Utilizing Numerical Simulation to Estimate the Volume of Oil Leaked Through a Damaged Secondary Containment Liner

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February 7, 2022

Executive Summary

Numerical analysis was used to simulate a catastrophic failure of the largest crude oil tank, Tank 11, in the Valdez Marine Terminal's (VMT) East Tank Farm (ETF). The goal of this analysis was to quantify the volume of oil that would escape Tank 11's secondary containment system in such a worst-case scenario. Field testing has revealed that a component of the ETF's secondary containment systems, known as the catalytically blown asphalt (CBA) liner, likely has unrepaired holes in it that could allow oil to reach groundwater in the event of a spill, but the secondary containment systems are required to protect groundwater from oil spill contamination. Alyeska's spill response activities (e.g. times and recovery/processing rates) were modelled based on their stated capacities. To simulate how much oil could leak through a damaged CBA liner, this analysis considered the following key factors, among others: full storage volume of Tank 11, area of Tank 11's secondary containment system, hydraulic conductivity or permeability of the earthen fill above the buried CBA liner, depth of that earthen fill, rate which spilled oil could be drained from the secondary containment area, time estimate for spill cleanup, and an estimate of the percentage of CBA liner damage (i.e., holes). The results of the simulation indicate that the earthen fill above the CBA liner will be fully saturated with oil in under 8 minutes. Assuming a value of 0.1% liner damage, the standing oil will be drained in approximately 2.8 days; however, 38,000 barrels of oil will have leaked from secondary containment during this time period. Over the entire 30-day clean-up window, the simulation estimates that approximately 125,000 barrels of oil will be discharged through damage in the CBA liner.

Background

The modeled components of Tank 11's secondary containment system include the gravel fill, soil bedding, CBA liner, and the industrial wastewater sewer (IWWS) system shown in Figure 1. The IWWS system is comprised of a network of catch-basins, manholes, and piping that provide surface drainage for ETF's secondary containment systems. Drainage from the IWWS system flows down to the VMT's Ballast Water Treatment Facility where it can be re-routed or processed before discharge to the marine waters of Port Valdez. While designed to drain oil in the event of a spill, the IWWS system normally drains stormwater runoff (i.e. rain and snowmelt) from each secondary containment area. The secondary containment systems for all 14 of the storage tanks in the ETF share the same generalized components and spatial relationships shown in Figure 1. There are seven secondary containment areas or dike cells in the ETF (Figure 2), referred to as Dike Cells #1-7, and each dike cell contains two steel, crude oil storage tanks. Crude Oil Storage Tank 11 is contained in Dike Cell #6 in the ETF.

