Methodologies for Evaluating Defects in the Catalytically Blown Asphalt Liner in the Secondary Containment System at the Valdez Marine Terminal

By

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EXECUTIVE SUMMARY

This report describes methods that can be used to evaluate the catalytically blown asphalt (CBA) liner in the secondary containment systems at Valdez Marine Terminal and provides recommendations on the most suitable methods for assessment. The report also describes a statistical method that was developed to compute the total number of defects (holes, cuts, cracks, or other features that fully penetrate the CBA liner and provide a pathway for liquid flow) in a secondary containment liner with a specified degree of statistical confidence based on outcomes from inspection over a portion of the liner. The statistical methodology was also used to demonstrate how much area of liner needs to be inspected to identify the defects in the liner. Charts are provided that can be used to determine the minimum area of evaluation to obtain an assessment of liner defects with an acceptable percentage of missed defects and an acceptable probability of mistake.

Findings from the study indicate that inferences based on evaluating only a fraction of a CBA liner are subject to considerable uncertainty, with a high probability of missing a significant fraction, if not a majority of defects. The minimum area of liner to assess depends on the acceptable fraction of defects missed and an acceptable probability of a mistaken inference. For typical statistical thresholds in environmental analysis (e.g., 99% probability of detection of defects), essentially the entire liner area needs to be evaluated if the defects are to be identified. In the context of estimating the total number of defects in the liner based on data collected from a partial-area inspection, at least 20% of the liner area should be assessed to reduce uncertainty in the estimated total number of defects.

Leak location and electrical resistance tomography surveys are recommended for evaluating the CBA liner at VMT. If the objective is to identify the defects in the CBA liner, the surveys should be applied over the entire CBA liner. If the objective is to estimate the number of defects for a leakage analysis, the surveys can be conducted over a fraction of the area (e.g., 20% or more) and the findings extrapolated using the method described in this report. A pilot study should be conducted to evaluate the leak location and electrical resistance tomography methodologies along with direct visual inspection to ground truth the outcomes of the surveys.

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1. INTRODUCTION

Secondary containment systems are employed at the Valdez Marine Terminal (VMT) to protect the subsurface environment should a leak or other spill occur from oil storage tanks at the terminal. Each secondary containment system consists of an area surrounding a set of tanks with a containment berm around the perimeter and a catalytically blown asphalt (CBA) liner placed across the surface. The liner is underlain by a layer of gravel prepared from crushed rock, and is overlain by a thin gravel bedding layer and a thick layer of cover soil comprised of gravel fill. The CBA layer was specified to be at least 8 millimeters (mm) thick (5/16 inches). The secondary containment systems at VMT were constructed in the 1970s, when lining technology was in its infancy.

The effectiveness of the secondary containment system depends greatly on the integrity of the CBA liner. If the liner contains defects (i.e., holes, cuts, cracks, or other features that fully penetrate the CBA liner and provide a pathway for liquid flow), oil flooding the secondary containment area would rapidly be released into the subsurface. The gravel surrounding the CBA liner exacerbates this condition, as the gravel subgrade provides no resistance to flow if a defect in the CBA exists, allowing rapid leakage of any oil spilled on the CBA liner. This makes the secondary containment system particularly vulnerable to defects in the liner. Thus, periodically evaluating the condition of the liner is critically important, especially as the liner ages.

In this study, direct and indirect methods to evaluate the integrity of the CBA liner were reviewed and compared. A statistical method was developed to evaluate how much area of liner needs to be inspected to draw statistically significant inferences regarding the condition of the liner. A method was also developed to estimate the total number of defects in the liner with a defined statistical significance based on an assessment of a portion of the liner.

Outcomes of this study are described in this report. Direct and indirect methods to evaluate the integrity of the CBA liner are described in Section 2, which includes specific recommendations regarding methodologies that should be employed to evaluate the CBA liner. The statistical methods are described in Section 3, which includes an example of how to estimate the total number of defects in a secondary containment liner based on data collected from an evaluation of a portion of the liner for a defined degree of statistical confidence. Section 3 also includes charts that can be used to determine the minimum area of evaluation to obtain a reliable assessment of liner defects with an acceptable probability of mistake. A summary and conclusions are in Section 4 and references are in Section 5.

2. ASSESSEMENT METHODS

The effectiveness of any lining system is influenced by the number of defects present in the liner. Liners with fewer defects typically are more effective, as fewer pathways exist through which liquid can escape (Giroud and Bonaparte 1989a,b). Assessments are often made to determine the number, size, and location of defects. Data collected from the assessment are then compared to specifications for an acceptable liner and repairs are made if needed. Most assessments are conducted immediately after construction of the lining system, although they can be conducted any time provided the liner is not covered with waste or other material that would prohibit assessment. This section reviews methods to detect the presence of defects in liners, emphasizing methods that can be used to determine the location and size of defects.

