference across barrier, mole/cm^3
ΔX = path length for diffusion, cm

The hydrogen flux is calculated to account for several diffusion resistances in series (e.g., concrete, asphaltic membrane, gunite, and soil). By analogy with ohms law, resistances in series are additive and the total resistance factor is the sum of the individual resistances. This technique of adding diffusional resistances is discussed in *Model Specifications for Protective Coatings for Concrete* (Hong Kong Government Civil Engineering Department 1994) and in previous Hanford Site work (Meacham et al. 2003). The diffusion flux equation may be written in terms of a resistance factor:

$$Q = \frac{D_e \Delta C}{\Delta X} = \frac{\Delta C}{R} \tag{3-3a}$$

Where R = resistance factor, $\Delta X/D_e$, sec/cm

Ambient hydrogen concentration in air is negligible when compared to the hypothetical SST headspace, so ΔC would simply be the steady-state hydrogen headspace concentration, C_g. Through conservation of mass and assuming hydrogen loss is through diffusion alone, the hydrogen generation rate is equal to the diffusion rate:

$$HGR = C_g \sum^{i} \frac{A_i}{R_i} \tag{3-4}$$

and the equilibrium hydrogen concentration is given by:

$$C_g = \frac{HGR}{\sum^{i} \frac{A_i}{R_i}} \tag{3-4a}$$

Where C_g = steady-state headspace hydrogen concentration
A_i = a specific barrier surface area
R_i = total resistance factor associated with barrier surface area A_i

4.0 INPUT DATA

4.1 SST DOME CONFIGURATIONS

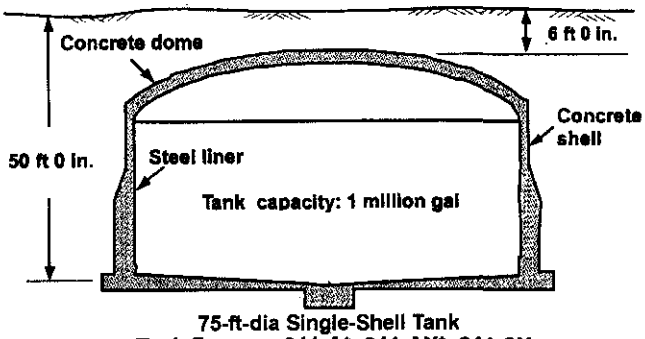
There are five tank farms containing 530,000-gallon tanks. Four of the five tank farms have tanks constructed from the same drawings (the 100 Series B, C, T, and U). Typical SST configurations are shown in Figure 4-1. The B, C, T, and U farm tanks were constructed in 1943 through 1944 while the BX-Farm tanks were constructed in 1947 and 1948. The 530,000-gallon tanks are geometrically the same and have the same material properties with minor differences in reinforcing steel arrangements and liner construction.

There are four tank farms containing 758,000-gallon tanks. The TX-Farm tanks were constructed in 1947 through 1948 followed by construction of the BY-Farm tanks in 1948 through 1949. Specifications for the S-Farm tanks were issued in November 1949, and the construction drawings were issued "as-built" in November 1951. Specifications for the TY-Farm tanks were issued in March 1951, and the design drawings were signed off "as-built" in June 1952. The 758,000-gallon tanks are geometrically identical, and have the same material properties with minor differences in reinforcing steel arrangements.

There are three tank farms containing 1-million-gallon tanks. Specifications for the SX Tank Farm were issued in May 1953, and the design drawings were signed off "as-built" in November 1954. Specifications for the A Tank Farm were issued in October 1953, and the construction drawings were issued "as-built" in April 1956. Specifications for the AX Tank Farm were issued in May 1963, and the construction drawings were issued "as-built" in February 1965. The 1 million-gallon tanks are geometrically similar with the exception of the basemats and foundations and have the same material properties with minor differences in concrete strength and reinforcing steel arrangements.

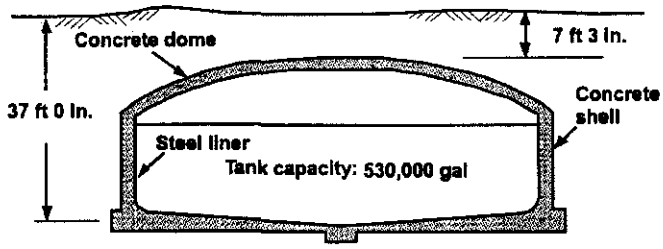
There are four tank farms containing 55,000-gallon tanks. All four of the farms (the 200 Series B, C, T, and U) contain tanks constructed from the same drawings. The B, C, T, and U-Farm tanks were constructed in 1943 through 1944.

Figure 4-1. Typical Configurations of Single-Shell Tanks at the Hanford Site.

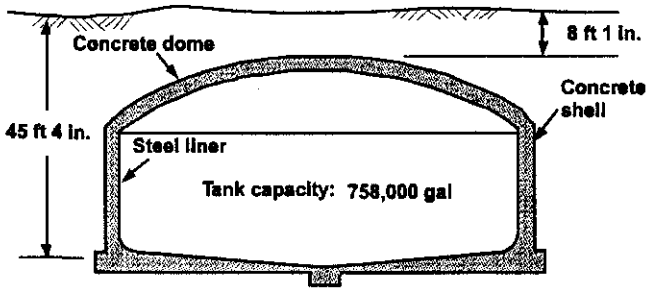


75-ft-dia Single-Shell Tank
Tank Farms: 241-A*, 241-AX*, 241-SX

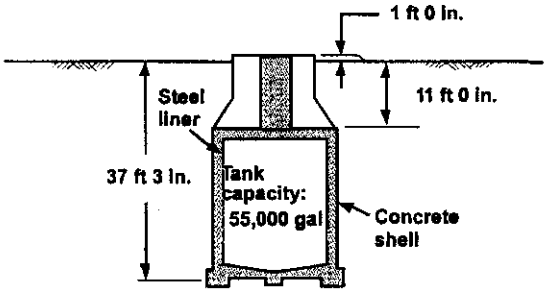
*A and AX have flat bottoms



75-ft-dia Single-Shell Tank
Tank Farms: 241-B, 241-BX, 241-C, 241-T, 241-U



75-ft-dia Single-Shell Tank
Tank Farms: 241-BY, 241-S, 241-TX, 241-TY



20-ft-dia Single-Shell Tank
Tank Farms: 241-B, 241-C, 241-T, 241-U

4.1.1 Single-Shell Tank Dome Diffusional Surface Area

4.1.1.1 A, AX, and SX Tank Dome Surface Area

The 100 Series SSTs have a radius of 37.5 ft (1143 cm), and the domes are approximately 12 ft (366 cm) high from the crown to the tank liner. The radius of curvature varies with height causing the dome to have an elliptical shape; however, the dome surface area can be approximated as a circular dome (see Figure 4-2). The surface area of a circular dome is given by (*CRC Standard Mathematical Tables*, Beyer 1981):

$$S = \pi\left(r^2 + h^2\right) \tag{4-1}$$

Where S = dome surface area (cm^2)
h = dome height (cm)
r = radius from centerline (cm)

Substituting in the values above, the interior surface area of the dome is:

$$S = \pi\left[(1143\text{ cm})^2 + (366\text{ cm})^2\right] = 4.53 \times 10^6\,\text{cm}^2$$

The A-Farm tanks have rectangular 11 ft (335 cm) by 14 ft (427 cm) concrete central pump pits that attach to the top of the dome (H-2-55911, *Waste Storage Tank Composite Section PUREX Waste Disposal Facility*). For simplification, diffusion is assumed not to occur across this area. The tanks also have several risers that penetrate the tank dome, and concrete pits that do not attach to the tank dome. These risers and pits are judged not to significantly affect hydrogen diffusion. The available surface area (S_A) for diffusion is:

$$S_A = 4.53 \times 10^6 - [(335)(427)] = 4.39 \times 10^6\,\text{cm}^2$$

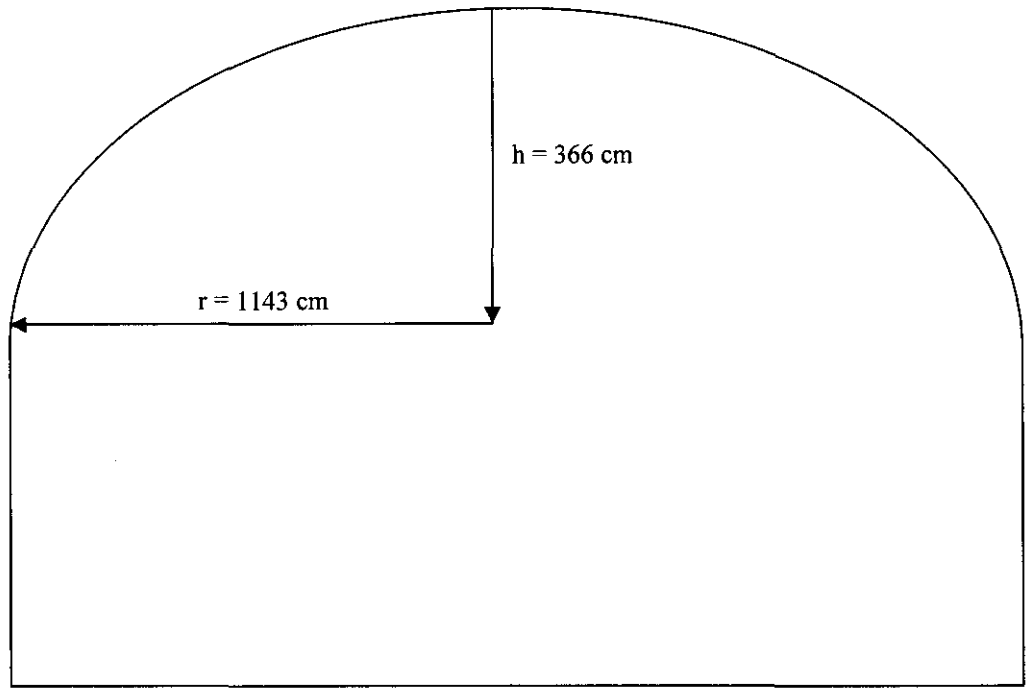
The AX and SX-Farm tanks have different riser and pit configurations, but the A-Farm tanks have the largest concrete pit that directly connects to a tank. A conservative surface area of 4.39×10^6 cm^2 will be used for the AX and SX-Farm tank calculations.

4.1.1.2 B, BX, C, T, and U 100 Series Tank Dome Surface Area

The B, BX, C, T, and U 100 Series tanks have rectangular central pits that are approximately 12 ft (366 cm) by 9 ft (274 cm). The pits do not appear to connect to the top of the tanks, but to simplify the calculation, diffusion is assumed not to occur across this area. The tanks also have several risers that penetrate the tank dome, and other concrete pits. These risers and pits are judged not to significantly affect hydrogen diffusion. The available surface area is:

$$S_A = 4.53 \times 10^6 - [(366)(274)] = 4.43 \times 10^6\,\text{cm}^2$$

Figure 4-2. Dome Surface Area Calculation.