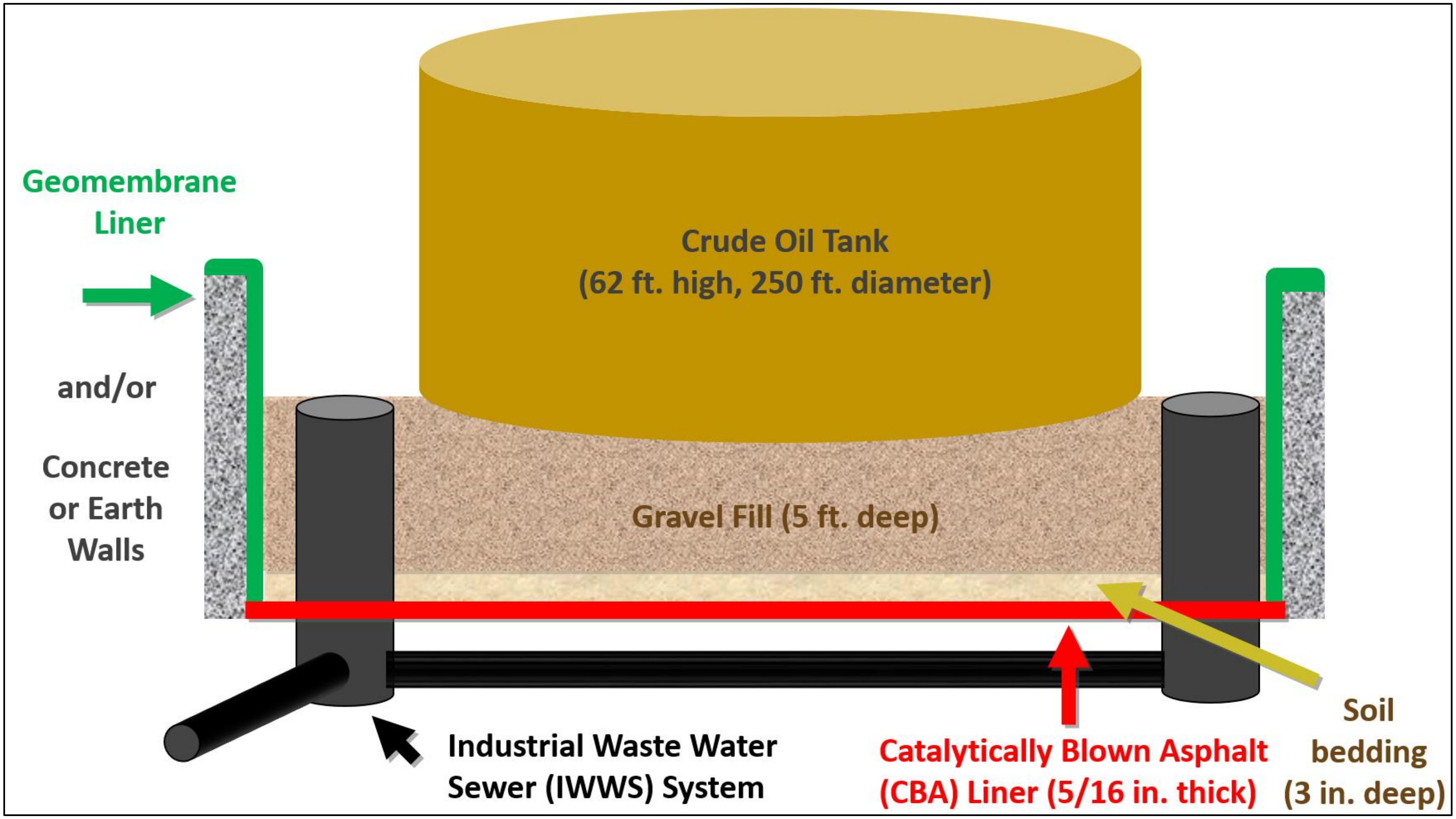

Figure 1. Generalized depiction of modeled secondary containment system components, not to scale.

