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MODELING LEAKAGE IN A FUEL TRANSFER PIPELINE USING COMPUTATIONAL FLUID DYNAMICS TECHNIQUES

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ABSTRACT
Stress Engineering Services, Inc. (SES) performed an assessment of leaks for an insurance company that occurred in a fuel transfer pipeline at a tank storage facility. Of specific interest were the duration and timing of the leaks, which occurred from a 30 foot section that entered an earthen containment berm. It was originally estimated that 28,900 gallons of gasoline and ethanol leaked periodically from two (2) pin holes in the pipeline during a two month period.

Early analysis efforts were not able to estimate the conditions that were necessary to cause the leaking fluid to break through the surface of the earthen berm (a phenomenon known as *daylighting*). Consequently, SES performed a more rigorous investigation to determine what conditions were required to produce daylighting, the significance of which involved quantifying the estimates of leak duration and the petroleum volumes.

This effort integrated assumptions and data from prior analyses to assess the effects of time-dependency using computational fluid dynamics (CFD) modeling techniques. The intent was to take the existing calculations and provide a more technically-defensible model to predict the timing and volume released using reasonable conditions. SES used soil permeability and actual pipe pressure data to simulate the pipeline leak and soil conditions. The results of the CFD analysis showed that it is possible for daylighting to occur within a two-month period. However, a specific combination of conditions associated with leak rates, leak duration, and soil permeability are required to generate daylighting in a relatively short period of time. The predominant observation is that there must be extended periods of continuous leaking involving leak rates of sufficient magnitude.

The significance of this work is that it presents a proven analytical method for modeling leaks in pipelines and addressing the effects of specific variables on the amount of released products and the time required to achieve specific leak volumes.

INTRODUCTION
Stress Engineering Services' initial efforts involved a review of prior investigations and analysis efforts that had been performed in assessing two leaks in the transfer line located at the storage terminal facility. SES was provided with study that provided detailed documentation on the pipeline leak. Of specific interest were a series of calculations performed by a consulting firm that estimated the volume of the leak. The following paragraphs are taken from the Background section of this document.

> *Within the operation area of the terminal pipeline is used to transfer fuel product from a manifold to various above-ground bulk storage tanks. This segment of the pipeline is above ground for its entire length except in two locations where it penetrates above grade soil berms. The soil berms provide containment for the tank farms at the terminal. Product was observed at the toe of the soil berm facing the operations area, approximately 25 (feet) east of the pipeline. Upon investigation, two holes were detected in the section of the pipe that is located within the soil berm adjacent to the operations area. The holes in the pipe were detected 8 feet from the face of the berm.*
>
> *The section of the pipeline where the leak occurred was experimentally tested to determine the leak rate from the pipeline as a function of internal pipeline pressure. In the lab, the pipeline leak varied from about 15 to 70 gallons per hour for the pressure range of 1 to 25 pounds per square inch.*
>
> *Additionally, an estimate of the lower bound of the potential release was made. Table 1 from the estimation is included. This table includes data from July 2001 (the only data available) that provides fuel transfer through the pipeline during one month of operation that includes:*
> - *Time of fuel transfer begin and end*
> - *Direction of fuel transfer (in or out of tank)*
> - *Volume of fuel transferred*
> - *Flow rate*
> - *Product type*
> - *Tank and leak location elevations; and*
> - *Product levels in the tank at the beginning and end of transfer.*

Using the transfer data and experimental pressure-leak correlations, a series of calculations were performed by the consulting firm prior SES involvement using the Darcy-Weisbach equation to estimate the total potential release volume. The results showed that for July 2001 alone, the volume was estimated to be 4,800 gallons, while from February 1 through July 30 of 2001 the total potential release volume for the six-month period would be 28,900 gallons (this value assumes that the leak rates for other months in this period are similar to the recorded data from July 2001).

This work also took into account the potential cumulative affects of repeated random release events by assuming that each release occurred independent of the other events. The consulting firm concluded that the time between each release event was sufficient for the leak contents from the prior release to drain into the underlying soil. This process continued until eventually the absorption capacity of the underlying soil in the berm was exceeded at which point the cumulative releases emerged at the toe of the berm.

A review of the consulting firm's conceptual model demonstrated that the assumed approach was reasonable and that the underlying assumptions of their work were based upon sound physical principles.

To expand on prior efforts by the consulting and others, SES performed a stand-alone investigation using CFD. The elements of the CFD model included the following:

- Berm and pipe geometry
- Soil properties (including anisotropy of permeability)
- Leak rate based upon existing data
- Periods of leaking and non-leaking based upon the July 2001 data presented in **Table 1**

SES drew heavily from prior analyses and documentation. Of particular importance to the discussion at hand is the following paragraph taken from the consulting firm's report. This firm also evaluated the potential for the released product to penetrate the soil without daylighting on the face of the berm. Because the release was not observed at the face of the berm until July 30, 2001, the volume of product released prior to that time was contained within the berm and underlying native soil. Based on our calculations, summarized below and attached to this memorandum, the estimated volume of product that could have been released between February 1 and July 30, 2001, could have been contained within the soil.