2.1 Direct Assessment

Direct assessments consist of direct visual inspection of the surface of the liner for the presence of defects. In some cases, the visual inspection is complemented with tools such as spark testers or pooling tests to facilitate identification of small defects that may be difficult to identify visually (Benson et al. 1999, 2001, TRI 2019). Complementary methods are particularly helpful in field environments where dirt and debris may be present and lighting of the surface can vary considerably, hindering visual identification of small defects.

Direct assessment is the best methodology to identify and quantify defects, especially when coupled with a complementary tool like a spark tester. Inferences from a direct assessment are unambiguous and the likelihood of missing defects is minimal. However, the method can only be applied if the liner is uncovered or if material overlying the liner is removed. Consequently, direct assessments are normally conducted immediately after the liner is installed as part of construction quality control and before any overlying materials are placed.

Direct assessments can be conducted on existing liners that are covered if the overlying material is removed, as has been practiced at the VMT (Fig. 2.1, Golder 2015, 2016, 2017, 2018). Removal of existing material imposes risk, as equipment used to remove overlying soils can damage the liner, necessitating repairs and creating ambiguity regarding whether a defect existed a priori or was caused by excavation. Direct assessments are also extremely labor intensive. Thus, in many cases only a fraction of the liner is evaluated. Findings from the partial evaluation are extrapolated to define an expected condition over the entire liner.