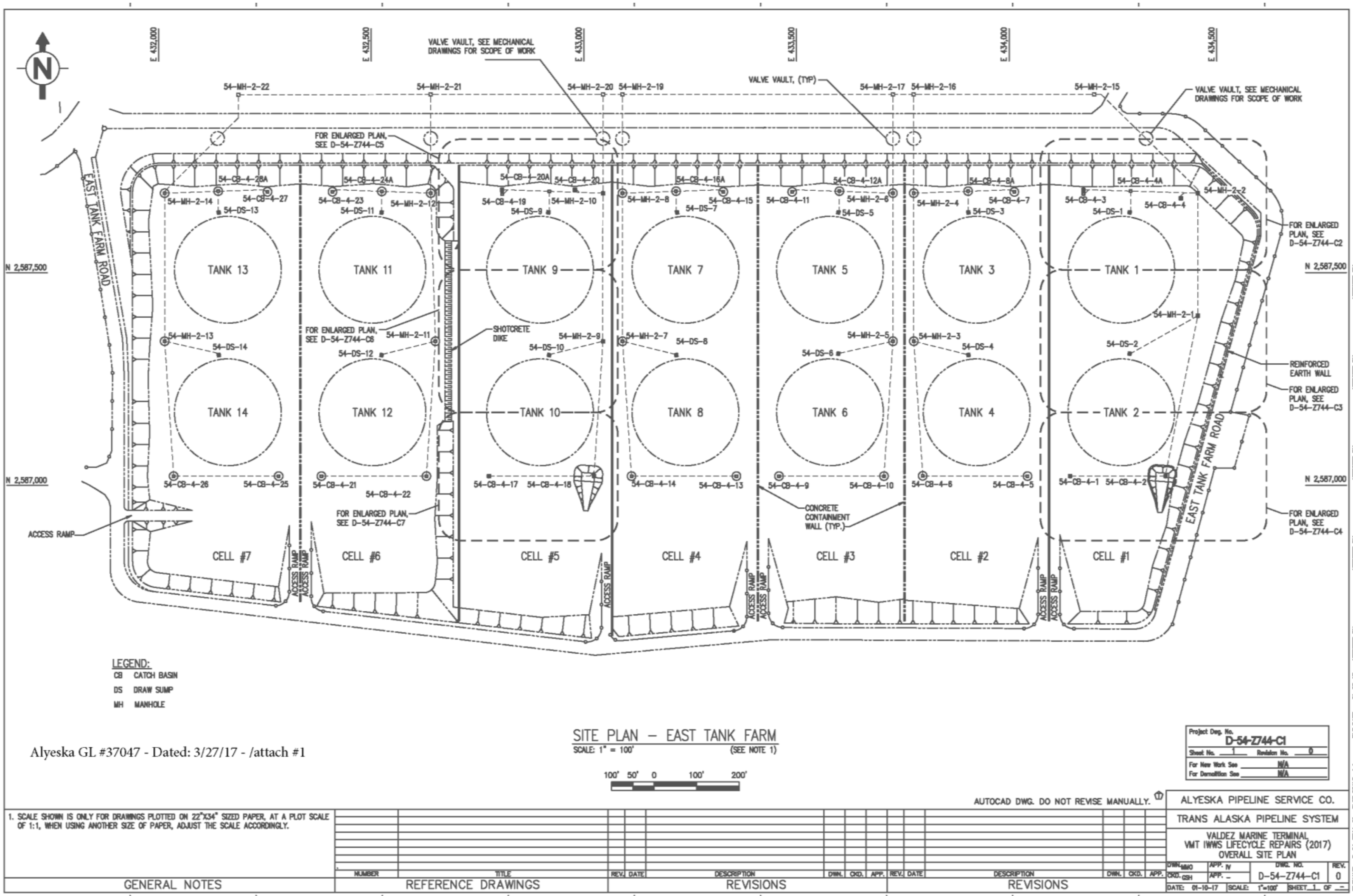

Figure 2. Site plan drawing of the East Tank Farm at the Valdez Marine Terminal

Darcy's Law provided the foundation for determining the hydraulic resistance of the secondary containment column (liner and fill). The liner damage ratio and Darcy constants for the fill materials were taken from previous work on the subject (Golder Associates, 2015). Darcy's Law can be used to calculate the volumetric flow rate through a column of porous material as:

$$Q = \frac{A\,k\,\Delta P}{\mu\,\Delta z} \quad (Darcy's\ Law) \qquad (Eq. 1)$$

Units[1]:

$$\frac{cm^3}{s} = \frac{(cm^2)(darcy)(atm)}{(cP)(cm)}$$

[1]: Customary (mixed) units: a substrate with a permeability of 1 darcy, subjected to a pressure gradient of 1 atmosphere per centimeter (atm/cm) will produce a flow rate 1 cubic centimeter per second (cm^3/s) through a cross-sectional area of 1 square centimeter (cm^2) for a fluid having a viscosity of 1 centipoise (cP).

The hydraulic conductivity is defined as:

$$\tau = \frac{Q}{A}$$

where A is the cross-sectional area of the column.

A generalized layered column consisting of N discrete layers, where layer i has a thickness Δz_i and a Darcy permeability coefficient k_i, can be analyzed by noting that for these columns:

$$Q_1 = Q_2 = \cdots Q_N \quad (continuity\ of\ flow)$$

and

$$\Delta P = \sum \Delta P_i$$

Eq. 1 can be re-written for a layered column as:

$$\Delta P = \sum \frac{Q\mu}{A}\frac{\Delta z_i}{k_i} = \frac{Q\mu}{A}\sum \frac{\Delta z_i}{k_i}$$

$$Q = \Delta P \frac{A}{\mu \sum \frac{\Delta z_i}{k_i}} \qquad (Eq. 2)$$

For the purpose of visualization, it may be useful to utilize an electrical analogy where the hydraulic resistance of a layer is defined as:

$$R_i = \frac{\mu}{A}\frac{\Delta z_i}{k_i}$$

ΔP is analogous to the difference in electrical potential across the circuit and Q in analogous to the electrical current. Darcy's Law is analogous to Ohms Law I=V/R and hydraulic resistance values combine in series or parallel as they would in an electrical circuit:

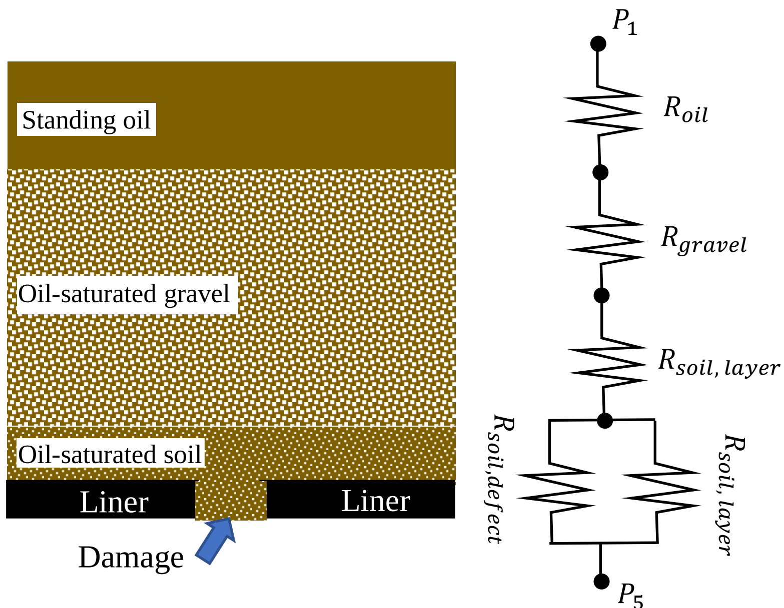

Figure 3: Electrical circuit analogue for fill column

Numerical mass transport simulation

Numerical simulation approximates the solution to a problem where a closed-form solution cannot be easily calculated (or does not exist). A model is defined to characterize the behavior of the system based on physical parameters (e.g. fluid level, viscosity, hydraulic resistance values, etc.). In the present study, the model is Darcy's Law for layered columns (see description above). The numerical analysis was carried out in MATLAB.

Starting at time = 0, the simulation steps forward in small increments (dt). The values of the parameters typically change over time; however, if the time steps are small enough, one can assume these parameters remain constant over the short time steps. The parameter values are then updated after each step based on the model. The simulation proceeds until some stop condition is met. The simulation is run using progressively smaller time steps until the value of the results of interest (e.g. volume of oil leaked) converges (stops changing). The converged value of the result of interest is an accurate approximation of the exact value.

Closed-form vs. numerical solution

The transient mass-transport simulation can be broken into three parts:

(1) the movement of the oil front from the surface of the fill to the liner

(2) mass transport in a fully saturated fill column

(3) mass transport through a partially saturated fill column as the level drops below the fill grade

Parts (1) and (3) require a numerical solution, but part (2) has a closed form solution. The closed form solution can be compared against the numerical simulation results for part (2) in order to validate the numerical routine.

For part (2), the governing differential equation is:

$$\frac{dz}{dt} = -c_1 z - c_2$$

where…

$$c_1 = \frac{\rho g \kappa}{\mu R_{col}}$$

κ is a conversion constant to produce ΔP in units of atm

and

$$c_2 = \frac{Volumetric\ oil\ capture\ rate\ of\ IWWS}{A}$$

The closed-form solution for this ODE, using the initial condition $z(0) = z_0$ is:

$$z(t) = -\frac{c_2}{c_1} + \frac{c_2 + c_1 z_0}{c_1} e^{-c_1 t}$$

This solution can be used to determine the time required for the fluid level to drop to the surface of the fill (grade line):

$$t_{drain} = -\frac{ln\left(\frac{c_2 + c_1 z_{fill}}{c_2 + c_1 z_0}\right)}{c_1}$$

and the volume of oil leaked during this period:

$$V_{leak} = \int_0^{t_{drain}} c_1 * z(t) * A\, dt$$

Parameter values

The parameter values used for the simulation are provided in the table below:

Parameter	Value	Justification / source
Simulation time	$30\ days$	Alyeska's stated spill clean-up timeline (Golder Associates, 2015, p. 11).
k_{gravel}	521	k was back-calculated using site-specific parameters. Derived from measured hydraulic conductivity for gravel fill at VMT reported by Golder (8e-2 cm/s) (Golder Associates, 2015, p. 10).

k_{soil}	3.26	k was back-calculated using site-specific parameters. Derived from measured hydraulic conductivity for soil fill at VMT reported by Golder (1e-2 cm/s) (Golder Associates, 2015, p. 10).
k_{liner}	~ 0	Assumed to be impervious relative to soil-filled damaged regions
μ	$9.852\ cP$	Dynamic viscosity of 2015 ANS crude oil sample (Fingas, 2016, p. iii)
ρ	$0.8639\ \frac{g}{cm^3}$	Density of 2015 ANS crude oil sample (Fingas, 2016, p. iii)
V_{tank}	$548{,}281\ barrels$	Tank 11, largest tank in East Tank Farm (Alyeska Pipeline Service Company, 2021, pp. 3.1-3)
A_{cell}	$307{,}097\ ft^2$	Area of dike cell containing the largest tank (Alyeska Pipeline Service Company, 2017).
Δz_{gravel}	$60\ in$	Fill depth of dike cell ranged from 3 -5 ft. but used 5 ft. to be conservative (Golder Associates, 2015, pp. ES-1).
Δz_{soil}	$3\ in$	Fill depth profile of dike cell (Golder Associates, 2015, p. 1)
Δz_{liner}	$\frac{5}{16}\ in$	Liner specification of dike cell (Golder Associates, 2015, p. 1)
Void volume fraction, gravel	0.38	http://www.geotesting.info/parameter/soil-porosity.html
Void volume fraction, soil/sand	0.46	http://www.geotesting.info/parameter/soil-porosity.html
Area ratio of damaged liner	0.001 (0.1%)	Per Austin Love's analysis of 2014-2017 visual inspection results by Golder Associates (Love, 2019).
Volumetric recovery rate	$4200\ gal/min$	Alyeska's stated IWWS flow rate from East Tank Farm (Alyeska Pipeline Service Company, 2021, pp. 2.3-8).
Residual saturation	0.1 (10%)	Brost, EJ, et. al. Non-Aqueous Phase Liquid (NAPL) Mobility Limits in Soil. 2000. API Soil and Groundwater Research Bulletin.

Assumptions

The assumptions incorporated in the physical model are described below:

1. *One-dimensional mass transport* – the resistance to lateral flow was assumed to be negligible. Given the relatively low resistance of the gravel and soil fill layers with respect to the damaged liner layer, this simplification seems appropriate. As the liner damage fraction increases or exit points become more localized, this assumption will become less accurate.

2. *Relative permeability neglected* – the presence of water in the fill column may substantially alter the oil imbibition rate and permeability. The local water table may also have a significant impact on mass transport of oil. The model used in this study assumes a dry fill column and a water table below the bottom liner level. This assumption constitutes the worst-case scenario.

3. *Oil capture window* – oil capture is limited to the times where the oil surface is above grade in the dike cell (i.e. standing oil is present). This assumption is based on physical descriptions of the IWWS drain systems in the dike cells. The drain points are stated to be at grade level. There may be sub-grade drain points; however, it is unclear whether these are large enough to maintain the stated capture rate of 4200 gal/min once the oil level drops below grade. Additional, sub-grade oil capture capacity can be easily incorporated at a later date when confirmed by Alyeska.

4. *Oil capture during excavation* – the method of excavation to be undertaken by Alyeska during the 30-day clean-up window is unclear at this time. It is possible that excavation of the fill might yield additional oil capture via fill removal (residual oil content) or direct pumping (in an excavated sump). Without knowledge of reasonable capture rates, this mode was omitted from the simulation.

Results

Progress of oil to the liner

The progress of the oil front through the fill column occurs rapidly. The simulation predicts that the oil will have reached the liner less than 10 minutes after release.