4.1.1.3 BY, S, TX, and TY Tank Dome Surface Area

The BY, S, TX, and TY tanks have central pits of which the largest is approximately 14.5 ft (442 cm) by 11 ft (335 cm). To simplify the calculation, diffusion is assumed not to occur across this area. The tanks also have several risers that penetrate the tank dome, and other concrete pits. These risers and pits are judged not to significantly affect hydrogen diffusion. The available surface area for diffusion is:

$$S_A = 4.53 \text{ x } 10^6 - [(442)(335)] = 4.38 \text{ x } 10^6 \text{cm}^2$$

4.1.1.4 B, C, T, and U 200 Series Tank Dome Surface Area

The B, C, T, and U-Farm 200-series tanks are 20 ft (610 cm) in diameter. A 1.0 ft thick flat plate forms the roof of the tank as shown in Figure 4-1. This roof is strengthened by the integral condenser hatchway trunk structures on top of the roof that extend to the surface. The walls of the hatchways form deep beams with a height of 12 ft spanning the 20-ft diameter tank. Because the roofs are flat, the surface area is:

$$S = \pi\,(305 \text{ cm})^2 = 2.92 \text{ x } 10^5 \text{cm}^2$$

However, the concrete condenser hatch way trunk structures cover just under half of this surface. Diffusion would follow the path of least resistance, suggesting that only half the roof surface area (i.e., 1.46×10^5 cm^2) should be used in the diffusion calculation.

4.1.2 SST Dome Coatings

Tank farms differ with respect to the effort made to providing dome waterproofing (*Single-Shell Tank System Integrity Assessment Report*, Rifaey 2002). A-Farm has a 2-ply asphaltic membrane applied to the top (H-2-55911). AX Farm shows no waterproofing (H-2-44562, *Structural Waste Storage Tanks Composite Section & Details*). BX-Farm shows a 3-ply asphaltic membrane covered with ¾-inch thick cement mortar (H-2-602, *Composite Tank Typical Details Concrete 241-BX*). The B, C, T, and U Farms have the same coatings as BX-Farm. SX-Farm shows no coatings (H-2-39511, *75 Ft. Storage Tanks Composite Section Waste Disposal Facility 241-SX*). S, BY, TX, and TY-Farms show the greatest effort with an internal coating of Lapidolith® surface treatment (a concrete hardener containing magnesium zinc fluorosilicate), and an exterior coating of ⅜-inch thick 3-ply asphaltic membrane covered by a ¾-inch layer of gunite (H-2-1783, *75 Foot Composite Storage Tank Sections*). The B, C, T, and U 200 Series tanks show a Lapidolith® interior coating and exterior coatings of ⅜-inch 3-ply asphaltic membrane covered by ¾-inch layer of mortar/gunite on flat surfaces and ½-inch layer of mortar/gunite on vertical surfaces. Dome coatings for the respective tank farms are summarized in Table 4-1.

Table 4-1. Single-Shell Tank Dome Coatings

Tank Farm	Coatings
A	No interior coating shown, exterior coating of ¼-inch thick 2-ply asphaltic membrane
AX	No coatings shown
B, BX, C, T, and U	No interior coating shown, exterior coatings of ⅜-inch thick 3-ply asphaltic membrane covered with ¾-inch thick cement mortar
BY, S, TX, and TY	Lapidolith® interior coating, exterior coatings of ⅜-inch thick 3-ply asphaltic membrane covered by a ¾-inch layer of gunite
SX	Lapidolith® interior coating, no exterior coatings shown
B, C, T, and U 200 Series	Lapidolith® interior coating, exterior coating of ⅜-inch thick 3-ply asphaltic membrane covered by ¾-inch layer of mortar/gunite on flat surfaces and ½-inch layer of mortar/gunite on vertical surfaces

4.2 CONCRETE EFFECTIVE DIFFUSIVITY

4.2.1 Diffusion Mechanisms

Concrete is a porous material through which gas flows under a pressure gradient. In the scenario presented here, there is no pressure gradient within the concrete to cause a bulk gas flow. Concentration gradients across the concrete barrier cause hydrogen to diffuse through the channels of connected porosity. The key problem here is to quantify how rapidly hydrogen can diffuse through the pores.

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Diffusion of gases through concrete has been the subject of a number of studies. Among the papers reviewed in this work are "Transport of Gases in Concrete Barriers" (Harris et al. 1992), "Transport of Oxygen through Concrete" (Lawrence 1984), "Laboratory Measurements of the Transport of Radon Gas Through Concrete Samples" (Renken and Rosenburg 1995), "Diffusion of Methane Through Concrete" (Chou Chen and Katz 1978), "Oxygen Diffusivity of Various Cementitious Materials" (Kobayashi and Shuttoh 1991), "Transport of Gases Through Concrete" (Atkinson et al. 1989), "Influence of Porosity and Water Content on the Diffusivity of CO_2 and O_2 Through Hydrated Cement Paste" (Houst and Wittmann 1994), and "In-Situ Determination of the Diffusion Coefficient of ^{222}Rn in Concrete" (Gadd and Borak 1995).

Three mechanisms have been identified for the diffusion of gases through concrete, and these are briefly described here. A more in-depth discussion of the three mechanisms is given by Lawrence (1984).

Ordinary gas diffusion - In this case, the mean free path of molecules is small compared to the dimensions of the open pore. Most molecular collisions occur between gas molecules so the diffusion process is the same as in a stagnant gas phase. Ordinary gas diffusivity is applicable, with account taken for fractional porosity (connected open spaces in the solid) and tortuosity of the concrete. A tortuosity factor is discussed later in this report.

Knudsen diffusion - In this case pore dimensions are small compared to the mean free path and most gas molecular collisions occur with the wall of the pore. Knudsen diffusion rates are predictable from the kinetic theory of gases.

Surface diffusion - In this case gas molecules are sorbed by the walls and are transported by solid-state diffusion. This mode of transport is quite slow, and based on the observed relative high effective diffusivity of gases through concrete, it is concluded that the surface mode of transport is negligible compared to ordinary gas diffusion.

Analyses of diffusion of oxygen through concrete led both Lawrence (1984) and Houst and Wittmann (1994) to conclude that ordinary diffusion was the dominant mechanism. The same should hold true for hydrogen because the mean free path of hydrogen in dilute H_2/air gas mixtures is not very different from the mean free path of oxygen molecules.

For transport in porous materials in which normal diffusion is the dominant mechanism, the effective diffusivity of a gas is related to its diffusivity as follows (Sherwood et al. 1975):

$$D_e = D\frac{\varepsilon}{\tau} \tag{4-2}$$

Where
D_e = effective diffusivity in porous solid, cm^2/sec
D = diffusivity in free gas phase, cm^2/sec
ε = fractional porosity, dimensionless
τ = tortuosity factor, dimensionless

The factor ε/τ is mainly a property of the porous solid, and may be calculated from measurements of D_e and known values of D for the test gas. Once values of ε/τ are known, D_e may be estimated for any other gas of interest (assuming mean free path is roughly the same) based on D for that gas and the applicable value of ε/τ.

4.2.2 Parameters Affecting Concrete Effective Diffusivity

Hanford Site tank farm concrete is judged to be made with a typical industrial standard water to cement volume ratio of 0.5. Concrete permeability increases as it ages, and rebar and construction joints also increase permeability. A few publications that bear on these factors are discussed below.

"Long Term Changes of Air Permeability by Rapid Test" (Kasai et al. 1986) measured changes in air permeability of concrete columns with time. A relatively rapid increase in permeability was observed during the first four months, with a continuing slower increase up to a total age of 30 months. Air permeability increased by factors of approximately three to six depending on water to cement ratio. Permeability increased most for concretes having the higher (0.65) water to cement ratios and least for concretes with the lower (0.45) water to cement ratios. The maximum age studied (30 months) is small compared to the age of Hanford Site SSTs, and it is likely that age-related increases in permeability would be greater than those observed by Kasai et al. (1986).

The presence of reinforcement bars increased permeability of dry concrete by a factor of between three and four as compared to the same concrete without rebar. These laboratory results were reported in "Transport of Gases in Concrete Barriers" (Harris et al. 1992). Because the magnitudes of effective diffusivity and permeability are closely related, the effective diffusivity of gases would probably increase by similar factors. Harris et al. (1992) also measured permeabilities in a grout containing a construction joint. Permeability in the sample having the construction joint increased by factors of three to ten depending on the relative humidity in the test. The dry test showed the largest (factor of ten) increase in permeability.

The increases in effective diffusivity from aging, cracking, reinforcing bars, and construction joints should apply to SST concrete domes.

4.2.3 Concrete Effective Diffusivity Estimate

Renken and Rosenberg (1995) measured the diffusivity of radon through concrete samples of three different mixes. Mix A was formulated to simulate typical basement slab mixes. Samples were kept superficially wet for three days after casting and then allowed to air cure in a basement for at least 60 days. Water to cement ratio for Mix A was 0.50. The diffusion tests were conducted with radon and apparently carried out at room (~20 °C) temperature. For Mix A, the effective diffusivity was reported as 4.96×10^{-4} cm^2/sec. Similar experiments conducted by Maas (1997) reported an average effective diffusivity of 2.83×10^{-4} cm^2/sec for concrete batches made with a water to cement ratio of 0.51. The average effective diffusivity from these two studies was 3.90×10^{-4} cm^2/sec. Tests were performed on concrete samples that had no rebar, no

construction joints, and were cured for only 60 days. This ε/τ value is most likely one to two orders of magnitude less than the actual value for the 50+ year old SST concrete domes that have rebar, construction joints, and have likely experienced age-related cracking.

A value of ε/τ may be calculated by dividing the effective diffusivity by the normal gas phase diffusivity of radon. The diffusivity of radon at room temperature is reported in "Multiphase Radon Generation and Transport in Porous Materials" (Rogers and Nielson 1991) to be 0.11 cm^2/sec. From a rearrangement of Equation 4-2, ε/τ is computed to be:

$$\varepsilon/\tau = \frac{D_e}{D} = \frac{3.90 \times 10^{-4}}{0.11} = 3.55 \times 10^{-3}$$

The effective diffusivity for hydrogen in concrete can be calculated from the ε/τ value and the diffusivity of hydrogen in air, which is 0.611 cm^2/sec at 0 °C (Perry et al. 1984) and about 0.66 cm^2/sec at the average Hanford Site ambient temperature of 13.5 °C:

$$D_e = (0.66\ cm^2/sec)\ (3.55 \times 10^{-3}) = 2.34 \times 10^{-3}\ cm^2/sec$$

Two other samples tested by Renken and Rosenberg (1995) yielded higher diffusivities but were not used because mix formulations are atypical concrete. Mix B used a water to cement ratio of 1.0 and included fly ash as a solid component in place of cement. This formulation yielded a concrete that did not solidify properly and was considered by Renken and Rosenburg (1995) only as an unconventional concrete comparison. Mix C used a water to cement ratio of 0.65, which is higher than normally used to produce concrete having a nominal compressive strength of 3,000 psi. The higher diffusivity for Mix C is consistent with the higher water/cement ratio.

Two concrete samples taken from a tunnel wall (age of concrete was not stated) were tested by Chou Chen and Katz (1978). The diffusivity of methane in nitrogen was measured in a test cell under dry and wet conditions. Although details of mix formulation, curing conditions, and age were not available (compressive strength was given as 3,000 psi which is identical to the SST dome design specifications), it seems likely that the tunnel wall would be similar to specifications for Hanford Site SST tank domes. The concrete was probably a number of years old, and age related cracking might have occurred as is expected for the SST domes. The samples did not contain rebar or construction joints. For these reasons, the tests provide a conservative method for deriving an effective diffusivity for the SST concrete domes.