Using the July 2001 product transfer data, the consulting firm concluded that daylighting would not occur as their calculations showed that the native soil was sufficient to contain the released petroleum from February to July 2001. SES agreed that this was a possibility and confirmed the consulting firm's results with its own independent non-CFD calculations that used closed-form solutions. However, based on modeling simulation efforts using this data the petroleum never produced daylighting, raising questions about how the release could have occurred over a long period of time.

Having developed an understanding for the technical aspects of the problem, SES elected to use CFD modeling techniques to develop possible scenarios to show that daylighting could have occurred within a relatively short period of time. As will be shown, slight deviations from the July 2001 data will produce daylighting in 100 hours (approximately 4 days) assuming continuous leaking. However, at the present time, there is no evidence to indicate that the pipeline operated continuously for 4 days.

The following sections of this paper provide details on the CFD models and the range of variables considered as part of the analysis. Included are the results of the analyses in the form of volume fraction contour plots and the calculated volume release data. SES also includes discussions on the conditions required for daylighting to occur within the proposed time period.

ANALYSIS METHODS AND RESULTS

Stress Engineering Services used CFD methods to determine the volumetric release of the contents into the earthen berm as well the spatial extents of the product release. A primary objective of the work was to estimate the time and conditions required for daylighting of the released contents to occur. The sections that follow provide details on the modeling efforts and the corresponding results. Several variables were considered in the CFD modeling efforts.

- Although the release data (i.e. pressure time map) presented in **Table 1** was the foundation for the analysis, additional efforts were undertaken to address the effects of extended periods of leaking not presented in this table.
- Address the effects of non-isotropic soil conductivity conditions where reduced conductivity is assumed in the vertical direction due to consolidation effects. As will be shown, the contour maps for the volume fractions of leak fluid differ when comparing isotropic to non-isotropic conductivities.

It should be noted that the worked performed by SES was progressive in that subsequent analysis efforts were based upon results from prior efforts. As an example, initial CFD efforts did not show daylighting using the July 2001 pressure-time map. However, extending the duration of the final leak an additional 300 hours resulted in daylighting. Details such as this are included in this paper.

Closed-form Analysis

After SES had reviewed the notebook produced by the consulting firm and the related calculations, SES performed its own set of independent calculations. Analytical methods were first applied to compute the transport of fluid in the berm. The extent of wetted region was estimated using analytical solutions. The results indicate that fluid transport predominantly occurs under the influence of gravity. By the closed-form analysis daylighting on the berm surface is not observed under the conditions studied.

The objective of this work was to examine the transport of fuel from a leak in the berm and identify conditions under which daylighting of the leaking fluid occurs. The flow behavior was studied by solving the transport equations analytically. The horizontal velocity of the fluid was assumed to decay as the square of the distance from the leak source; whereas, the vertical velocity due to gravity was considered constant. As the fluid migrates away from the leak source gravitational effects dominate, the fluid is transported vertically downwards and does not reach the berm edge.

The flow behavior of the leaking fluid in the berm can be described using conservation of mass and momentum; however, these equations are non-linear and cannot be solved analytically. Numerical techniques such CFD can be applied to solve these non-linear equations. In the present work, the conservation equations of mass, momentum are simplified and then solved analytically.

The migration of fluid due to a steady leak for a period of 10 hrs was studied for various leak rates including 80 ft^3/day, 170 ft^3/day (listed by the consulting firm as the leak rate for normal operating conditions), and 240 ft^3/day (listed by the consulting firm as the leak rate for the highest operating conditions). **Figure 1** depicts the wetted zone for a leak rate of 240 ft^3/day and, as can be seen, no daylighting occurs for the assumed 10 hour period of leaking.

Although the results confirmed previous calculations showing that daylighting was not likely to occur, the limitations of the analytical solutions precluded the possibility of making this a definitive statement. For this reason, SES recommended that additional investigations be performed using computational fluid dynamics. The benefits of this approach were several-fold. First, the numerical simulation would not be limited to the assumptions associated with the analytical solutions. Secondly, the CFD approach permitted sensitivity studies to be performed by considering variations in critical variables such as leakage rate, periods of leaking, soil conductivity and associated anisotropy.

CFD Analysis Methods and Techniques

Once the analytical solutions were developed using the closed-form equations, analyses were performed using CFD. This method is based on first principles of mass, momentum and energy conservation. The conservation equations for mass, momentum and energy are solved at thousands of locations within the flow domain. These locations are created by generating a mesh, which happens to be two-dimensional in the present analysis across the cross-section of the berm. CFD provides flow variables such as velocity, pressure, temperature, density, concentration, etc. at thousands of locations within the domain. Unlike experimental methods, CFD provides full-field data. Pressure, velocity, density, temperature and other quantities of interest are obtained at each and every point in the simulated flow domain. CFD methods are widely applied within various industries to examine fluid flow and heat transfer behavior. CFD study of a full-scale model can be carried out, thus eliminating scale-up issues. These benefits make CFD a viable tool for analysis, design and rapid proto-typing. In the present work, commercially available CFD software FLUENT, from Fluent Inc. is used. SES used the geometry for the earthen berm as presented in the consulting firm's earlier report.