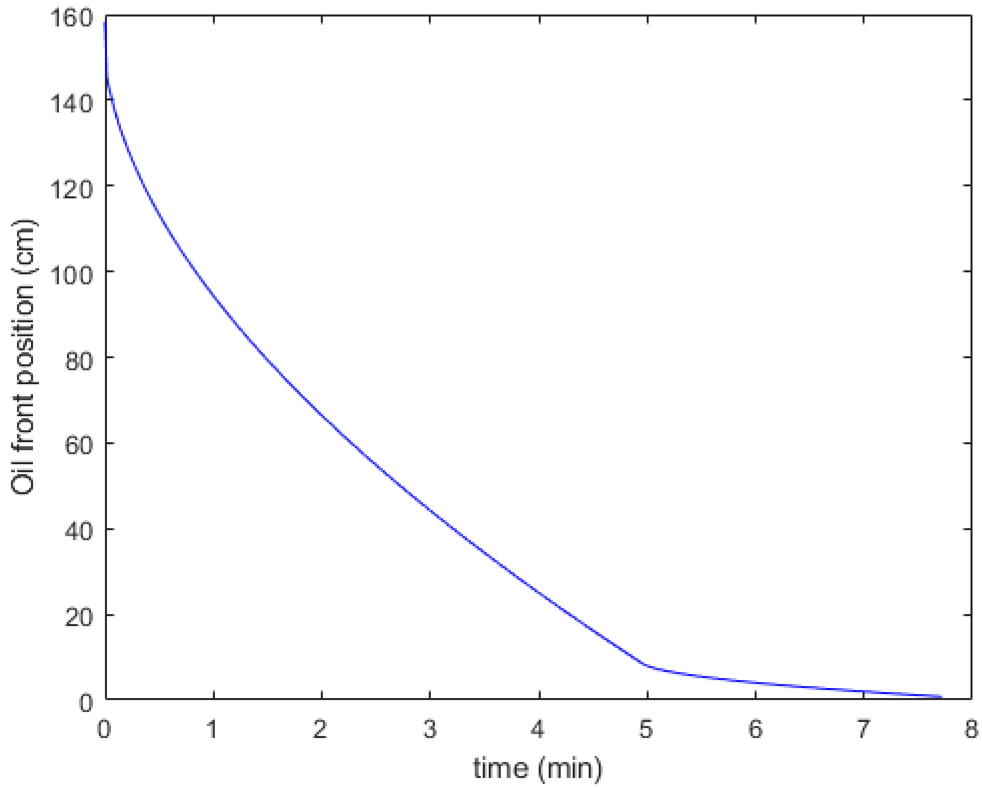

Figure 4: Oil front progress to liner

Standing oil recovery

The simulation predicts that the oil level will drop over the first 67 hours (2.8 days) as it leaks through damage in the liner and is captured by the IWWS drainage system. During this time period, 38,000 barrels of oil will leak through the damaged CBA liner and 400,000 barrels of oil will be drained via the IWWS (i.e. recovered). The results of the numerical solution match those of the closed-form solution, which confirms the functionality of the numerical implementation.