Measured effective diffusivities of methane in nitrogen were reported by Chou Chen and Katz (1978) as 3.08×10^{-3} cm^2/sec and 1.28×10^{-3} cm^2/sec for two samples of tunnel wall concrete. The gas phase diffusivity of methane in nitrogen was estimated from a correlating equation (Sherwood et al. 1975) to be 0.22 cm^2/sec at 25 °C. Values for ε/τ are $3.08 \times 10^{-3}/0.22 = 0.014$ and $1.28 \times 10^{-3}/0.22 = 0.00582$, respectively. The corresponding effective diffusivities for hydrogen would be:

$$D_e = (0.66\ cm^2/sec)\ (0.014) = 9.2 \times 10^{-3}\ cm^2/sec$$

and

$$D_e = (0.66\ cm^2/sec)\ (0.00582) = 3.8 \times 10^{-3}\ cm^2/sec$$

The lower of these two values (3.8×10^{-3} cm^2/sec) is judged to be a conservative effective diffusivity for hydrogen diffusion through the SST concrete domes.

4.3 HARDENED CONCRETE EFFECTIVE DIFFUSIVITY

Some interior tank dome surfaces were covered with Lapidolith®, a magnesium zinc fluorosilicate concrete hardener. Lipdolith® is a commercial concrete hardener that was first patented in 1913 and is still used today. The hardener penetrates the concrete surface to depth up to ⅛th-inch and reacts with the free lime to tightly bind the cement, sand, and aggregate particles, but does not form a film over the concrete surface. One of the benefits of Lapidolith® listed in the technical data ("Lapidolith Technical Data," ChemRex 2002) is that it produces a breathable surface. Therefore, Lapidolith® is judged to have a negligible effect on gaseous diffusion through the concrete.

4.4 ASPHALTIC MEMBRANE EFFECTIVE DIFFUSIVITY

An asphaltic membrane waterproofing was applied over the concrete dome on some SSTs. The asphaltic waterproofing was applied at a rate of 40 to 50 $lbf/100\ ft^2$ as a tack layer followed by three layers of impregnated cotton fabric with the same rate of asphalt applied between each layer and a final layer of asphalt at the same rate on top of the last fabric layer.

An estimate of the effective diffusivity of hydrogen through the membrane maybe made by assuming the membrane to be solid asphalt with no porosity. In reality, hot-mopping of the felts would be unlikely to completely fill all voids in the felts, and a residual non-zero porosity would remain after the built up roofing was completed. The existence of porosity would increase effective diffusivity as compared to the zero porosity case calculated here.

Data on hydrogen diffusion through solid asphalt are not available. However a fairly extensive study of oxygen diffusion through thin layers of asphalt has been reported in "The Measurement of Oxygen Transport Parameters for Asphalt/Aggregate and Asphalt/Glass Systems Using an Electrodynamic Balance" (Periasamy 1995). Periasamy (1995) coated small glass spheres with asphalt and studied the uptake of oxygen by the tar as a function of time by means of an electromagnetic balance. From the shape of the mass uptake transient, both oxygen solubility and diffusivity were measured in solid asphalt. The data on permeability are shown in Table 4-2.

Inspection of the permeability data listed in Table 4-2 shows that measured permeabilities vary significantly from run to run. For example, for runs one and two done with glass substrate, permeabilities are 13.0 and 59.1 barrer. The data differ by a factor of 59.1/13 = 4.55. Another feature of the permeability data is that there is little correlation with the test parameters of temperature, substrate material or asphalt type. The average of all 40 permeabilities is 31 barrer. An uncertainty band of a factor of two should be recognized in applying this mean value.

Table 4-2. Permeability of Asphalt to Oxygen.

Substrate Particle	Run No.	Asphalt Material	Temperature (°C)	Permeability (barrer)[1]
glass	1	AAB1	21	13.0
glass	2	AAB1	22	59.1
glass	3	AAG1	21	31.6
glass	4	AAG1	21	8.23
glass	5	AAG1	21	7.48
glass	6	AAG1	21	8.11
glass	7	AAG1	40	4.45
glass	8	AAG1	40	19.3
glass	9	AAG1	61	12.1
glass	10	AAG1	61	38.7
glass	11	AAG1	61	39.8
glass	12	AAG1	61	6.33
glass	13	AAK1	21	7.01
glass	14	AAK1	21	40.0
glass	15	AAK1	21	2.32
glass	16	AAK1	40	2.23
glass	17	AAK1	40	67.3
glass	18	AAK1	40	7.0
glass	19	AAK1	60	13.1
glass	20	AAK1	61	12.8
glass	21	AAK1	61	2.59
aggregate	1	AAB1	21	56.9
aggregate	2	AAB1	21	64.4
aggregate	3	AAB1	21	28.1
aggregate	4	AAB1	21	36.6
aggregate	5	AAB1	22	53.4
aggregate	6	AAG1	24	22.7
aggregate	7	AAG1	23	5.87
aggregate	8	AAG1	40	33.7
aggregate	9	AAG1	41	13.3
aggregate	10	AAG1	60	21.3
aggregate	11	AAG1	61	86.9
aggregate	12	AAK1	21	15.1
aggregate	13	AAK1	22	13.2
aggregate	14	AAK1	24	195
aggregate	15	AAK1	40	9.9
aggregate	16	AAK1	41	56.1
aggregate	17	AAK1	59	20.5
aggregate	18	AAK1	59	52.2
aggregate	19	AAK1	60	46.4

Note: [1]barrer = 10^{-10} [cm^3(STP) cm]/(cm^2 sec cm Hg)

Periasamy, R., 1995, "The Measurement of Oxygen Transport Parameters for Asphalt/Aggregate and Asphalt/ Glass Systems Using an Electrodynamic Balance," *Fuel Science and Technology Int'l.*, 13(6), pp. 699-711.

To convert permeability in barrer to effective diffusivity in cm^2 /sec, multiply by 0.76×10^{-8} cm^2/sec-barrer:

$$31 \text{ barrer} \times 0.76 \times 10^{-8} \text{ cm}^2 / \text{sec barrer} = 2.4 \times 10^{-7} \text{ cm}^2 / \text{sec}.$$

This effective diffusivity, 2.4 x 10^{-7} cm^2/sec, applies to oxygen. Based on experimental data on hydrogen and oxygen permeabilities in a number of solid polymers, the ratio of hydrogen to oxygen permeability is estimated to be 4.14. The data on which the H_2:O_2 permeability ratio is based is summarized in Meacham et al. (2003) and the technical basis for applying the ratio is presented in *Diffusion in Polymers* (Crank and Park 1968). Using the permeability ratio of 4.14, the best estimate for the effective diffusivity of hydrogen in a solid asphaltic membrane is:

$$D_e = 4.14\ (2.4 \times 10^{-7}\ cm^2 / sec) = 9.9 \times 10^{-7} cm^2 / sec.$$

As noted above, an uncertainty band of a factor of two should be applied so a conservative value of 5.0 x 10^{-7} cm^2/sec will be used in the diffusion calculation.

4.5 MORTAR/GUNITE EFFECTIVE DIFFUSIVITY

A protective finish of mortar or gunite was often applied over the asphaltic membrane to prevent mechanical damage during backfill. B, BX, C, T, and U Farms construction specifications called for ¾-inch Portland cement grout reinforced with chicken wire over the entire surface of the membrane waterproofing. Mortar is a cement paste mixed with sand and has typical water to cement ratios of 0.45 to 0.55. The cement to aggregate ratio is greater than that for concrete, and therefore, the permeability would be greater than for concrete. Experiments show that mortar porosity was more than twice that of air cured concrete (*Transport in Brick, Stone and Concrete*, Hall and Hoff 2002). This is because the main pores and capillaries in concrete exist in the cement paste and not the aggregates. Therefore, the effective diffusivity of hydrogen through mortar should be greater than that of concrete. The galvanized wire mesh would offer little diffusion resistance because it is mostly open area.

Gunite is a mortar or concrete pneumatically projected at high velocity onto surfaces. It consists primarily of Portland cement and aggregate. Dry cement mixture is forced through a nozzle with compressed air where it mixes with water and is blown onto a wire frame. Specifications called for a ¾-inch layer on gunite over the asphaltic membranes in BY, S, TX, and TY-Farms.

Gunite would have an even greater porosity than mortar, because of the application method. The mortar/gunite layers are assumed to have the same effective diffusivity as the concrete, 3.8 x 10^{-3} cm^2/sec.

4.6 SOIL EFFECTIVE DIFFUSIVITY

The SSTs are buried in the ground at the Hanford Site. Therefore, hydrogen diffusing through the domes would encounter soil overburden as a final diffusion barrier. Pores in Hanford Site soils are expected to be large in size compared to the mean free path of gas molecules; therefore, ordinary gas diffusion in a porous medium would be the controlling phenomenon. The porosity and tortuosity of soil overburden has been estimated from diffusion measurements reported in "Binary Gas Diffusion of Methane-Nitrogen through Porous Solids" (Chen et al. 1997).

The binary gas diffusion of methane-nitrogen mixtures through a number of porous solids was measured. Two of the test cells used finely divided materials (fine glass beads and sand) that are judged to be representative of Hanford Site soils. Data from the two test cells are summarized in Table 4-3.

Table 4-3. Diffusivity of Methane/Nitrogen in Finely Divided Granular Solids.

Material	Effective Diffusivity at 35 °C, cm^2 /sec	Porosity
Fine Glass Beads	0.0592	0.374
Sand	0.0685	0.371

Note: Chen, L. L., D. L. Katz and M. R. Tek, 1997, "Binary Gas Diffusion of Methane-Nitrogen Through Porous Solids," *AIChE Journal*, Vol. 23, No. 3, pp. 336-341.

The data of Table 4-3 may be used to compute a tortuosity factor. Rearranging Equation 4-2, τ is calculated from D_e and ε:

$$\tau = \frac{D\,\varepsilon}{D_e} \tag{4-2a}$$

The binary diffusivity of methane/nitrogen gas is estimated from a correlating equation, Sherwood et al. (1975), to be 0.257 cm^2/sec. Thus, for glass beads, τ is computed to be:

$$\tau = \frac{0.257(0.374)}{0.0592} = 1.62$$

For sand, τ is computed to be:

$$\tau = \frac{0.257(0.371)}{0.0685} = 1.39$$

These data are applied to soil overburden based on engineering judgment that 20% of the open pore space is occupied by water (to account for rainfall at the Hanford Site). The reduced porosities are thus 0.8 (0.374) = 0.299, and 0.8 (0.371) = 0.297. Using these values, ε/τ values for the two sample materials are computed to be 0.299/1.62 = 0.185 and 0.297/1.39 = 0.214, respectively. The corresponding effective diffusivities are 0.185 x 0.66 = 0.12 cm^2/sec, and 0.214 x 0.66 = 0.14 cm^2/sec. The lower of these two values, 0.12 cm^2/sec, was selected for the report calculations.

4.7 FLAMMABLE GAS GENERATION RATES

Hydrogen generation rate estimates for the 149 SSTs are shown in Table 4-4. Values are from Hu and Barker (2003).

Table 4-4. Hydrogen Generation Rate Estimates for the 149 Single-Shell Tanks.