Figure 2 provides a schematic diagram of the modeled region that includes the berm soil and the pipeline. The berm is three-dimensional in shape; however, the leaking fluid forms an axisymmetric region (spherical or ellipsoidal in shape). In view of this an axisymmetric model is used to simulate the flow behavior. This model is based on axisymmetric conditions where the plotted region (in **Figure 2** and all additional contour plots) actually represents a cross-section of one-half of the berm. Axisymmetric models assume that variables (input or calculated) do not vary as functions of circumferential position. These types of models are often used to simplify complex modeling efforts and reduce the time required for computing solutions. Although the pipeline and berm are not geometrically axisymmetric, this approach is valid as the intent of the modeling effort is to determine the time required for daylighting in a single direction. A fully three-dimensional model is likely to produce similar results.

The assumptions associated with the axisymmetric CFD model are provided in the following bullets:

- Berm slope: 2H:1V = 26.5 degrees slope
- Berm base: 13-feet
- Berm height: 6-feet
- Top of pipe at 3-feet from berm top surface
- Leak is located on underside of pipe
- Water table at 5-feet below ground level
- Soil porosity: 0.3
- Hydraulic conductivity of soil : 3 ft/day.
- Fluid density (average): 760 Kg/m3.
- Fluid viscosity (average): 0.8 e-3 Pa.s

In terms of modeling loading and boundary conditions, the following assumptions were made.

- Leak fluid cannot penetrate the water table
- Leak rate varied as per pipe pressure data
- Leak rate estimated from pipe pressure and leak data generated by from experimental work (presented in **Table 1**).

As stated previously, a progressive modeling effort was undertaken to permit SES to address the effects of important variables as part of a sensitivity study. These efforts considered the following modeling configurations:

- Steady-state continuous leak at 240 ft^3/day over 350 total hours
- Periodic leak schedule based upon the data from July 2001
- Additional analyses to address extended periods of leaking
- Additional analyses to address the effects of reduced conductivity in the vertical direction (anisotropic soil conductivities) associated with soil consolidation

The following sections of this paper include discussions on modeling methods and results for each of the above modeling configurations.

CFD Model Considering Steady-State Continuous Leaks

Because of the inability of the SES closed-form solutions to generate daylighting (also consistent with the consulting firm's findings), SES recommended the use of CFD to solve the problem numerically. Although leak data from July 2001 was available, for the first round of CFD analyses SES elected to use a combination of leak rate and extended period of leaking that would ensure daylighting because it was already clear from the closed-form analytical solutions what conditions did not produce daylighting.

To perform an initial assessment of the CFD model and its ability to simulate the pipeline leak, conditions were assumed based upon a continuous leak of 240 ft^3/day over 350 total hours. The leak rate of 240 ft^3/day is based on a maximum estimated leak rate. The following considerations were made in performing this specific analysis.

- Leaking fluid cannot penetrate the water table
- Steady state leak modeled over a period of 350 hrs at 240 ft^3/day
- Pipe not included in this model
- On and off switching of leak not modeled. Leak is assumed to occur continuously over simulated period (~ + 350 hrs)
- Other objects buried in the berm or ground not modeled.
- Varying permeability not modeled

As the model marches through time, data are extracted at specific points in time. To present the extent of the fluid leakage, contour plots are provided that show volume fraction of leak fluid in the assumed domain where RED is100% volume of leak fluid and BLUE is void.

Figure 3 provides the leakage contour plots at assuming a constant leak rate of 240 ft^3/day. Note that after 10 hours there is no daylighting at the edge of the berm; however, after 300 hours there is clear daylighting at the base of the berm. Note that daylighting on the top surface of berm observed, which is probably due to absence of the pipe in this particular CFD model. Although this model did not represent actual data from the provided July 2001 product transfer data, the results demonstrated the validity of the modeling efforts and the ability to modify variables required for performing a sensitivity analysis. The results also demonstrated the necessity of assuming long periods of uninterrupted leakage in order for daylighting to occur (unless additional soil conductivity data are considered).

CFD Model Considering Periodic Leaking

Once the analysis of the continuous leakage model was completed, the next step was to model the data presented from the previous reports. These data were based upon product transfer tickets from the storage facility during July 2001. To start the modeling effort conservatively, SES used actual transfer ticket data for generating the analysis matrix provided in **Table 1**. Note in this table that each period of leaking or non-leaking is assigned a time step for modeling purposes.

As with the previous analysis efforts, data were extracted after each step (corresponding to a specific time period in July 2001). For presentation purposes leakage contour maps were generated that showed the extent of the leaking fluid in the assumed domain. This shows how the leaking fluid is transported in the soil and the berm.

Figure 4 provides leakage contour plots for all twelve (12) steps listed in **Table 1**. While it is noted that the extent of leakage is greater at the end of the month (Step #11) when compared to the results for the beginning of the month (Step #1), it is more important to note how the results at the end of Step #12 show how the fluid has been absorbed into the soil during an extended time periods with no leaking. During the no-leak period fluid migrates towards the water table and leaves a void near the pipe. After a long period of non-leaking, the analyses shows that the additional leaking practically starts from a restart position as if no prior leaking had existed. This observation was important point for future analyses efforts.