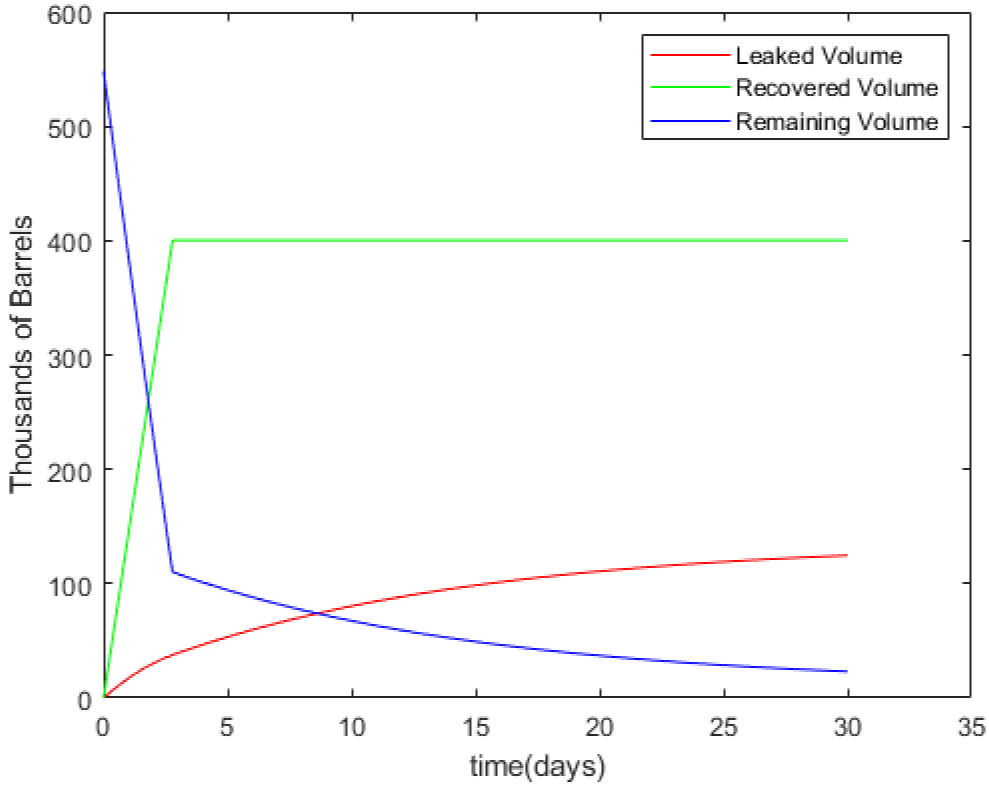

Figure 5: Oil volume cumulative plots. Leaked Volume line represents the volume of oil that has leaked through holes in the CBA liner. Recovered Volume line represents oil captured and processed by IWWS. Remaining Volume line represents oil still in the secondary containment dike cell (both residual and pooled).

30-day totals

Over the 30-day clean-up window, the simulation predicts that 125,000 barrels (23%) of oil will leak through damaged areas of the liner and 400,000 barrels (73%) of oil will be recovered via grade-level drain systems. At the end of the 30-day simulation 23,000 barrels (4%) of oil remained in the earthen fill column. It is reasonable to assume that this remaining oil would be recovered by Alyeska during excavation.

Given the total leaked volume of oil and the duration of the simulation, the effective (average) hydraulic conductivity of the dike cells is 2.7 x10^-5 cm/s. This is 27 times the permeability value of 10^-6 cm/s required for secondary containment in the Alaska Department of Environmental Conservation's regulations (Alaska Department of Environmental Conservation, 2021). However, because the crude oil storage tanks were built prior to 1992, that permeability rate requirement is not applicable to the secondary containment systems at the VMT, rather the secondary containment systems must be designed and constructed to have the "impermeability necessary to protect groundwater from contamination and to contain a discharge or release until it can be detected and cleaned up"

Sensitivity Analysis (area ratio of damaged liner)

The area ratio of the damaged liner is the model parameter with the largest uncertainty. Simulations were performed over a range of area ratio values to determine the sensitivity of the final volumes (leaked, recovered, remaining) to this parameter. Figure 6 contains a semi-log plot of the results. The quantity of leaked oil is clearly quite sensitive to this parameter, ranging from 2,500 barrels for 0.001% damage area ratio to 455,000 barrels for 10% damage area ratio.