Tank	HGR liters/day	Tank	HGR liters/day	Tank	HGR liters/day
A-101	177	C-101	28	T-108	22
A-102	24	C-102	36	T-109	24
A-103	114	C-103	94	T-110	37
A-104	168	C-104	51	T-111	38
A-105	0	C-105	35	T-112	24
A-106	77	C-106	39	T-201	6
AX-101	81	C-107	56	T-202	4
AX-102	35	C-108	25	T-203	6
AX-103	117	C-109	27	T-204	6
AX-104	27	C-110	28	TX-101	29
B-101	32	C-111	30	TX-102	32
B-102	23	C-112	35	TX-103	28
B-103	24	C-201	2	TX-104	25
B-104	35	C-202	2	TX-105	47
B-105	31	C-203	2	TX-106	40
B-106	26	C-204	2	TX-107	23
B-107	28	S-101	62	TX-108	27
B-108	25	S-102	50	TX-109	42
B-109	27	S-103	36	TX-110	40
B-110	32	S-104	37	TX-111	36
B-111	37	S-105	37	TX-112	46
B-112	23	S-106	41	TX-113	45
B-201	5	S-107	38	TX-114	40
B-202	5	S-108	42	TX-115	42
B-203	8	S-109	41	TX-116	42
B-204	8	S-110	43	TX-117	38
BX-101	25	S-111	44	TX-118	35
BX-102	27	S-112	45	TY-101	26
BX-103	27	SX-101	80	TY-102	24
BX-104	27	SX-102	88	TY-103	32
BX-105	24	SX-103	334	TY-104	23
BX-106	23	SX-104	87	TY-105	31
BX-107	34	SX-105	185	TY-106	22
BX-108	23	SX-106	50	U-101	23
BX-109	30	SX-107	33	U-102	56
BX-110	31	SX-108	36	U-103	64
BX-111	28	SX-109	86	U-104	34
BX-112	27	SX-110	31	U-105	60
BY-101	43	SX-111	37	U-106	61
BY-102	32	SX-112	29	U-107	40
BY-103	38	SX-113	23	U-108	55
BY-104	49	SX-114	39	U-109	45
BY-105	48	SX-115	23	U-110	30
BY-106	54	T-101	27	U-111	37
BY-107	53	T-102	22	U-112	24
BY-108	35	T-103	23	U-201	2
BY-109	32	T-104	33	U-202	2
BY-110	60	T-105	25	U-203	2
BY-111	33	T-106	22	U-204	2
BY-112	32	T-107	28	--	--

Note: NA = Not Available, no HGR calculation for tank A-105 was possible.
Hu, T.A., and S.A. Barker, 2003, *Steady-State Flammable Gas Release Rate Calculation and Lower Flammability Level Evaluation for Hanford Tank Waste*, RPP-5926, Rev. 3, CH2M HILL Hanford Group, Inc., Richland, Washington.

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5.0 ANALYSIS RESULTS

This section presents analysis results by tank farm. Where the HGR was lower than that necessary to keep concentrations below the LFL, an equilibrium concentration is calculated.

5.1 A-FARM TANKS

The A-Farm tanks have a ¼-inch thick 2-ply asphaltic membrane over the concrete dome. The diffusional resistances come from the concrete dome, asphaltic membrane, and soil.

5.1.1 Concrete Resistance

The concrete effective diffusivity is 3.8×10^{-3} cm^2/sec and the thickness is 1 ft 3 inches (38 cm). The resistance term is then:

$$R_{Concrete} = \frac{38\ cm}{3.8 \times 10^{-3}\ cm^2/sec} = 10000\ sec/cm$$

5.1.2 2-Ply Asphaltic Membrane Resistance

The 2-ply asphaltic membrane is ¼-inch (0.635 cm) thick and has an effective diffusivity of 5.0×10^{-7} cm^2/sec. The resistance term is then:

$$R_{2-Ply} = \frac{0.635\ cm}{5.0 \times 10^{-7}\ cm^2/sec} = 1.27 \times 10^6\ sec/cm$$

5.1.3 Soil Resistance

The soil overburden effective diffusivity is 0.12 cm^2/sec. The soil layer thickness varies from 6 ft at the dome crest to about 18 ft where the dome meets the sidewall. An average soil depth of 12 ft (366 cm) will be used in the calculation. The resistance term is then:

$$R_{Soil} = \frac{366\ cm}{0.12\ cm^2/sec} = 3050\ sec/cm$$

5.1.4 Maximum Diffusible Hydrogen

Setting the gas concentration to a 0.04 volume fraction, the maximum diffusible HGR is given by Equation 3-4:

$$\left(\frac{0.04\ liter\ H_2}{1000\ cm^3}\right)\left(\frac{4.39 \times 10^6\ cm^2}{10000 + 1.27 \times 10^6 + 3050\ sec/cm}\right)\left(\frac{86400\ sec}{1\ day}\right) = 12\ liter\ H_2/day$$

From Table 4-4, all of the A Farm tanks except for tank 241-A-105 (which does not have an estimated HGR) have a HGR greater than 12 liters/day.

5.2 AX-FARM TANKS

The AX-Farm has no coatings on the concrete dome, and the diffusional resistance comes from the dome and overlying soil.

5.2.1 Concrete Resistance

The concrete effective diffusivity is 3.8 x 10^{-3} cm^2/sec, and the thickness is 1 ft 3 inches (38 cm). The resistance term is then:

$$R_{Concrete} = \frac{38\ \text{cm}}{3.8 \times 10^{-3}\ \text{cm}^2/\text{sec}} = 10000\ \text{sec/cm}$$

5.2.2 Soil Resistance

The soil overburden effective diffusivity is 0.12 cm^2/sec. The soil layer thickness varies from about 6 ft at the dome crest to about 18 ft where the dome meets the sidewall. An average soil depth of 12 ft (366 cm) will be used in the calculation. The resistance term is then:

$$R_{Soil} = \frac{366\ \text{cm}}{0.12\ \text{cm}^2/\text{sec}} = 3050\ \text{sec/cm}$$

5.2.3 Maximum Diffusible Hydrogen and Equilibrium Concentrations

Setting the allowable gas concentration to a 0.04 volume fraction, the maximum diffusible HGR is give by Equation 3-4:

$$\left(\frac{0.04\ \text{liter}\ H_2}{1000\ \text{cm}^3}\right)\left(\frac{4.39 \times 10^6\ \text{cm}^2}{10000 + 3050\ \text{sec/cm}}\right)\left(\frac{86400\ \text{sec}}{1\ \text{day}}\right) = 1160\ \text{liter}\ H_2/\text{day}$$

The HGR would have to be less than 1160 liters/day to have a steady-state equilibrium concentration below the LFL. From Table 4-4, all of the AX tanks have an HGR less than 1160 liters/day. Table 5-1 shows the steady-state equilibrium hydrogen concentration (calculated using Equation 3-4a) at the HGR shown in Table 4-3 for a hypothetically sealed AX-Farm tank.

Table 5-1. Equilibrium Hydrogen Concentration in Hypothetically Sealed AX Farm Tanks.

Tank	HGR[1] (liters/day)	Equilibrium Concentration (% of LFL)
AX-101	81	7.0
AX-102	35	3.0
AX-103	117	10
AX-104	27	2.3

Notes [1] Hu, T.A., and S.A. Barker, 2003, *Steady-State Flammable Gas Release Rate Calculation and Lower Flammability Level Evaluation for Hanford Tank Waste*, RPP-5926, Rev. 3, CH2M HILL Hanford Group, Inc., Richland, Washington.

5.3 B, BX, C, T, AND U 100 SERIES TANKS

The B, BX, C, T, and U-Farm tanks have a ⅜-inch thick 3-ply asphaltic membrane and a ¾-inch thick layer of cement mortar over the concrete dome. The diffusional resistances come from the concrete dome, asphaltic membrane, mortar, and soil.

5.3.1 Concrete Resistance

The concrete effective diffusivity is 3.8×10^{-3} cm^2/sec, and the thickness is 1 ft 3 inches (38 cm). The resistance term is then:

$$R_{Concrete} = \frac{38 \text{ cm}}{3.8 \times 10^{-3} \text{ cm}^2 / \text{sec}} = 10000 \text{ sec/cm}$$

5.3.2 3-Ply Asphaltic Membrane Resistance

The 3-ply asphaltic membrane is ⅜-inch (0.9525 cm) thick and has an effective diffusivity of 5.0×10^{-7} cm^2/sec. The resistance term is then:

$$R_{3\text{-Ply}} = \frac{0.9525 \text{ cm}}{5.0 \times 10^{-7} \text{ cm}^2 / \text{sec}} = 1.90 \times 10^{6} \text{ sec/cm}$$

5.3.3 Mortar Resistance

Mortar is assumed to have the same effective diffusivity as the concrete, 3.8×10^{-3} cm^2/sec. Drawing specifications give the mortar thickness as ¾-inch (1.905 cm). The resistance term is then:

$$R_{Mortar} = \frac{1.905 \text{ cm}}{3.8 \times 10^{-3} \text{ cm}^2 / \text{sec}} = 500 \text{ sec/cm}$$

5.3.4 Soil Resistance

The soil overburden effective diffusivity is 0.12 cm^2/sec. The soil layer thickness varies from about 7.25 ft at the dome crest to about 19.25 ft where the dome meets the sidewall. An average soil depth of 13.25 ft (404 cm) will be used in the calculation. The resistance term is then:

$$R_{Soil} = \frac{404\ \text{cm}}{0.12\ \text{cm}^2/\text{sec}} = 3370\ \text{sec/cm}$$

5.3.5 Maximum Diffusible Hydrogen

From Equation 3-4, the maximum diffusible HGR is:

$$\left(\frac{0.04\ \text{liter}\ H_2}{1000\ \text{cm}^3}\right)\left(\frac{4.43 \times 10^6\ \text{cm}^2}{10000 + 1.90 \times 10^6 + 500 + 3370\ \text{sec/cm}}\right)\left(\frac{86400\ \text{sec}}{1\ \text{day}}\right) = 8.0\ \text{liter}\ H_2/\text{day}$$

From Table 4-4, all of the B, BX, C, T, and U-Farm tanks have a HGR greater than 8.0 liters/day.

5.4 BY, S, TX, AND TY TANKS

The BY, S, TX, and TY-Farm tanks have a ⅜-inch thick 3-ply asphaltic membrane and a ¾-inch thick layer of gunite over the concrete dome. The diffusional resistances come from the concrete dome, asphaltic membrane, gunite, and soil.