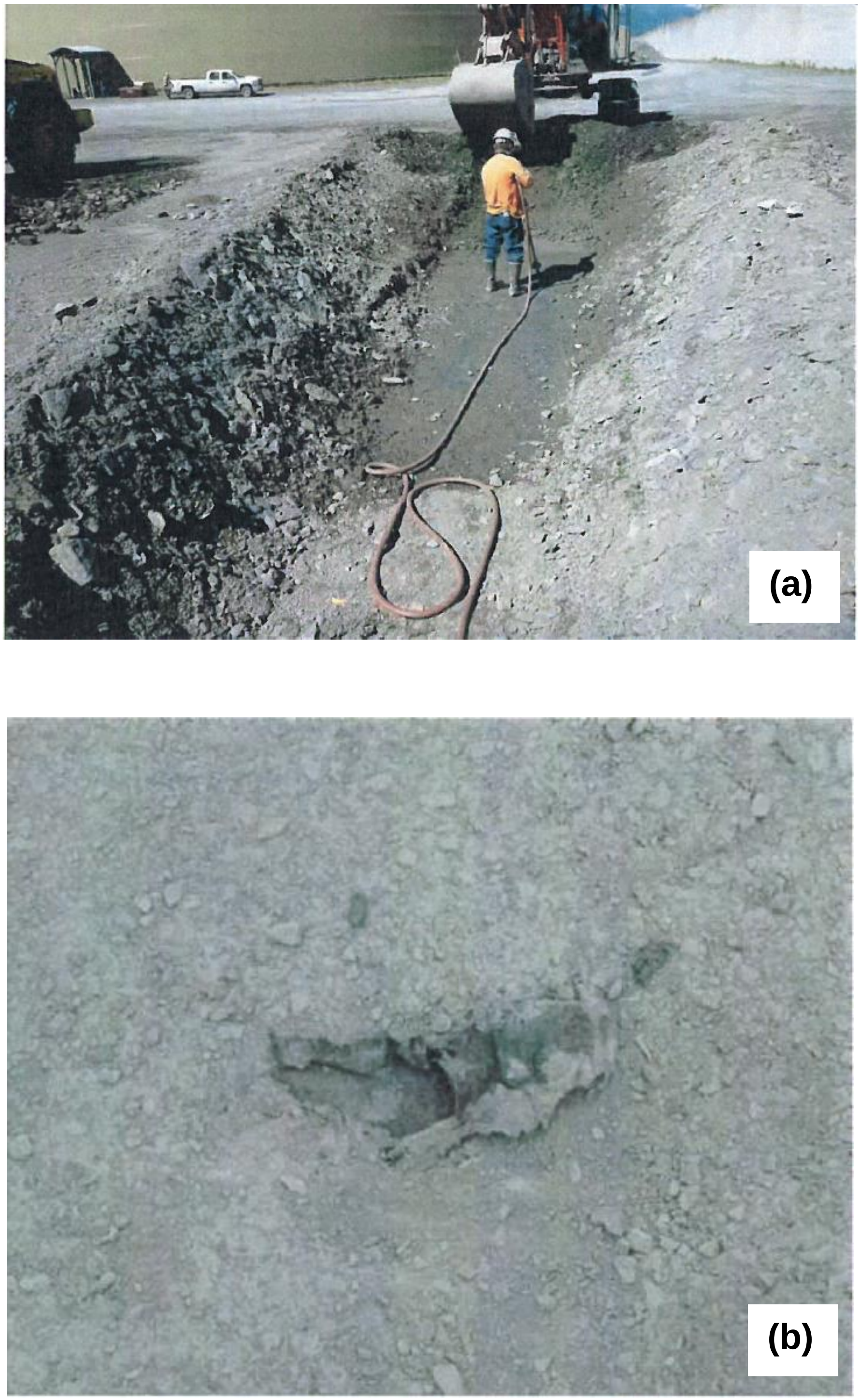


Fig. 2.1. Removing overlying gravelly material from the VMT secondary containment area to expose the CBA liner (a). Defect encountered during visual inspection of the liner (b) (from Golder 2015).

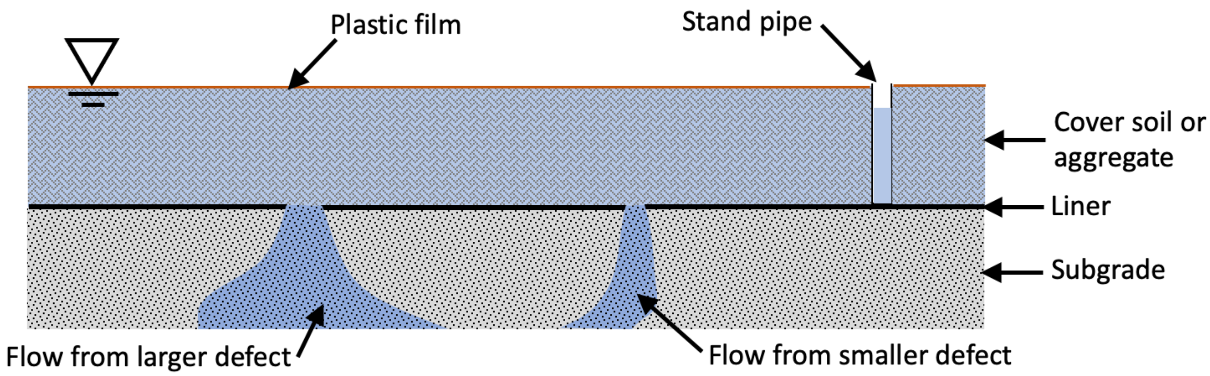
2.2 Indirect Assessments

Indirect assessments consist of imposing a boundary condition on the surface of the liner, or on material placed on the liner, and measuring a response that is influenced by the presence of defects in the liner. The boundary condition could be hydraulic (e.g., water pressure), pneumatic (e.g., gas pressure), chemical, or electrical. A key difference between indirect and direct methods is that the presence and characteristics of defects are *inferred* from an indirect method, rather than being observed directly. Thus, outcomes of indirect assessments inherently have ambiguity that is absent from direct assessments. This ambiguity is often addressed by coupling indirect and direct methods, using the indirect method to identify or locate defects followed by visual inspection, excavation, and repair.

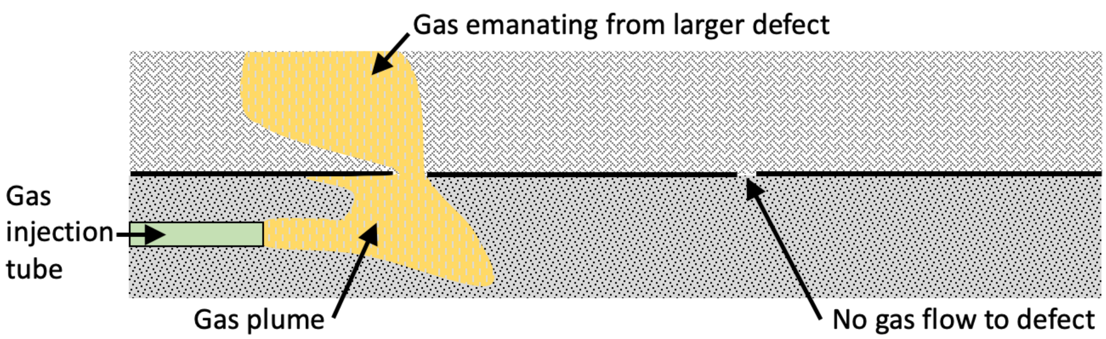
2.2.1. Hydraulic and Pneumatic Assessments. Hydraulic and pneumatic assessments consist of applying a fluid pressure on the upper or lower surface of the liner, and recording the response to the applied boundary condition (Fig. 2.2). For example, water may be pooled on the surface of the liner and the elevation monitored to determine if leakage is occurring (Benson et al. 1999, 2001, Golder 2013, Calendine et al 2018). Alternatively, a gas (e.g., argon) or smoke might be applied on the lower boundary, with detection on the surface to identify defects.