CFD Model Considering Extended Periods of Leaking

After the first series of analyses were completed considering the leaking on/off July 2001 data, additional investigations were undertaken to explore the effects of extended periods of leaking (refer to data posted in **Table 1**). The first analysis considered continuing the leakage associated with Step #9 in **Table 1** that was the maximum reported in July 2001 at 69.7 gallons per hour. The contour plot associated with the results for this period is provided in **Figure 5**. Daylighting was shown to occur under these conditions after only 100 hours of leakage. To address the effects of a reduced leakage rate, a similar analysis was performed by extending the leakage from Step #11 that was 54.7 gallons per hour (listed in **Table 1**). For these conditions, daylighting was observed between 250 and 300 hours. These results demonstrate the effects of accumulated fluid within the berm and the critical nature of the released volume reaching a certain magnitude before daylighting will occur.

CFD Model Considering Anisotropic Permeability

After all of the analyses had been completed to address the effects of leakage rate on the time required for daylighting, questions were posed about the effects of anisotropy in the permeability of the soil. Due to consolidation, it is reasonable to assume that the soil conductivity in the vertical direction has a lower magnitude than it does in the horizontal direction. Therefore, SES elected to perform a series of investigation addressing this phenomenon (referred to in this document as the conductivity ratio, CR).

SES performed a sensitivity study assuming that the conductivity in the vertical direction had a magnitude that was one-third the magnitude in the horizontal direction (CR = 1/3, where CR is the *conductivity ratio*). The analysis was terminated at the end of Step #9 because it was clear that no daylighting was going to occur. Analyses were also undertaken by reducing the permeability ratio where the conductivity in the vertical direction had a magnitude that was one-tenth (CR = 1/10) the magnitude in the horizontal direction. This particular portion of the analysis considered leakage rates associated with Step #11 with results plotted in **Figure 6**.

The results of the sensitivity study associated with the conductivity ratio clearly demonstrate that the anisotropy of the soil significantly impacts the migration of the fluid even during a relatively short period of time. Although it is unlikely that the hydraulic conductivity ratio will have a magnitude as low as 1/10, this bounding exercise demonstrates the effects of anisotropy in soil conductivity. A conductivity ratio of 1/3 is more likely to have existed in the earthen berm soil at the terminal storage facility.

DISCUSSION OF RESULTS

In performing the engineering assessment SES assumed a range of boundary and loading conditions in order to perform sensitivity studies. In performing these types of studies for the given problem, these analyses provide important insights about how the leak conditions could have generated daylighting conditions. Of equal importance are insights gained regarding those variables that were not critical.

The predominant observations from the analysis work show that for daylighting to occur the following conditions are important.

- Leak rate and volume of release
- Conductivity of the soil, especially with regards to directional dependence
- Duration of the leak and time spacing between leaks

It is convenient to summarize the CFD analytical efforts in terms of scenarios that include specific operating and boundary conditions. **Table 2** includes four (4) analytical scenarios that were the foundation for the CFD modeling efforts. Included in this table are conditions associated with each scenario, volume of released product, and if daylighting was observed in the analysis.

There are several important observations that are made in reviewing the modeling scenarios provided in **Table 2**.

- Because of the inability of the SES closed-form solutions to generate daylighting (also consistent with the findings from other consulting firms), Scenario 1 was considered. This analysis clearly demonstrated that daylighting could occur, but that an extended period of leaking was required and a leak rate of sufficient magnitude was required (75 gallons per hour compared to the July 2001 maximum value of 69.7 gallons per hour as listed in **Table 1**).
- Because of the ability to generate daylighting in Scenario 1, SES chose for both pressure cases in Scenario 2 to be based on the July 2001 leak data originally provided by terminal storage facility. SES performed several sensitivity studies and found that re-running the entire July 2001 leak history would not produce daylighting. These findings reinforced the necessary conditions observed in the insights gained with Scenario 1 (extended period of leaking and leak rate of sufficient magnitude).
- Scenario 3 built upon the insights gained in the two previous modeling scenarios. SES recognized that in order for daylighting to occur, a period of continuous leaking must be added to the existing July 2001 data. As noted in **Table 2**, SES elected to perform a sensitivity study on leak rate by assessing both 69.7 and 54.7 gallons per hour. The results in Scenario 3 show that daylighting can occur using the selected conditions. It is equally important to note that a smaller volume of released petroleum was required to produce daylighting if the magnitude of the leak

rate is increased. Under these conditions, daylighting also occurs in a shorter period of time.

- The effects of anisotropy in soil conductivity are specifically addressed in Scenario 4. SES used the Scenario 2b data to model the vertical soil conductivity as 1/3 the conductivity in the horizontal direction (CR=1/3). As noted in **Table 2**, this condition did not produce daylighting. SES then decreased the conductivity ratio, CR, to be 1/10 which did result in daylighting. Although a CR=1/10 is not typical for most soil conditions that do not involve subsurface rock formations, these results do show the effects of anisotropy in the soil conductivity. Two additional points should be noted relative to the Scenario 4 results: Had SES elected to use a period of continuous leaking (as used in Scenario 3), Scenario 4a with CR=1/3 would have produced daylighting

COMMENTS AND CLOSURE

This paper provides results obtained by Stress Engineering Services, Inc. related to an assessment of the transfer pipeline leakage during 2001 using computational fluid dynamics analysis techniques. As part of this effort, a sensitivity study was performed to address the effects of leakage rate, period of leakage, and anisotropy in soil conductivity (referred to as the conductivity ratio). The primary questions initially posed were under what conditions will daylighting occur and what period of time was required. Of particular focus was release data from July 2001 that was based upon actual product transfer tickets from the terminal facility.