5.4.1 Concrete Resistance

The concrete effective diffusivity is 3.8×10^{-3} cm^2/sec, and the thickness is 1 ft 3 inches (38 cm). The resistance term is then:

$$R_{Concrete} = \frac{38\ \text{cm}}{3.8 \times 10^{-3}\ \text{cm}^2/\text{sec}} = 10000\ \text{sec/cm}$$

5.4.2 3-Ply Asphaltic Membrane Resistance

The 3-ply asphaltic membrane is ⅜-inch (0.9525 cm) thick and has an effective diffusivity of 5.0×10^{-7} cm^2/sec. The resistance term is then:

$$R_{3\text{-}Ply} = \frac{0.9525\ \text{cm}}{5.0 \times 10^{-7}\ \text{cm}^2/\text{sec}} = 1.90 \times 10^6\ \text{sec/cm}$$

5.4.3 Gunite Resistance

Gunite is assumed to have the same effective diffusivity as the concrete, 3.8 x 10^{-3} cm^2/sec. Drawing specifications give the gunite thickness as ¾-inch (1.905 cm). The resistance term is then:

$$R_{Gunite} = \frac{1.905 \text{ cm}}{3.8 \times 10^{-3} \text{ cm}^2/\text{sec}} = 500 \text{ sec/cm}$$

5.4.4 Soil Resistance

The soil overburden effective diffusivity is 0.12 cm^2/sec. The soil layer thickness varies from about 8 ft at the dome crest to about 20 ft where the dome meets the sidewall. An average soil depth of 14 ft (427 cm) will be used in the calculation. The resistance term is then:

$$R_{Soil} = \frac{427 \text{ cm}}{0.12 \text{ cm}^2/\text{sec}} = 3560 \text{ sec/cm}$$

5.4.5 Maximum Diffusible Hydrogen

From Equation 3-4, the maximum diffusible HGR is:

$$\left(\frac{0.04 \text{ liter } H_2}{1000 \text{ cm}^3}\right)\left(\frac{4.38 \times 10^6 \text{cm}^2}{10000 + 1.90 \times 10^6 + 500 + 3560 \text{ sec/cm}}\right)\left(\frac{86400 \text{ sec}}{1 \text{ day}}\right) = 7.9 \text{ liter } H_2/\text{day}$$

The HGR would have to be less than 7.9 liters/day to have a steady-state equilibrium concentration below the LFL. From Table 4-4, all of the BY, S, TX, and TY tank wastes have an HGR greater than 7.9 liters/day.

5.5 SX-FARM TANKS

The SX-Farm has no exterior coatings on the concrete dome, but does have an interior coating of Lapidolith® hardener. From the discussions in Section 4.3, the concrete hardener would have a negligible effect on diffusional properties; therefore, the diffusional resistance comes from the dome and overlying soil.

5.5.1 Concrete Resistance

The concrete effective diffusivity is 3.8 x 10^{-3} cm^2/sec, and the thickness is 1 ft 3 inches (38 cm). The resistance term is then:

$$R_{Concrete} = \frac{38 \text{ cm}}{3.8 \times 10^{-3} \text{ cm}^2/\text{sec}} = 10000 \text{ sec/cm}$$

5.5.2 Soil Resistance

The soil overburden effective diffusivity is 0.12 cm^2/sec. The soil layer thickness varies from 6 ft at the dome crest to about 18 ft where the dome meets the sidewall. An average soil depth of 12 ft (366 cm) will be used in the calculation. The resistance term is then:

$$R_{Soil} = \frac{366\ \text{cm}}{0.12\ \text{cm}^2/\text{sec}} = 3050\ \text{sec/cm}$$

5.5.3 Maximum Diffusible Hydrogen and Equilibrium Concentrations

Setting the allowable gas concentration to a 0.04 volume fraction, the maximum diffusible HGR is give by Equation 3-4:

$$\left(\frac{0.04\ \text{liter}\ H_2}{1000\ \text{cm}^3}\right)\left(\frac{4.39 \times 10^6\ \text{cm}^2}{10000 + 3050\ \text{sec/cm}}\right)\left(\frac{86400\ \text{sec}}{1\ \text{day}}\right) = 1160\ \text{liter}\ H_2/\text{day}$$

The HGR would have to be less than 1160 liters/day to have a steady-state equilibrium concentration below the LFL. From Table 4-4, all of the SX tanks have an HGR less than 1160 liters/day. Table 5-2 shows the steady-state equilibrium hydrogen concentration (calculated using Equation 3-4a) at the HGR shown in Table 4-4 for a hypothetically sealed SX-Farm tank.

Table 5-2. Equilibrium Hydrogen Concentration in Hypothetically Sealed SX-Farm Tanks.

Tank	HGR[1] (liters/day)	Equilibrium Concentration (% of LFL)
SX-101	80	6.9
SX-102	88	7.6
SX-103	334	29
SX-104	87	7.5
SX-105	185	16
SX-106	50	4.3
SX-107	33	2.8
SX-108	36	3.1
SX-109	86	7.4
SX-110	31	2.7
SX-111	37	3.2
SX-112	29	2.5
SX-113	23	2.0
SX-114	39	3.4
SX-115	23	2.0

Notes: [1]Hu, T.A., and S.A. Barker, 2003, *Steady-State Flammable Gas Release Rate Calculation and Lower Flammability Level Evaluation for Hanford Tank Waste*, RPP-5926, Rev. 3, CH2M HILL Hanford Group, Inc., Richland, Washington.

5.6 B, C, T, AND U 200 SERIES TANKS

The B, C, T, and U-Farm 200 series tanks have a ⅜-inch thick 3-ply asphaltic membrane and a ¾-inch thick layer of cement mortar over the concrete dome. The diffusional resistances come from the concrete dome, asphaltic membrane, mortar, and soil.

5.6.1 Concrete Resistance

The concrete effective diffusivity is 3.8×10^{-3} cm^2/sec, and the thickness is 1 ft (30 cm). The resistance term is then:

$$R_{Concrete} = \frac{30\ cm}{3.8 \times 10^{-3}\ cm^2/sec} = 7900\ sec/cm$$

5.6.2 3-Ply Asphaltic Membrane Resistance

The 3-ply asphaltic membrane is ⅜-inch (0.9525 cm) thick and has an effective diffusivity of 5.0×10^{-7} cm^2/sec. The resistance term is then:

$$R_{3-Ply} = \frac{0.9525\ cm}{5.0 \times 10^{-7}\ cm^2/sec} = 1.90 \times 10^{6}\ sec/cm$$

5.6.3 Mortar Resistance

Mortar is assumed to have the same effective diffusivity as the concrete, 3.8×10^{-3} cm^2/sec. Drawing specifications give the thickness as ¾-inch (1.905 cm). The resistance term is then:

$$R_{Mortar} = \frac{1.905\ cm}{3.8 \times 10^{-3}\ cm^2/sec} = 500\ sec/cm$$

5.6.4 Soil Resistance

The soil overburden effective diffusivity is 0.12 cm^2/sec. The soil layer thickness is about 11 ft (335 cm). The resistance term is then:

$$R_{Soil} = \frac{335\ cm}{0.12\ cm^2/sec} = 2800\ sec/cm$$

5.6.5 Maximum Diffusible Hydrogen

From Equation 3-4, the maximum diffusible HGR is:

$$\left(\frac{0.04 \text{ liter } H_2}{1000 \text{ cm}^3}\right)\left(\frac{1.46 \text{ x } 10^5 \text{cm}^2}{7900 + 1.90 \text{ x } 10^6 + 500 + 2800 \text{ sec/ cm}}\right)\left(\frac{86400 \text{ sec}}{1 \text{ day}}\right) = 0.26 \text{ liter } H_2 / \text{day}$$

From Table 4-4, all of the B, C, T, and U-Farm 200 series tank wastes have a HGR greater than 0.26 liters/day.

6.0 CONCLUSIONS

Calculations show that the AX and SX-Farm SSTs do not require ventilation of any kind to keep flammable gas concentrations below the LFL. Hydrogen diffusion alone would be sufficient to keep headspace concentrations well below the LFL if the tanks were hypothetically sealed airtight.

The A, B, BX, BY, S, T, TX, TY, and U SST domes all have an asphaltic membrane covering that would reduce gaseous diffusion. About 7.9 liters of hydrogen per day in the 100 Series SSTs would put equilibrium hydrogen concentrations near the LFL if the only means of dissipating hydrogen were diffusion. The 200 Series SSTs domes have a relatively smaller diffusional surface area, and about 0.26 liters of hydrogen per day would put equilibrium hydrogen concentrations near the LFL.

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7.0 REFERENCES

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APPENDIX A

INDEPENDENT REVIEW

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Title: Peer Review of Inline Calcs for RPP-18491 REV. 0 Identifier: _____ Rev: 0

Originator: NOT APPLICABLE Date: _____

Checker: S. A. BARKER NA Date: _____

Calculation Review Checklist

Calculation Reviewed: RPP-18491 Rev. 0

Scope of Review: Complete document
(e.g., document section or portion of calculation)

Engineer/Analyst: J. E. Meacham J E Mea Date: 11/5/03

Organizational Mgr: NW KIRCH / NW Kirch Date: 11/5/03

Yes	No	NA*		
[X]	[ ]	[ ]	1.	Analytical and technical approaches and results are reasonable and appropriate.
[X]	[ ]	[ ]	2.	Necessary assumptions are reasonable, explicitly stated, and supported.
[ ]	[ ]	[X]	3.	Ensure calculations that use software include a paper printout, microfiche, CD ROM, or other electronic file of the input data and identification to the computer codes and versions used, or provide alternate documentation to uniquely and clearly identify the exact coding and execution process.
[X]	[ ]	[ ]	4.	Input data were checked for consistency with original source information.
[X]	[ ]	[ ]	5.	For both qualitative and quantitative data, uncertainties are recognized and discussed.
[X]	[ ]	[ ]	6.	Mathematical derivations were checked including dimensional consistency of results.
[X]	[ ]	[ ]	7.	Calculations are sufficiently detailed such that a technically qualified person can understand the analysis without requiring outside information.
[ ]	[ ]	[X]	8.	Software verification and validation are addressed adequately.
[X]	[ ]	[ ]	9.	Limits/criteria/guidelines applied to the analysis results are appropriate and referenced. Limits/criteria/guidelines were checked against references.
[X]	[ ]	[ ]	10.	Conclusions are consistent with analytical results and applicable limits.
[X]	[ ]	[ ]	11.	Results and conclusions address all points in the purpose.
[X]	[ ]	[ ]	12.	Referenced documents are retrievable or otherwise available.
[X]	[ ]	[ ]	13.	The version or revision of each reference is cited.
[X]	[ ]	[ ]	14.	The document was prepared in accordance with Attachment A, "Calculation Format and Preparation Instructions."
[X]	[ ]	[ ]	15.	All checker comments have been dispositioned and the design media matches the calculations.

S. A. Barker S A Barker 11/5/03
Checker (Printed Name and Signature) Date

- If No or NA is chosen, an explanation must be provided on or attached to this form.

Title: Peer Review of Inline Calcs for RPP-18491 REV. 0 Identifier: Rev: 0

Originator: NOT APPLICABLE Date:

Checker: S. A. BARKER Date: 11/5/03

Calculation Review Checklist Explanation for boxes checked No or NA	
Item	**Explanation**
NA-3	Software was not included as part of this report. All in-line calculations were checked.
NA-8	Software was not included as part of this report. All in-line calculations were checked.

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CH2MHILL Hanford Group, Inc.

SA Barker

Peer Review RPP-18491 Rev 0

Diffusion of Hydrogen Through SST Concrete Dome

Section 4.1.1 SST Dome Diffusional Surface Area

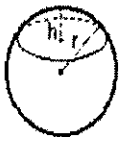
Section 4.1.1.1 A, AX, and SX Tank Dome Surface Area

From MathCAD

VOLUMES AND SURFACE AREAS

reference tables

Spherical Cap



Volume:

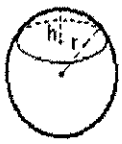
$$\frac{1}{3}\cdot\pi\cdot h^2\cdot(3\cdot r - h)$$

Surface area:

$$2\cdot\pi\cdot r\cdot h$$

Find the Volume

Example: Find the volume and surface area of a spherical cap given the radius, *r*, and height, *h* or radius of circle intersecting the sphere, *a*.