Hydraulic methods provide a direct assessment of leakage rate, but generally do not provide information on the number, size, or location of defects, as the total leakage rate is measured and both small and large defects may contribute to the leakage rate (Fig. 2.2a). The accuracy of hydraulic method depends greatly on the accuracy with which the leakage rate can be measured. More accurate estimates are obtained for higher leakage rates, as a variety of factors affect the accuracy of measuring the volume of water leaking from the liner. These include evaporation from the surface, water level fluctuations due to barometric pressure effects and wind, and the ambiguity in the volume of pores in the overlying material. These errors become less significant as the volume of leakage increases, making higher leakage rates more accurate than lower leakage rates on a relative basis.

Pneumatic methods provide an indication of the location of defects, but do not provide quantitative information on the size or number of defects. The accuracy of pneumatic methods depends on the ability to apply gas pressure or smoke across the entire bottom surface of the liner in the area to be evaluated. Because the liner is in place, however, there is no means to confirm whether the gas or smoke has reached all points of interest (Fig. 2.2b).



(a) hydraulic test



(a) pneumatic test

Fig. 2.2. Conceptual drawings of hydraulic (a) and pneumatic/smoke (b) testing of liners.

As with all tracer techniques, pneumatic methods can “miss” defects because the gas or smoke is not in contact with all areas of the liner. Information on the size and shape of defects is obtained by removing the materials above the liner where smoke or gas is detected, and then searching for the defect through which the gas or smoke was flowing. That may or may not be near the location where the gas or smoke was observed on the surface, depending on the flow path of the gas after migrating from the defect.

2.2.2. Geophysical Methods. Geophysical methods consist of applying an electrical or mechanical signal to the surface of the liner or the surrounding materials, and measuring the response to the signal (Kearey et al. 2002). The type of response depends on the geophysical method applied and the type of defects in the liner.

2.2.2.1 Leak Location Surveys

The most common geophysical method used to evaluate the integrity of liners constructed with thin non-polar materials (e.g., geomembranes and CBA liners) is the “electrical leak location survey” (Fig. 2.3). A high voltage and low direct current (DC) power source is used to apply an electric field across the surface of the liner (Peggs 2007, Koerner et al. 2013, Calendine et al. 2018, Gilson-Beck 2019). The cathode is buried beneath the liner, and the anode is moved across the surface of the liner or earthen materials over the liner. When intact, the non-polar liner acts as an insulator that prevents current flow. When a defect in the liner exists, moisture in the adjacent pores provides electrical continuity and current flows through the defect and the adjacent soils. This current flow is recorded as a change in voltage or current associated with the location of the electrode on the surface. The specific location and size of the defect is identified by removing the soils overlying the liner in the vicinity of the location where the survey identified the presence of a defect.

Leak location surveys are very effective, even for identifying very small defects (Beck et al. 2013, Koerner et al. 2013, Gilson-Beck 2019). However, they are normally conducted on exposed liner or on liner covered with an earthen layer of modest thickness (~0.3 meters (m)), such as a leachate collection system. Applying leak location surveys to liners covered with much thicker layers, such as the overlying material in the secondary containment system at VMT, is uncommon. However, testing of secondary containment liners at five pump station tank farms along the Trans Alaska Pipeline System by Anderson et al. (2002) demonstrated that a leak location survey could identify small defects, even with overlying material in place.