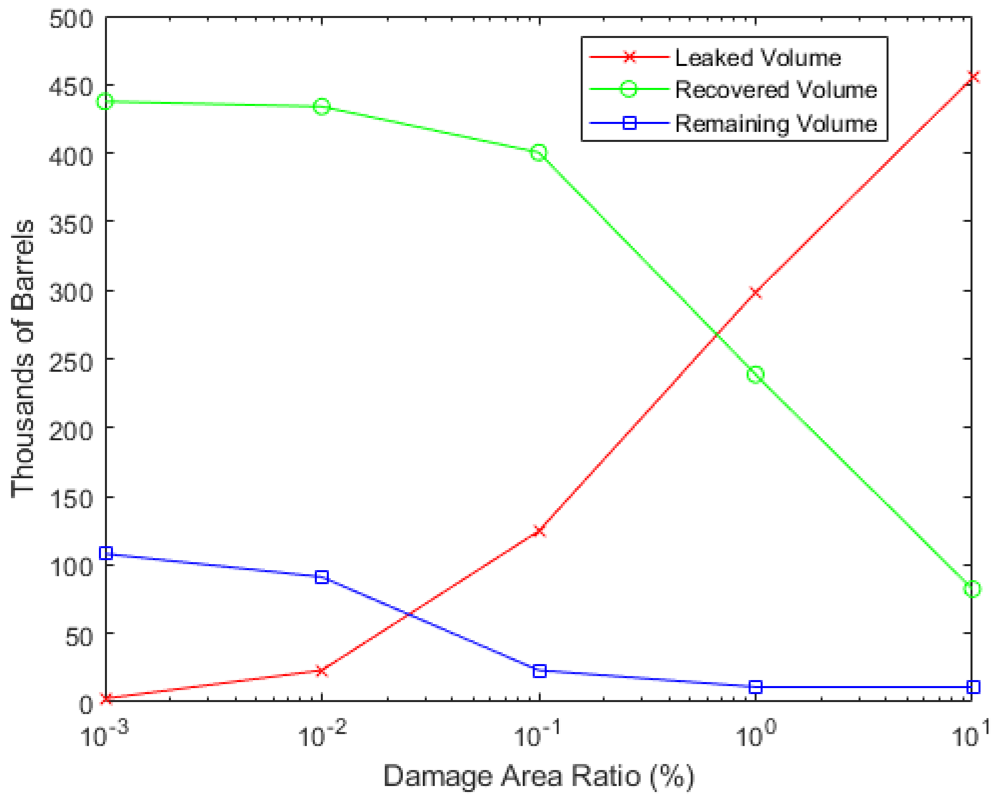

Figure 6: Final oil volume totals (end of simulation) as a function of liner damage area ratios. Leaked Volume line represents the volume of oil that has leaked through holes in the CBA liner. Recovered Volume line represents oil captured and processed by IWWS. Remaining Volume line represents oil still in the secondary containment dike cell (both residual and pooled).

Conclusions and Recommendations

The results generated by the model described in this report should serve as a starting point for future discussions and analysis of Alyeska's secondary containment systems. It is important to remember that a model attempts to approximate reality. The better the model (and the inputs), the more accurate the results. Having said this, the results of this model raise some concerns. The following actions are recommended:

1. *Better characterize the nature of the liner damage* – the easiest way to improve predictive mass transport models is to better characterize the liner damage. This includes more accurate estimation of the damage area ratio and improved modelling of the hydraulic characteristics of the damage orifices. The former can be accomplished via some combination of direct inspection (digs) and indirect inspection (e.g. electrical resistance survey). The latter may require more advanced modelling techniques and/or experiments. Given the high sensitivity of the leaked oil volume to the liner damage area ratio (Figure 6), and the relatively high uncertainty in the estimation of this parameter, quantification of liner damage will likely have the largest return-on-investment in terms of improving the accuracy of the simulation.

2. *Fill water content and water table data* – As discussed in the Assumptions section, both the presence of water in the fill column and level of the local water table may significantly alter the mass transport of oil, and thus, the leaked oil volume. Efforts should be made to quantify these parameters and to adjust the model accordingly. As presented, the model represents the worst-case scenario of a dry fill column and a water table that is lower than the dike cell floor liner.

3. *Better characterize the oil recovery processes* – a more detailed description of the oil recovery systems (e.g. drains, pumps) and excavation techniques will likely increase the recovered oil volume and decrease the spilled volume. Even if the processes cannot be quantified, a thorough review of the existing Alyeska procedures and methods in the context of the simulation results is a worthwhile endeavor.

4. *Evaluate current tertiary containment strategies* – It may be useful to explore the use of lined settlement ponds or tanks at the VMT to temporarily store large quantities of oil and oil saturated fill for processing. If oil can be more rapidly transferred from the dike cells (with a damaged liner) to a tertiary holding tank/pond, the result will be a lower volume of leaked oil. Mass transport models can be used to help predict the effect of such modifications.

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