$r := 1.967765 \times 10^3 \cdot cm$ $a := 1143 \cdot cm$ $h := 366 \cdot cm$

$r = 64.56\,ft$ $a = 37.50\,ft$ $h = 12.01\,ft$

$r = 1.97 \times 10^3\,cm$

Title: Peer Review of Inline Calcs for RPP-18491 REV. 0 Identifier: Rev: 0

Originator: NOT APPLICABLE Date:

Checker: S. A. BARKER Date: 11/5/03

$$Volume_{spherical_cap} := \frac{1}{3}\cdot\pi\cdot h^2\cdot(3\cdot r - h)$$

$$Volume_{spherical_cap} = 205.20\,kilo\cdot gal$$

From Perry's 5th Ed and CRC Standard Math Tables, 19th Ed:

$$Volume_{spherical_sect1} := \frac{1}{6}\cdot\pi\cdot h\cdot\left(3\cdot a^2 + h^2\right)$$

$$Volume_{spherical_sect1} = 205.20\,kilo\cdot gal$$

Find the surface area.

From MathCAD

$$SA_{spherical_cap} := 2\cdot\pi\cdot r\cdot h$$

$$\boxed{SA_{spherical_cap} = 4.53\times 10^6\,cm^2}$$ <========= page 9

$$SA_{spherical_cap} = 4.87\times 10^3\,ft^2$$

From Perry's 5th Ed and CRC Standard Math Tables, 19th Ed

$$SA_{spherical_sect1} := \pi\cdot\left(h^2 + a^2\right)$$

$$\boxed{SA_{spherical_sect1} = 4.53\times 10^6\,cm^2}$$ <========= page 9

$$SA_{spherical_sect1} = 4.87\times 10^3\,ft^2$$

Taking into account the central pump pit...

$$SA_{diffusion_A} := SA_{spherical_sect1} - 11\cdot ft\cdot 14\cdot ft$$

$$\boxed{SA_{diffusion_A} = 4.38\times 10^6\,cm^2}$$ <========= page 9

Compare to RPP-13019, Tank Volume Determination

Title: Peer Review of Inline Calcs for RPP-18491 REV. 0 Identifier: Rev: 0

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Checker: S. A. BARKER Date: 11/5/03

SST_Dome_In :=
...\SST Tank drawing data 031023 .xls

SST_Dome_In =

	1	2	3
1	0.00	0.00	"Dome height 1 (ft)"
2	"A"	0.00	1.19
3	"AX"	0.00	0.72
4	"B100"	0.00	1.19
5	"B200"	0.00	$8.33 \cdot 10^{-6}$
6	"BX"	0.00	1.19
7	"BY"	0.00	1.19
8	"C100"	0.00	1.19
9	"C200"	0.00	$8.33 \cdot 10^{-6}$
10	"S"	0.00	1.19
11	"SX"	0.00	1.19
12	"T100"	0.00	1.19
13	"T200"	0.00	$8.33 \cdot 10^{-6}$
14	"TX"	0.00	1.19
15	"TY"	0.00	1.19
16	"U100"	0.00	1.19

$j := 2..16$

$SST_Dome_In_{j,1} =$ $SST_Dome_In_{j,11} \cdot ft^3 =$

"A"	246.8	kilo·gal
"AX"	258.4	
"B100"	246.9	
"B200"	0.0	
"BX"	246.2	
"BY"	249.3	
"C100"	246.9	
"C200"	0.0	
"S"	249.3	
"SX"	246.8	
"T100"	246.9	
"T200"	0.0	
"TX"	249.3	
"TY"	249.3	
"U100"	246.9	

Title: Peer Review of Inline Calcs for RPP-18491 REV. 0 Identifier: Rev: 0

Originator: NOT APPLICABLE Date:

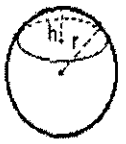
Checker: S. A. BARKER Date: 11/5/03

The volume calculated based on the simplifying assumpotion that the dome was spherical in shape is less than the eliptical volume calculated in RPP-13019. This indicates that the surface area is also smaller. As a result the diffusion values are small and therefor conservative.

Section 4.1.1.2 B, BX, C, T, and U-100 Series Tank Dome Surface Area

Find the Volume

Example: Find the volume and surface area of a spherical cap given the radius, *r*, and height, *h* or radius of circle intersecting the sphere, *a*.



$r := 1.967765 \times 10^3 \cdot cm$ $a := 1143 \cdot cm$ $h := 366 \cdot cm$

$r = 64.56\,ft$ $a = 37.50\,ft$ $h = 12.01\,ft$

$r = 1.97 \times 10^3\,cm$

$$Volume_{spherical_cap} := \frac{1}{3} \cdot \pi \cdot h^2 \cdot (3 \cdot r - h)$$

$Volume_{spherical_cap} = 205.20\,kilo \cdot gal$

From Perry's 5th Ed and CRC Standard Math Tables, 19th Ed:

$$Volume_{spherical_sect1} := \frac{1}{6} \cdot \pi \cdot h \cdot \left(3 \cdot a^2 + h^2\right)$$

$Volume_{spherical_sect1} = 205.20\,kilo \cdot gal$

Find the surface area.

From MathCAD

$SA_{spherical_cap} := 2 \cdot \pi \cdot r \cdot h$

$\boxed{SA_{spherical_cap} = 4.53 \times 10^6\,cm^2}$ <=========

$SA_{spherical_cap} = 4.87 \times 10^3\,ft^2$

From Perry's 5th Ed and CRC Standard Math Tables, 19th Ed

$SA_{spherical_sect1} := \pi \cdot \left(h^2 + a^2\right)$

$\boxed{SA_{spherical_sect1} = 4.53 \times 10^6\,cm^2}$ <=========

Title: Peer Review of Inline Calcs for RPP-18491 REV. 0 Identifier: Rev: 0

Originator: NOT APPLICABLE Date:

Checker: S. A. BARKER Date: 11/5/03

$SA_{spherical_sect1} = 4.87 \times 10^3\ ft^2$

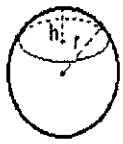
Taking into account the central pump pit...

$SA_{diffusion_B100} := SA_{spherical_sect1} - 12 \cdot ft \cdot 9 \cdot ft$

$\boxed{SA_{diffusion_B100} = 4.42 \times 10^6\ cm^2}$ <=========

page 10

Section 4.1.1.3 BY, S, TX, and TY Series Tank Dome Surface Area



$r := 1.967765 \times 10^3 \cdot cm$ $a := 1143 \cdot cm$ $h := 366 \cdot cm$

$r = 64.56\,ft$ $a = 37.50\,ft$ $h = 12.01\,ft$

$r = 1.97 \times 10^3\ cm$

$Volume_{spherical_cap_BY} := \frac{1}{3} \cdot \pi \cdot h^2 \cdot (3 \cdot r - h)$

$Volume_{spherical_cap_BY} = 205.20\,kilo \cdot gal$

From Perry's 5th Ed and CRC Standard Math Tables, 19th Ed:

$Volume_{spherical_sectBY1} := \frac{1}{6} \cdot \pi \cdot h \cdot \left(3 \cdot a^2 + h^2\right)$

$Volume_{spherical_sectBY1} = 205.20\,kilo \cdot gal$

Find the surface area.

From MathCAD

$SA_{spherical_capBY} := 2 \cdot \pi \cdot r \cdot h$

$\boxed{SA_{spherical_capBY} = 4.53 \times 10^6\ cm^2}$ <=========

$SA_{spherical_capBY} = 4.87 \times 10^3\ ft^2$

From Perry's 5th Ed and CRC Standard Math Tables, 19th Ed

$SA_{spherical_sectBY1} := \pi \cdot \left(h^2 + a^2\right)$

$\boxed{SA_{spherical_sectBY1} = 4.53 \times 10^6\ cm^2}$ <=========

$SA_{spherical_sectBY1} = 4.87 \times 10^3\ ft^2$

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Taking into account the central pump pit...

$SA_{diffusion_BY} := SA_{spherical_sectBY1} - 14.5 \cdot ft \cdot 11 \cdot ft$

$\boxed{SA_{diffusion_BY} = 4.38 \times 10^{6} cm^{2}}$ <========= page 10

Section 4.1.1.4 B, C, T, and U-200 Series Tank Dome Surface Area

Find the Volume

Example: Find the surface area of a FLAT cap given the radius, *r*.

$r := \frac{20}{2} \cdot ft$

$r = 10.00\,ft$

$r = 304.80\,cm$

Find the surface area. (Use 1/2 area because of hatchway structure)

$SA_{cap} := 0.5 \cdot \pi \cdot r^{2}$

$\boxed{SA_{cap} = 1.46 \times 10^{5} cm^{2}}$ <========= page 10

$SA_{cap} = 157.08\,ft^{2}$

Section 4.2.3 Concrete Effective Diffusivity Estimate (page 13)

$\frac{\varepsilon}{\tau} = \frac{D_e}{D} = \frac{3.90 \cdot 10^{-4}}{0.11}$ $\frac{3.90 \cdot 10^{-4}}{0.11} = 3.55 \times 10^{-3}$ diffusivity of Radon

$D_{0_C} := 0.611 \cdot \frac{cm^{2}}{sec}$

$D_{13.5_C} := 0.66 \cdot \frac{cm^{2}}{sec}$

Effective Diffusivity -- Hydrogen in Air

$D_e := D_{13.5_C} \cdot \frac{3.90 \cdot 10^{-4}}{0.11}$

$D_e = 2.34 \times 10^{-3} \frac{cm^{2}}{sec}$

Effective Diffusivity -- Methane in Nitrogen

Title: Peer Review of Inline Calcs for RPP-18491 REV. 0 Identifier: Rev: 0

Originator: NOT APPLICABLE Date:

Checker: S. A. BARKER Date: 11/5/03

$$\frac{3.08 \cdot 10^{-3} \cdot \frac{cm^2}{sec}}{0.22 \cdot \frac{cm^2}{sec}} = 0.014$$

$$\frac{1.28 \cdot 10^{-3} \cdot \frac{cm^2}{sec}}{0.22 \cdot \frac{cm^2}{sec}} = 5.818 \times 10^{-3}$$

Corresponding Diffusivities for hydrogen

$D_{e_concrete_H2_01} := 0.66 \cdot \frac{cm^2}{sec} \cdot 0.014$ $\quad D_{e_concrete_H2_01} = 9.24 \times 10^{-3} \frac{cm^2}{sec}$

$D_{e_concrete_H2_02} := 0.66 \cdot \frac{cm^2}{sec} \cdot 5.818 \times 10^{-3}$ $\quad D_{e_concrete_H2_02} = 3.84 \times 10^{-3} \frac{cm^2}{sec}$