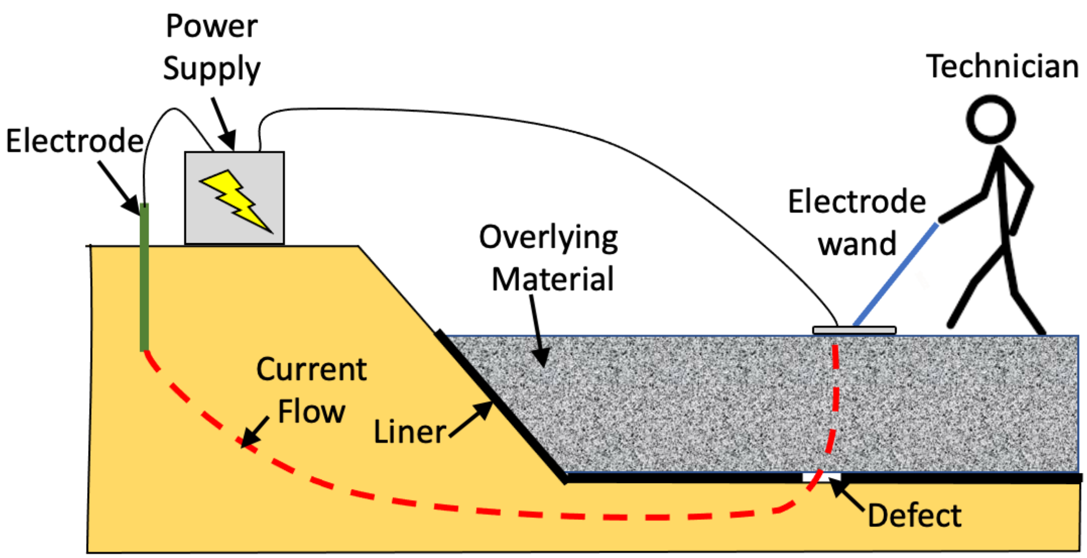


Fig. 2.3. Schematic illustrating principle by which electrical leak location surveys are used to identify defects in a liner.

2.2.2.2 Streaming Potential Assessment

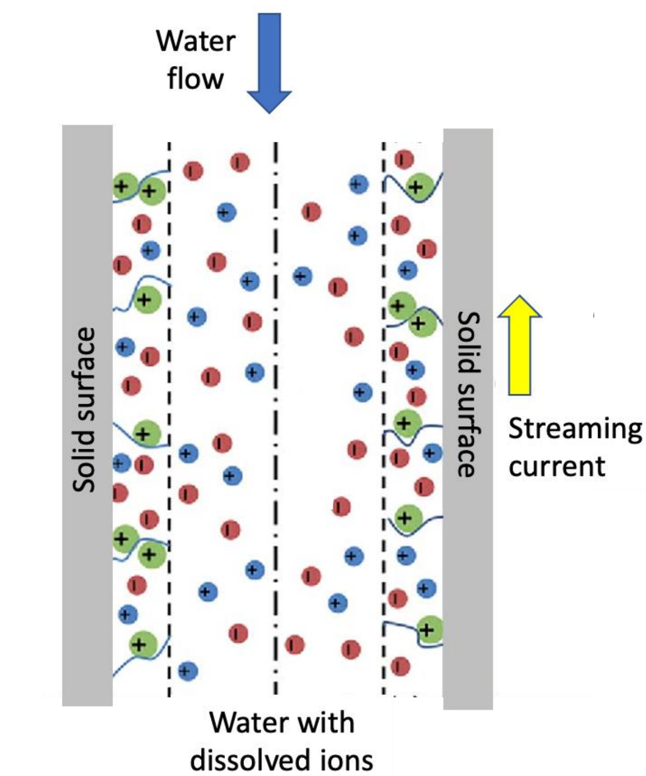
Streaming current is electrical transmission associated with the migration of ionic species in flowing water (Fig. 2.4). The streaming current is observed as a voltage (potential) drop associated with flowing water (Fink 2006, Baker and Cull 2004, Jougnot et al. 2020). In a liner application with water pooled on the surface, streaming current will be present where flow is occurring through defects in the liner, and a streaming current assessment could be conducted concurrently with a hydraulic assessment. Concurrent assessments would provide information on both rate of flow (hydraulic assessment) and direction and location of flow (streaming potential).

Changes in voltage associated with streaming current are extremely small and difficult to measure. These measurements can be made in the laboratory, but become nearly impossible in the field as other sources of electrical noise overwhelm the magnitude of the voltage changes in the flow field. Thus, while a streaming potential assessment is viable in principle, applying the principle for leak location is impractical in the field.