There are several important observations associated with the CFD results that are listed below.

- Extended periods of non-leaking resulted in the soil absorbing within the berm the contents that were released from the prior periods of leaking. This was especially noticeable with the July 2001 data where a 15-day no-leak period existed. After a long period of non-leaking, the analyses showed that additional leaking practically started from a position as if no prior leaking had existed.
- From a sensitivity standpoint, the amount of product released significantly impacts the time required for daylighting, especially when considering the accumulation of fluid within the berm. As a point of reference, consider two competing volume releases: one being 69.7 gallons per hour and the other 54.7 gallons per hour. The larger leakage rate results in daylighting after approximately 100 hours, while the lower leakage rate requires between 250 and 300 hours to generate daylighting.
- Although not a major focus of the study, the effects of anisotropy in soil conductivity are important. When the conductivity in the vertical direction is less than in the horizontal direction, the resulting leakage profile is more elliptical than the predominantly circular pattern observed with the isotropic conductivity models. The likelihood for daylighting to occur is increased when the soil conductivity in the vertical direction is less than it is in the horizontal direction.

While it is possible that additional investigations could be performed, the results reported in this study show that daylighting could have occurred within a relatively short period of time by assuming extended periods of leaking. The effects associated with reduced soil conductivity in the vertical direction and increased flow rates reduce the time required for daylighting to occur. These results are consistent with the trends reported previously by others. However, the use of computational fluid dynamics permitted detailed sensitivity analyses. The results of these sensitivity analyses are not available using the analytical methods employed by other organizations that performed prior investigations of the transfer line.
The CFD analysis results demonstrate that daylighting could have occurred for released volumes ranging from approximately 6,000 gallons to 25,000 gallons and for periods of time ranging from 100 hours to as long as one year or more.

The computational fluids dynamics modeling efforts demonstrate that it is entirely possible for daylighting to occur using plausible boundary and loading conditions. When considering the entire battery of modeled scenarios, it is clear that plausible conditions do exist that result in daylighting. In order for daylighting to occur, conditions must exist that involve specific combinations of extended periods of leaking, a leak rate of sufficient magnitude, and anisotropy of soil conductivities.

REFERENCES

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[3] M. Harr, *Ground Water and Seepage*, Dover publications, 1990.
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Table 1 – Model Conditions for Pressure (based on actual July 2001 fuel tranfer data)

Step #	Time (hours)	Leakage Rate (gallons/hour)	Leaked Fluid (gallons)
1	26.5	28.5	757.5
2	26.6	0	0
3	20.8	40.0	833.0
4	26.4	0	0
5	11.5	48	555.8
6	122.5	0	0
7	13.4	35.5	476.4
8	13.1	0	0
9	19.2	69.7	1342.1
10	369	0	0
11	17.8	54.7	975.3
12	24	0	0
TOTAL	**667.1**		**4940.2**

Table 2 – CFD Modeling Scenarios

Scenario	Description	Volume of Product Released	Daylighting (YES or NO)
1	Continuous leaking (***330 hours***)	24,685 gallons (240 ft^3/day · 330hrs)	YES
2	Leak rates based upon tabulated existing data **only for July 2001** considering two different pressure levels: a. Pipeline beginning pressure (***667 hours***) b. Static head end pressure (***667 hours***)	4,940 gallons (a) 6,212 gallons (b)	NO (a) NO (b)
3	Increased intensity of leak rate and ran model for a continuous period of time a. 69.7 gallons per hour (***100 hours***) b. 54.7 gallons per hour (***250-300 hours***)	10,934 gallons (a) 19,982 gallons (b)	YES (a) YES (b)
4	Anisotropy in soil conductivity (used Scenario 2b leak data - **only for July 2001**). CR is ratio of vertical to horizontal conductivity. a. CR = 1/3 (***256 hours***) b. CR = 1/10 (***667 hours***)	4,913 gallons (a) 6,212 gallons (b)	NO (a) YES (b)

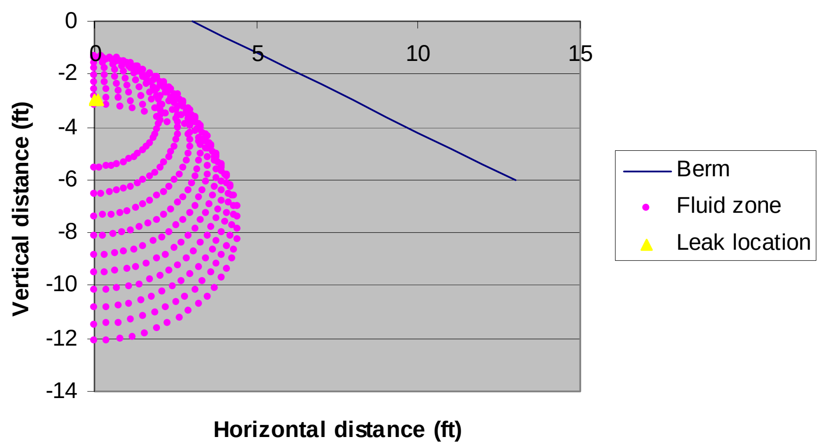

Figure 1 - Wetted zone after 10 hours of leaking (leak rate=240 ft^3/day)