Title: Peer Review of Inline Calcs for RPP-18491 REV. 0 Identifier: Rev: 0

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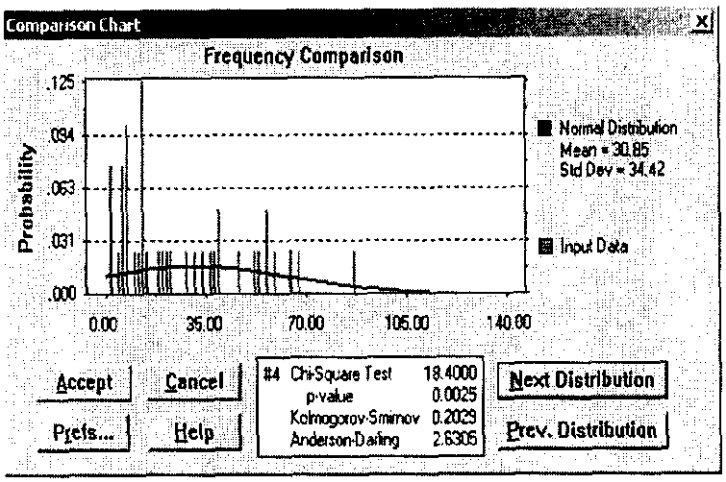
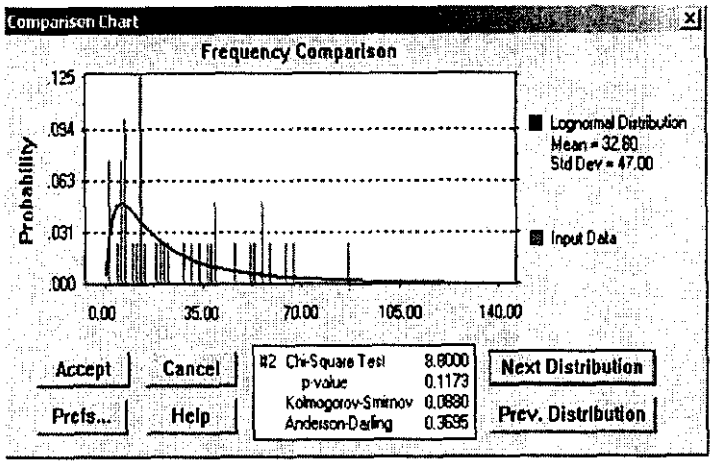
Checker: S. A. BARKER Date: 11/5/03

Section 4.4 Asphaltic Membrane Effective Diffusivity

Permeability (barrer)[1]
13
59.1
31.5
8.23
7.48
8.11
4.45
19.3
12.1
38.7
39.8
6.33
7.01
40
2.32
2.23
67.3
7
13.1
12.8
2.59
56.9
64.4
28.1
36.6
53.4
22.7
5.87
33.7
13.3
21.3
86.9
15.1
13.2
195
9.9
56.1
20.5
52.2
46.4





Average	30.8505
Median	19.90
Std Dev	34.4248245

Title: Peer Review of Inline Calcs for RPP-18491 REV. 0 Identifier: Rev: 0

Originator: NOT APPLICABLE Date:

Checker: S. A. BARKER Date: 11/5/03

type	mean	std dev
lognormal	32.8	47

$cm_Hg := \frac{1}{76} \cdot atm$

$barrer := 10^{-10} \cdot \frac{cm^3 \cdot cm}{cm^2 \cdot sec \cdot cm_Hg}$

$Permiability_{asphalt} := 30.85 \cdot barrer$

$D_{e_O2_asphalt} := Permiability_{asphalt} \cdot 0.76 \cdot 10^{-8} \cdot \frac{cm^2}{sec \cdot barrer}$

$D_{e_O2_asphalt} = 2.34 \times 10^{-7} \frac{cm^2}{sec}$

$D_{e_H2_asphalt_raw} := 4.14 \cdot D_{e_O2_asphalt}$

$D_{e_H2_asphalt_raw} = 9.71 \times 10^{-7} \frac{cm^2}{sec}$ $\frac{D_{e_H2_asphalt_raw}}{2} = 4.85 \times 10^{-7} \frac{cm^2}{sec}$

$D_{e_H2_asphalt} := \frac{D_{e_H2_asphalt_raw}}{2}$

$D_{e_H2_asphalt} = 4.85 \times 10^{-7} \frac{cm^2}{sec}$

Section 4.6 Soil Effective Diffusivity

$\tau = \frac{D \cdot \varepsilon}{D_e}$ (Page 18)

$D_{e_glassbeads} := 0.0592 \cdot \frac{cm^2}{sec}$ $\varepsilon_{glassbeads} := 0.374$

$D_{e_sand} := 0.0685 \cdot \frac{cm^2}{sec}$ $\varepsilon_{sand} := 0.371$

$D_{methane_nitrogen} := 0.257 \cdot \frac{cm^2}{sec}$

$\tau_{glassbeads} := \frac{D_{methane_nitrogen} \cdot \varepsilon_{glassbeads}}{D_{e_glassbeads}}$ $\tau_{glassbeads} = 1.62$

$\tau_{sand} := \frac{D_{methane_nitrogen} \cdot \varepsilon_{sand}}{D_{e_sand}}$ $\tau_{sand} = 1.39$

Assume that 20% of void space is filled by moisture

$\varepsilon_{glassbeads_wet} := 0.8 \cdot \varepsilon_{glassbeads}$ $\varepsilon_{glassbeads_wet} = 0.299$

$\varepsilon_{sand_wet} := 0.8 \cdot \varepsilon_{sand}$ $\varepsilon_{sand_wet} = 0.297$

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$$\frac{\varepsilon_{glassbeads_wet}}{\tau_{glassbeads}} = 0.184$$

$$\frac{\varepsilon_{sand_wet}}{\tau_{sand}} = 0.213$$

$$D_{e_glassbeads} := \frac{\varepsilon_{glassbeads_wet}}{\tau_{glassbeads}} \cdot D_{13.5_C} \qquad D_{e_glassbeads} = 0.12 \frac{cm^2}{sec}$$

$$D_{e_sand} := \frac{\varepsilon_{sand_wet}}{\tau_{sand}} \cdot D_{13.5_C} \qquad D_{e_sand} = 0.14 \frac{cm^2}{sec}$$

Section 5.0 Analysis Results

Section 5.1 A-Farm Tanks

Section 5.1.2 Concrete Resistance

$$thickness_{concrete_A} := 1 \cdot ft + 3 \cdot in \qquad thickness_{concrete_A} = 38.10\,cm$$

$$R_{concrete_A} := \frac{thickness_{concrete_A}}{D_{e_concrete_H2_02}}$$

$$R_{concrete_A} = 9.92 \times 10^3 \frac{sec}{cm}$$

Section 5.1.2 2-ply Asphaltic Membrane Resistance

$$thickness_{asphalt_A} := \frac{1}{4} \cdot in \qquad thickness_{asphalt_A} = 0.64\,cm$$

$$R_{asphalt_A} := \frac{thickness_{asphalt_A}}{D_{e_H2_asphalt}}$$

$$R_{asphalt_A} = 1.31 \times 10^6 \frac{sec}{cm}$$

Section 5.1.3 Soil Resistance

$$thickness_{soil_A} := 12 \cdot ft \qquad thickness_{soil_A} = 365.76\,cm$$

$$R_{soil_A} := \frac{thickness_{soil_A}}{D_{e_glassbeads}}$$

$$R_{soil_A} = 3.01 \times 10^3 \frac{sec}{cm}$$

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Section 5.1.4 Maximum Diffusible Hydrogen

$C_g := \frac{0.04 \cdot l_H2}{1000cm^3}$ $l_H2 := 1 \cdot liter$

$Sum_R_A := R_{concrete_A} + R_{asphalt_A} + R_{soil_A}$

$Diffusable_H2_{max} := C_g \cdot \frac{SA_{diffusion_A}}{Sum_R_A}$

$\boxed{Diffusable_H2_{max} = 11.5 \frac{l_H2}{day}}$ <==========

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$$HGR_A := \begin{pmatrix} 177 \\ 24 \\ 114 \\ 168 \\ 0 \\ 77 \end{pmatrix} \cdot \frac{liter}{day}$$

$j := 1..6$

$$Conc_{equil_A_j} := \frac{\frac{HGR_{A_j} \cdot \frac{1000}{86400}}{\left(\frac{liter}{day}\right)}}{\frac{\left(\frac{SA_{diffusion_A}}{Sum_R_A}\right)}{\left(\frac{cm^3}{sec}\right)}}$$

$\frac{Conc_{equil_A_j}}{\%LFL} =$

1544
209
995
1466
0
672

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Section 5.2 AX-Farm Tanks

Section 5.2.1 Concrete Resistance

$thickness_{concrete_AX} := 1 \cdot ft + 3 \cdot in$ $\quad thickness_{concrete_AX} = 38.10\,cm$

$$R_{concrete_AX} := \frac{thickness_{concrete_AX}}{D_{e_concrete_H2_02}}$$

$$R_{concrete_AX} = 9.92 \times 10^3 \frac{sec}{cm}$$

Section 5.2.x 2-ply Asphaltic Membrane Resistance

None shown $\quad R_{asphalt_AX} := 0 \cdot \frac{sec}{cm}$

Section 5.2.2 Soil Resistance

$thickness_{soil_AX} := 12 \cdot ft$ $\quad thickness_{soil_AX} = 365.76\,cm$

$$R_{soil_AX} := \frac{thickness_{soil_AX}}{D_{e_glassbeads}}$$

$$R_{soil_AX} = 3.01 \times 10^3 \frac{sec}{cm}$$

Section 5.2.3 Maximum Diffusible Hydrogen

$$C_g := \frac{0.04 \cdot l_H2}{1000 cm^3}$$

$Sum_R_{AX} := R_{concrete_AX} + R_{asphalt_AX} + R_{soil_AX}$ $\quad Sum_R_{AX} = 1.29 \times 10^4 \frac{sec}{cm}$

$$Diffusable_H2_{max_AX} := C_g \cdot \frac{SA_{diffusion_A}}{Sum_R_{AX}}$$

$$\boxed{Diffusable_H2_{max_AX} = 1.17 \times 10^3 \frac{l_H2}{day}}$$ <==========

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$$HGR_{AX} := \begin{pmatrix} 81 \\ 35 \\ 117 \\ 27 \end{pmatrix} \cdot \frac{liter}{day}$$

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$j := 1..4$

$$Conc_{equil_j} := \frac{\dfrac{HGR_{AX_j} \cdot \dfrac{1000}{86400}}{\left(\dfrac{liter}{day}\right)}}{\dfrac{\left(\dfrac{SA_{diffusion_A}}{Sum_R_{AX}}\right)}{\left(\dfrac{cm^3}{sec}\right)}}$$

$$\frac{Conc_{equil_j}}{\%LFL} =$$

6.92
2.99
9.99
2.31

<==========

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Section 5.3 B, BX, C, T, and U-100 Farm Tanks

Section 5.3.1 Concrete Resistance

$thickness_{concrete_B100} := 1 \cdot ft + 3 \cdot in$ $\qquad thickness_{concrete_B100} = 38.10\,cm$

$$R_{concrete_B100} := \frac{thickness_{concrete_B100}}{D_{e_concrete_H2_02}}$$

$$R_{concrete_B100} = 9.92 \times 10^3 \frac{sec}{cm}$$

Section 5.3.2 2-ply Asphaltic Membrane Resistance

$thickness_{asphalt_B100} := \frac{3}{8} \cdot in$ $\qquad thickness_{asphalt_B100} = 0.95\,cm$

$$R_{asphalt_B100} := \frac{thickness_{asphalt_B100}}{D_{e_H2_asphalt}}$$

$$R_{asphalt_B100} = 1.96 \times 10^6 \frac{sec}{cm}$$

Section 5.3.3 Mortar Resistance

$thickness_{mortar_B100} := \frac{3}{4} \cdot in$ $\qquad thickness_{mortar_B100} = 1.90\,cm$