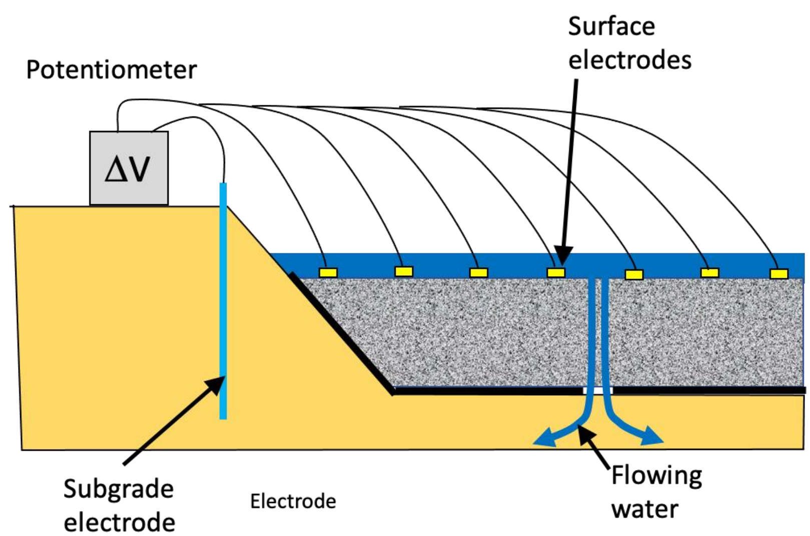
2.2.2.3 Electrical Resistance Tomography

Electrical resistance tomography (ERT) is a more elaborate application of the geoelectric principles employed in a leak location survey. An array of electrodes is deployed across the surface of the liner and around the periphery of the liner (Fig. 2.5). A current is applied across every combination of electrode couples in the array and the voltage drop across each couple is measured. The array of voltage drops is then used to constrain a three-dimensional inversion of Gauss' Law to obtain a map of electrical resistivity over the entire domain of assessment (Schmia et al. 1996, Zhou 2019).

The contrast in electrical properties between the liner and the overlying and underlying materials results in stark contrasts in electrical resistivity. Areas of intact liner are depicted in resistivity maps from ERT as zones with very high electrical resistivity (intact liner is an electrical insulator). Defects adjacent to more conductive material have much higher electrical resistivity and are depicted as conductive zones in the resistivity map (Daily et al 2001). However, transitions between more resistive and more conductive areas in the map are not as sharp as they are in reality, as inversion of the three-dimensional electrical field creates smoothing in areas where transitions in resistivity occur.



(a) Water flow and streaming potential



(b) Conceptual field application

Fig. 2.4. Schematic illustrating principle of streaming current due to water flow (a) and conceptual illustration of set up to identify liner defects with streaming current (b).

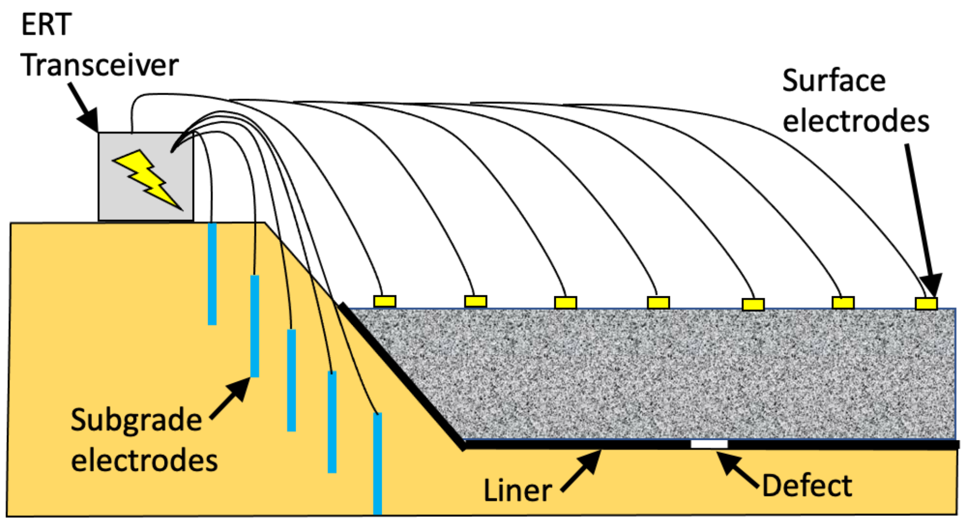


Fig. 2.5. Schematic illustrating electrode distribution employed for a conceptual deployment of electrical resistance tomography (ERT).

The accuracy of ERT for identifying defects in a liner depends on the density of the electrodes placed on the surface and in the subgrade around the perimeter, the thickness of material above and below the liner, and the contrast in electrical resistivity between the liner and the adjacent soils (Dailey et al. 2001). Wet soils adjacent to the liner promote greater contrasts in electrical resistivity, permitting identification of smaller defects as well as more precise location of defects. Denser electrode spacings also result in greater precision in the resistivity map, thereby improving predictions of location and size of defects.