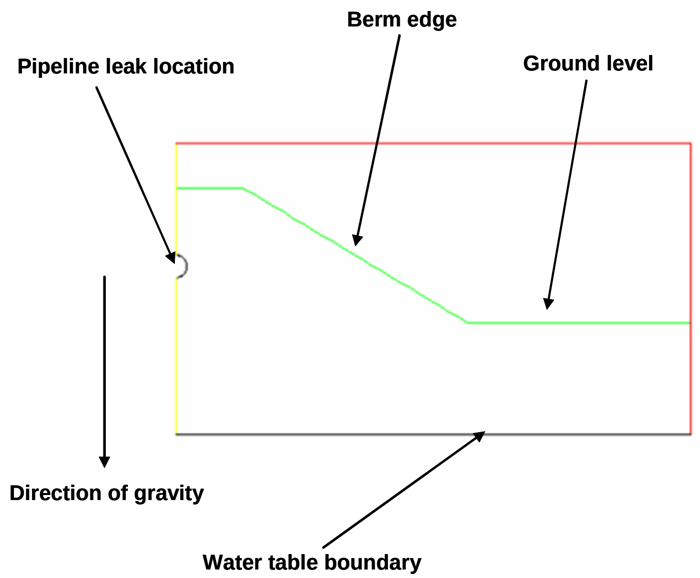

Figure 2 – Schematic diagram of CFD modeling domain

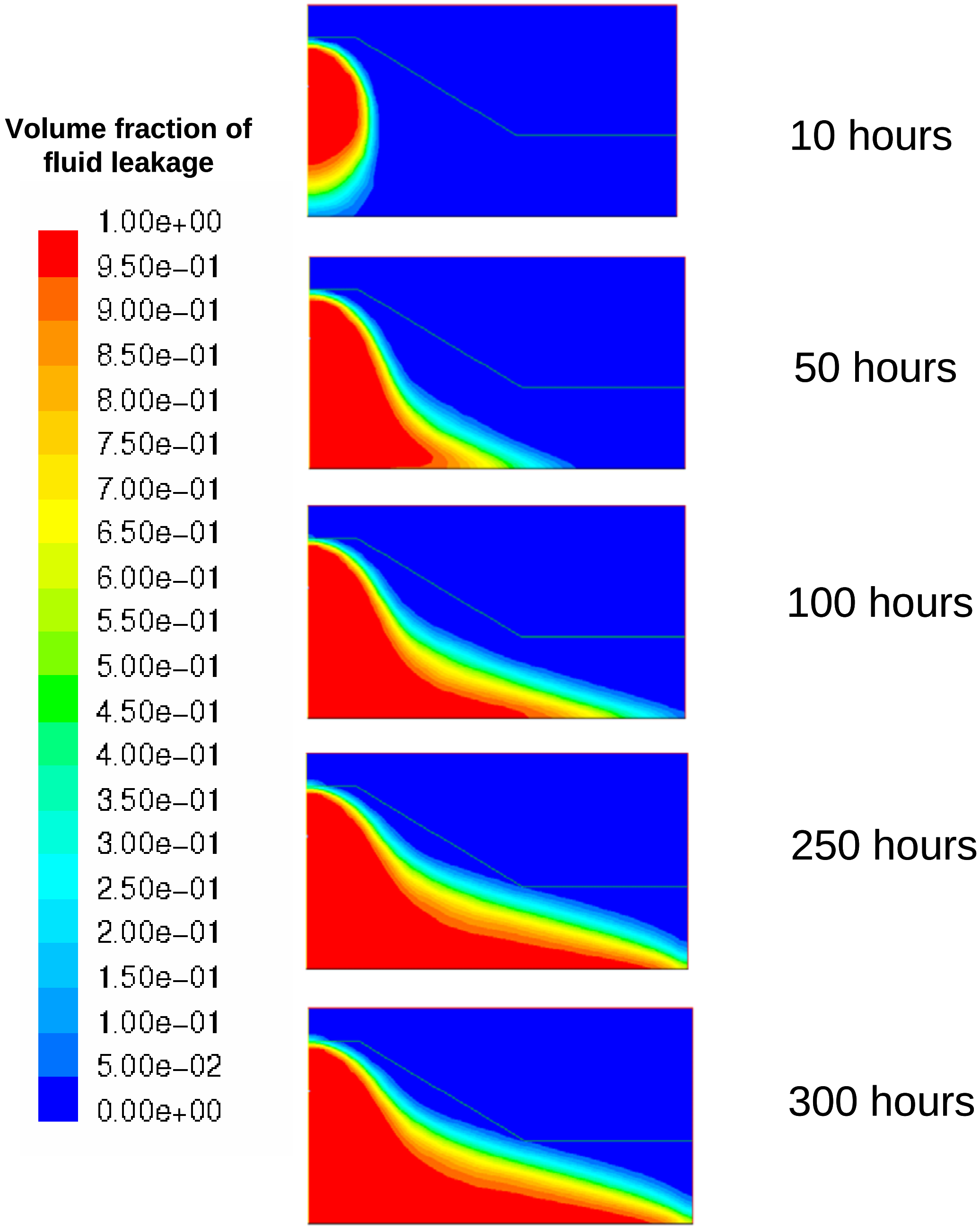

Figure 3 – CFD contour plots with continuous leaking at 240 ft^3/day

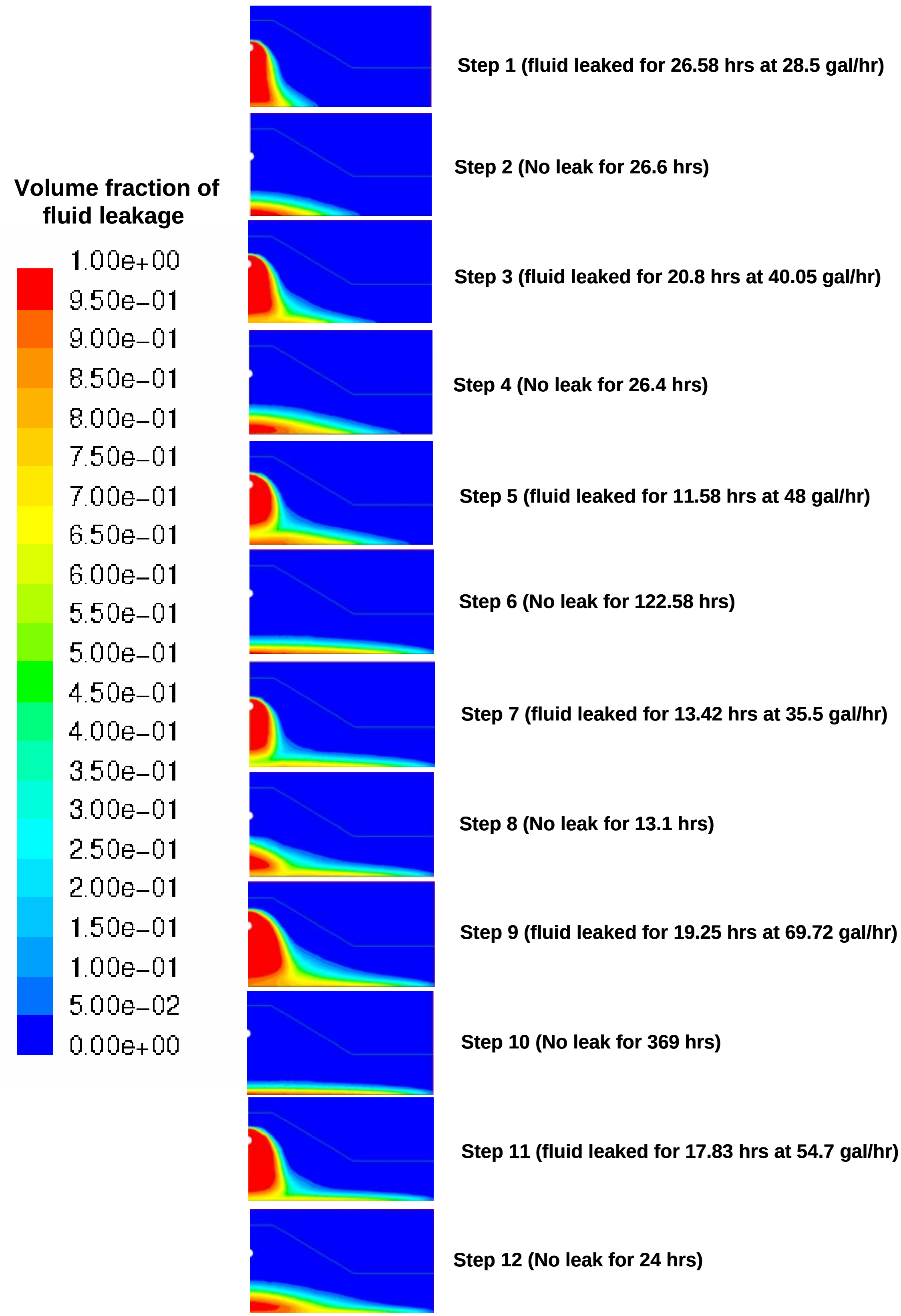
Volume fraction of fluid leakage
1.00e+00
9.50e-01
9.00e-01
8.50e-01
8.00e-01
7.50e-01
7.00e-01
6.50e-01
6.00e-01
5.50e-01
5.00e-01
4.50e-01
4.00e-01
3.50e-01
3.00e-01
2.50e-01
2.00e-01
1.50e-01
1.00e-01
5.00e-02
0.00e+00
Step 1 (fluid leaked for 26.58 hrs at 28.5 gal/hr)
Step 2 (No leak for 26.6 hrs)
Step 3 (fluid leaked for 20.8 hrs at 40.05 gal/hr)
Step 4 (No leak for 26.4 hrs)
Step 5 (fluid leaked for 11.58 hrs at 48 gal/hr)
Step 6 (No leak for 122.58 hrs)
Step 7 (fluid leaked for 13.42 hrs at 35.5 gal/hr)
Step 8 (No leak for 13.1 hrs)
Step 9 (fluid leaked for 19.25 hrs at 69.72 gal/hr)
Step 10 (No leak for 369 hrs)
Step 11 (fluid leaked for 17.83 hrs at 54.7 gal/hr)
Step 12 (No leak for 24 hrs)