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$$R_{mortar_B100} := \frac{thickness_{mortar_B100}}{D_{e_concrete_H2_02}}$$

$$R_{mortar_B100} = 496.11 \frac{sec}{cm}$$

Section 5.3.4 Soil Resistance

$thickness_{soil_B100} := 13.25 \cdot ft$ $\qquad$ $thickness_{soil_B100} = 403.86\,cm$

$$R_{soil_B100} := \frac{thickness_{soil_B100}}{D_{e_glassbeads}}$$

$$R_{soil_B100} = 3.32 \times 10^{3} \frac{sec}{cm}$$

Section 5.3.5 Maximum Diffusible Hydrogen

$$C_g := \frac{0.04 \cdot l_H2}{1000cm^3}$$

$$Sum_R_{B100} := R_{concrete_B100} + R_{asphalt_B100} + R_{mortar_B100} + R_{soil_B100}$$

$$Diffusable_H2_{mB100_AX} := C_g \cdot \frac{SA_{diffusion_B100}}{Sum_R_{B100}} \qquad Sum_R_{B100} = 1.98 \times 10^{6} \frac{sec}{cm}$$

$$\boxed{Diffusable_H2_{mB100_AX} = 7.74 \frac{l_H2}{day}}$$ <==========> page 23

$$HGR_{B100} := \begin{pmatrix} 22 \\ 23 \\ 24 \\ 25 \end{pmatrix} \cdot \frac{liter}{day}$$

$i := 1..4$

$$Conc_{equil_i} := \frac{\dfrac{HGR_{B100_i} \cdot \dfrac{1000}{86400}}{\left(\dfrac{liter}{day}\right)}}{\dfrac{\left(\dfrac{SA_{diffusion_B100}}{Sum_R_{B100}}\right)}{\left(\dfrac{cm^3}{sec}\right)}}$$

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$\frac{Conc_{equil}}{\%LFL} =$
284.32
297.24
310.17
323.09

<==========

Section 5.4 BY, S, TX, and TY Farm Tanks

Section 5.4.1 Concrete Resistance

$thickness_{concrete_BY} := 1 \cdot ft + 3 \cdot in$ $\quad thickness_{concrete_BY} = 38.10\,cm$

$$R_{concrete_BY} := \frac{thickness_{concrete_BY}}{D_{e_concrete_H2_02}}$$

$$R_{concrete_BY} = 9.92 \times 10^{3}\,\frac{sec}{cm}$$

Section 5.4.2 2-ply Asphaltic Membrane Resistance

$thickness_{asphalt_BY} := \frac{3}{8} \cdot in$ $\quad thickness_{asphalt_BY} = 0.95\,cm$

$$R_{asphalt_BY} := \frac{thickness_{asphalt_BY}}{D_{e_H2_asphalt}}$$

$$R_{asphalt_BY} = 1.96 \times 10^{6}\,\frac{sec}{cm}$$

Section 5.4.3 Mortar Resistance

$thickness_{mortar_BY} := \frac{3}{4} \cdot in$ $\quad thickness_{mortar_BY} = 1.90\,cm$

$$R_{mortar_BY} := \frac{thickness_{mortar_BY}}{D_{e_concrete_H2_02}}$$

$$R_{mortar_BY} = 496.11\,\frac{sec}{cm}$$

Section 5.4.4 Soil Resistance

$thickness_{soil_BY} := 14 \cdot ft$ $\quad thickness_{soil_BY} = 426.72\,cm$

$$R_{soil_BY} := \frac{thickness_{soil_BY}}{D_{e_glassbeads}}$$

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$R_{soil_BY} = 3.51 \times 10^{3} \frac{sec}{cm}$

Section 5.4.5 Maximum Diffusible Hydrogen

$C_g := \frac{0.04 \cdot l_H2}{1000cm^3}$

$Sum_R_{BY} := R_{concrete_BY} + R_{asphalt_BY} + R_{mortar_BY} + R_{soil_BY}$

$Diffusable_H2_{mBY_AX} := C_g \cdot \frac{SA_{diffusion_BY}}{Sum_R_{BY}}$ $Sum_R_{BY} = 1.98 \times 10^{6} \frac{sec}{cm}$

$Diffusable_H2_{mBY_AX} = 7.65 \frac{l_H2}{day}$ <========== page 25

$HGR_{BY} := \begin{pmatrix} 22 \\ 23 \\ 24 \\ 25 \end{pmatrix} \cdot \frac{liter}{day}$

$j := 1..4$

$$Conc_{equil_j} := \frac{\frac{HGR_{BY_j} \cdot \frac{1000}{86400}}{\left(\frac{liter}{day}\right)}}{\frac{\left(\frac{SA_{diffusion_BY}}{Sum_R_{BY}}\right)}{\left(\frac{cm^3}{sec}\right)}}$$

$\frac{Conc_{equil_j}}{\%LFL} =$

287.46
300.52
313.59
326.65

<==========

Section 5.5 SX Farm Tanks

Section 5.5.1 Concrete Resistance

$thickness_{concrete_SX} := 1 \cdot ft + 3 \cdot in$ $thickness_{concrete_SX} = 38.10cm$

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$$R_{concrete_SX} := \frac{thickness_{concrete_SX}}{D_{e_concrete_H2_02}}$$

$$R_{concrete_SX} = 9.92 \times 10^{3} \frac{sec}{cm}$$

Section 5.5.2 2-ply Asphaltic Membrane Resistance

$thickness_{asphalt_SX} := 0 \cdot in$ $\qquad$ $thickness_{asphalt_SX} = 0.00\,cm$

$$R_{asphalt_SX} := \frac{thickness_{asphalt_SX}}{D_{e_H2_asphalt}}$$

$$R_{asphalt_SX} = 0.00 \frac{sec}{cm}$$

Section 5.5.3 Mortar Resistance

$thickness_{mortar_SX} := 0 \cdot in$ $\qquad$ $thickness_{mortar_SX} = 0.00\,cm$

$$R_{mortar_SX} := \frac{thickness_{mortar_SX}}{D_{e_concrete_H2_02}}$$

$$R_{mortar_SX} = 0.00 \frac{sec}{cm}$$

Section 5.5.4 Soil Resistance

$thickness_{soil_SX} := 12 \cdot ft$ $\qquad$ $thickness_{soil_SX} = 365.76\,cm$

$$R_{soil_SX} := \frac{thickness_{soil_SX}}{D_{e_glassbeads}}$$

$$R_{soil_SX} = 3.01 \times 10^{3} \frac{sec}{cm}$$

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Section 5.5.5 Maximum Diffusible Hydrogen

$$C_g := \frac{0.04 \cdot l_H2}{1000cm^3}$$

$$Sum_R_{SX} := R_{concrete_SX} + R_{asphalt_SX} + R_{mortar_SX} + R_{soil_SX}$$

$$Diffusable_H2_{mSX_AX} := C_g \cdot \frac{SA_{diffusion_A}}{Sum_R_{SX}} \qquad Sum_R_{SX} = 1.29 \times 10^4 \frac{sec}{cm}$$

$$\boxed{Diffusable_H2_{mSX_AX} = 1.17 \times 10^3 \frac{l_H2}{day}}$$ <==========

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$$HGR_{SX} := \begin{pmatrix} 80 \\ 88 \\ 334 \\ 87 \\ 185 \\ 50 \\ 33 \\ 36 \\ 86 \\ 31 \\ 37 \\ 29 \\ 23 \\ 39 \\ 23 \end{pmatrix} \cdot \frac{liter}{day}$$

$$j := 1..15$$

$$Conc_{equil_j} := \frac{\dfrac{HGR_{SX_j} \cdot 1000}{\left(\dfrac{liter}{day}\right) \cdot 86400}}{\dfrac{\left(\dfrac{SA_{diffusion_A}}{Sum_R_{SX}}\right)}{\left(\dfrac{cm^3}{sec}\right)}}$$

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$\frac{Conc_{equil_j}}{\%LFL} =$

6.8
7.5
28.5
7.4
15.8
4.3
2.8
3.1
7.3
2.6
3.2
2.5
2.0
3.3
2.0

<==========

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Section 5.6 B, C, T, and U 200 Series Tanks

Section 5.6.1 Concrete Resistance

$thickness_{concrete_B200} := 1 \cdot ft + 0 \cdot in$ $\quad thickness_{concrete_B200} = 30.48\,cm$

$$R_{concrete_B200} := \frac{thickness_{concrete_B200}}{D_{e_concrete_H2_02}}$$

$$R_{concrete_B200} = 7.94 \times 10^{3} \frac{sec}{cm}$$

Section 5.6.2 2-ply Asphaltic Membrane Resistance

$thickness_{asphalt_B200} := \frac{3}{8} \cdot in$ $\quad thickness_{asphalt_B200} = 0.95\,cm$

$$R_{asphalt_B200} := \frac{thickness_{asphalt_B200}}{D_{e_H2_asphalt}}$$

$$R_{asphalt_B200} = 1.96 \times 10^{6} \frac{sec}{cm}$$

Section 5.6.3 Mortar Resistance

$thickness_{mortar_B200} := 0.75 \cdot in$ $\quad thickness_{mortar_B200} = 1.90\,cm$

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$$R_{mortar_B200} := \frac{thickness_{mortar_B200}}{D_{e_concrete_H2_02}}$$

$$R_{mortar_B200} = 496.11 \frac{sec}{cm}$$

Section 5.6.4 Soil Resistance

$thickness_{soil_B200} := 11 \cdot ft$ $\qquad$ $thickness_{soil_B200} = 335.28\,cm$

$$R_{soil_B200} := \frac{thickness_{soil_B200}}{D_{e_glassbeads}}$$

$$R_{soil_B200} = 2.76 \times 10^{3} \frac{sec}{cm}$$

Section 5.6.5 Maximum Diffusible Hydrogen

$$C_g := \frac{0.04 \cdot l_H2}{1000cm^3}$$

$$Sum_R_{B200} := R_{concrete_B200} + R_{asphalt_B200} + R_{mortar_B200} + R_{soil_B200}$$

$$Diffusable_H2_{mB200_AX} := C_g \cdot \frac{SA_{cap}}{Sum_R_{B200}} \qquad Sum_R_{B200} = 1.97 \times 10^{6} \frac{sec}{cm}$$

$$\boxed{Diffusable_H2_{mB200_AX} = 0.26 \frac{l_H2}{day}}$$ <========== page 27

$$HGR_{B200} := \begin{pmatrix} 5 \\ 5 \\ 8 \\ 8 \\ 2 \\ 2 \\ 2 \\ 2 \\ 6 \\ 4 \\ 6 \\ 6 \\ 2 \\ 2 \\ 2 \\ 2 \end{pmatrix} \cdot \frac{liter}{day}$$

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$j := 1..16$

$$Conc_{equil_j} := \frac{\dfrac{HGR_{B200_j} \cdot \dfrac{1000}{86400}}{\left(\dfrac{liter}{day}\right)}}{\dfrac{\left(\dfrac{SA_{cap}}{Sum_R_{B200_j}}\right)}{\left(\dfrac{cm^3}{sec}\right)}}$$

$\dfrac{Conc_{equil_j}}{\%LFL} =$

1956.8
1956.8
3130.8
3130.8
782.7
782.7
782.7
782.7
2348.1
1565.4
2348.1
2348.1
782.7
782.7
782.7
782.7

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