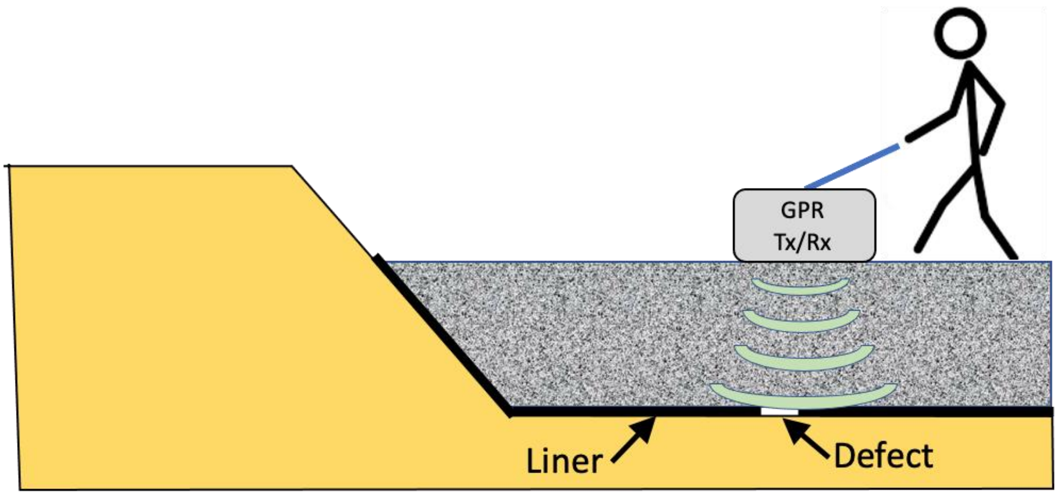
Like other geophysical methods, ERT provides an indication of the size and location of a liner defect. Defining the size, location, and extent of defects requires removal of material directly over the defect location, followed by visual inspection.

2.2.2.4 Ground Penetrating Radar

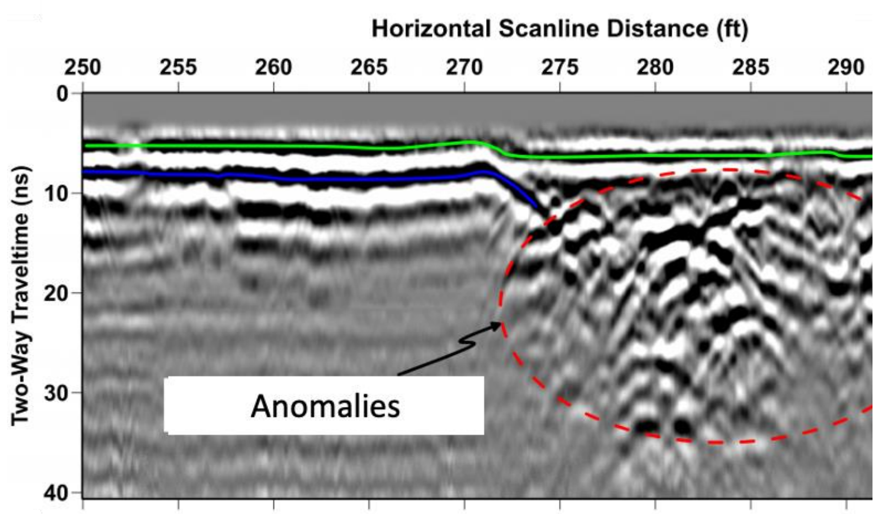
Ground penetrating radar (GPR) is a geoelectric method based on measuring reflections of electromagnetic (EM) waves transmitted into a medium (Daniels 2007, Utsi 2017). Reflections are created when the transmitted EM wave encounters a material with contrasting electrical properties (Fig 2.6). The location of the object is determined by estimating the round-trip travel time of the wave when the reflection is received at the GPR transceiver. The methodology is directly analogous to locating aircraft in the atmosphere with airborne radar, except the distance computations have greater uncertainty in GPR as the dielectric properties of the transmitting medium are more uncertain than those of the atmosphere.

When applied in a liner application, the transceiver is set on the surface of the overlying material and an EM wave is transmitted downward (Fig. 2.6). When the wave encounters a material with contrasting dielectric properties, such as a CBA liner or a geomembrane, the wave is reflected and travels back towards the transceiver. Those reflections differ when the wave encounters a defect. Consequently, the transceiver receives contrasting reflections from the liner and from defects. Analysis of these reflections is used to create a map of the liner and the defects.