Figure 4 – CFD contour plots with periodic leak rates

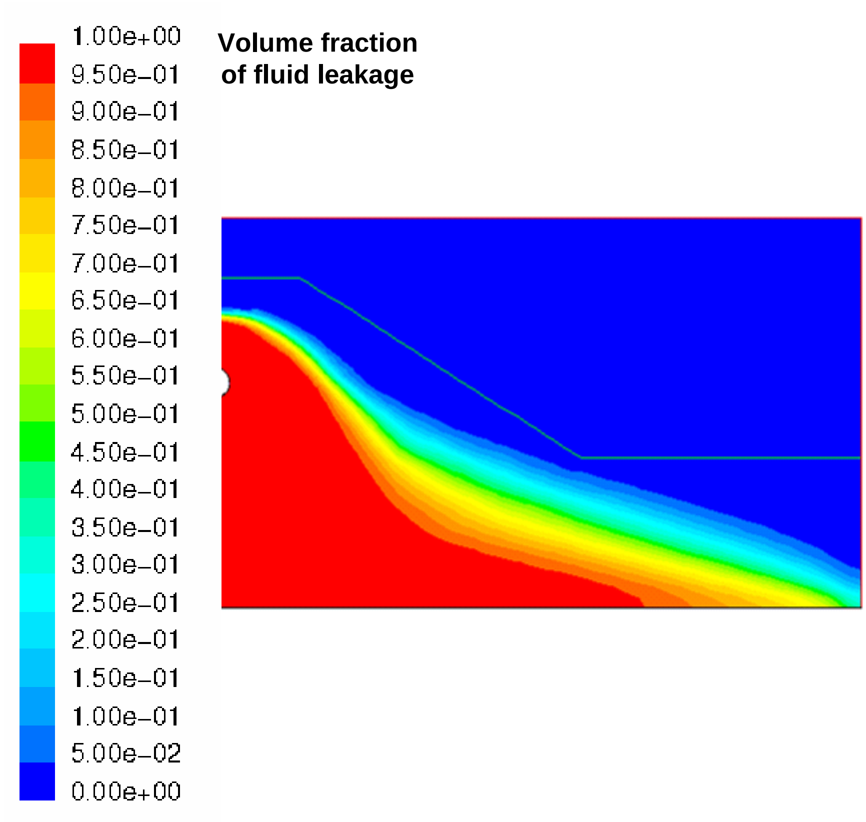

Figure 5 – Leakage distribution for *extended* Step #9 (daylighting at 100 hours)

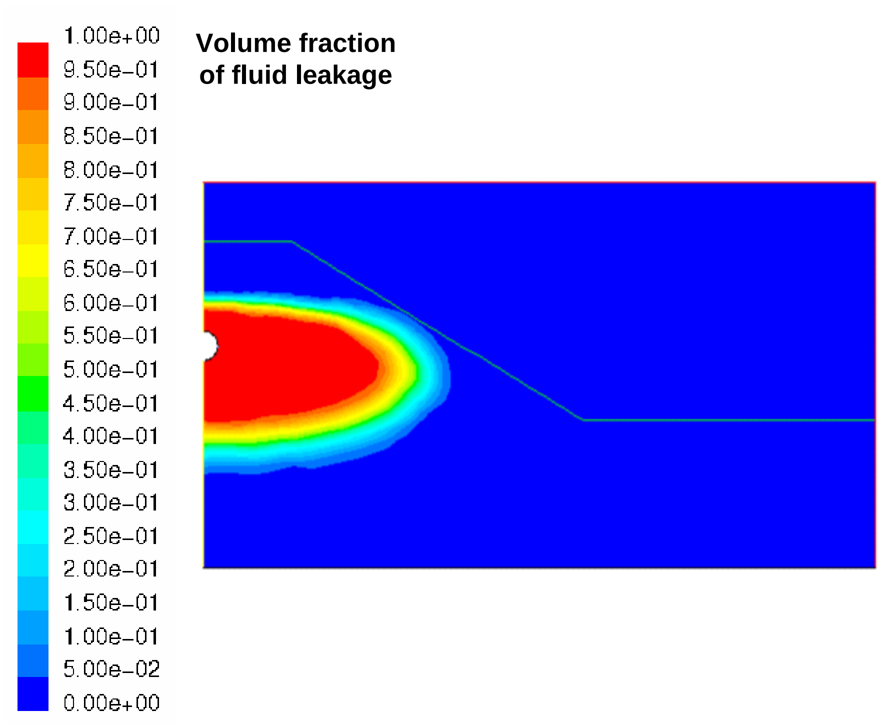

Figure 6 – Leakage distribution at the end of Step #11 (CR = 1/10)