While the principles on which GPR functions are sensitive to the difference in geoelectric properties of the liner and the defects, resolving reflections from very small features such as liner defects is difficult with GPR. The reflections from small features tend to get lost amongst other reflections from other variations in geoelectric properties of the materials through which the wave is propagating (Anderson et al. 2002). Additionally, resolving small defects becomes increasingly difficult when the material overlying the liner is thicker. For these reasons, GPR generally is not effective in identifying or locating liner defects in liners.



(a)



(b)

Fig. 2.6. Schematic illustrating concept of GPR survey of lining system (a) and example of GPR image illustrating anomalies in waveform (b). EM waves shown in GREEN in (a).

2.3 Implications for Assessment

Advantages and disadvantages of the aforementioned assessment techniques are summarized in Table 2.1 along with a ranking of the relative efficacy of the methods in the context of detecting defects in the CBA liner at VMT. All of the methods have merits, although GPR and streaming potential (efficacy rank of 4 and 5) have too many disadvantages and too few advantages to warrant consideration.

Of the indirect methods, the conventional leak location survey is ranked highest in efficacy (efficacy ranking = 1). This established method can be used with material overlying the liner in place. However, once defects are located, the material overlying the liner needs to be removed in the vicinity of defects to fully characterize the defect. Additionally, leak location surveys generally are not used for liners with an overlying layer as thick as is present in the secondary containment areas at VMT. Sensitivity analyses and a pilot test will need to be conducted to assess the efficacy of leak location survey methodology, and to define suitable operating parameters. ERT has the second highest efficacy ranking of the indirect methods, largely because experience with ERT in evaluating liners is limited. Past experience from Anderson et al. (2002) should be helpful when evaluating the significance of thickness of the overlying material.

Visual inspection is a viable method with equal efficacy ranking as ERT. The primary challenge with visual inspection is the considerable effort to remove materials overlying the liner and the level of care that must be used to remove the overlying material without damaging the liner. From this perspective, an indirect method with comparable or higher efficacy ranking is preferred (ERT, leak location survey).

Both a leak location survey and ERT are recommended for pilot testing at VMT. These should be followed with visual inspection, albeit conducted with great care to ensure no damage to the liner occurs during inspection. The visual inspection would be used to ground truth the outcomes of the leak location survey and the ERT evaluation.

Table 2.1. Advantages and disadvantages of liner assessment methods.

Method	Direct or Indirect	Advantages	Disadvantages	Efficacy Ranking
Visual inspection	Direct	- Defects are observed directly, providing specific location and size	- Requires removal of overlying material - Potential damage during removal - High effort	2
Hydraulic	Indirect	- Provides direct measure of effectiveness of liner - No disturbance of liner or adjacent materials	- No information on location or size of defects - Lower leakage rates have high uncertainty - High effort	3
Pneumatic	Indirect	- Can locate defects - No disturbance of liner or adjacent materials	- Defects can be missed as contact of gas or smoke on lower surface liner unknown - Defects may not be near location where gas or smoke emanates on surface - Requires removal of overlying material to characterize defects	3
Leak Location Survey	Indirect	- Directly locate defects in liner - No disturbance of overlying materials - Established commercial method	- Must expose liner to characterize defect - May be affected by thickness of layer overlying liner	1
Streaming Potential	Indirect	- Response is directly related to flow through defects	- Response often swamped by other electrical noise - Very little experience in application	5
Electrical Resistance Tomography	Indirect	- Response directly related to contrast in properties between liner and defects - Provides map of area of assessment to define location and relative size of defects	- Labor intensive to conduct - Requires 3D inversion to identify defects - Limited experience	2
Ground Penetrating Radar	Indirect	- Response sensitive to contrasting electrical properties liner and defect - History of using technology for identifying anomalies	- Signal unable to identify small anomalies typical of liner defects - Field evaluations not successful	4

3. EFFECT OF EVALUATION AREA ON DETECTING AND QUANTIFYING DEFECTS

As described in Section 2, direct or indirect methods can be used to detect and quantify the presence of defects in a CBA liner or geomembrane buried beneath a layer of protective cover soil, like that used for secondary containment at VMT. Direct methods consist of unearthing the barrier followed by visual inspection of the liner surface and the delineation and quantification of defects. Indirect methods consist of imposing a boundary condition on the liner, and measuring a response (e.g., electrical current) associated with that boundary condition that is related to the location and geometric characteristics of the defects. Direct methods are preferred in the context of having clear evidence of a defect, as visual inspection is the most direct means to ascertain whether a defect exists. However, direct methods are risky and costly, as the unearthing procedure requires considerable effort and can create defects that did not exist a priori. Indirect methods are less costly and avoid the risk associated with unearthing the barrier but can be less precise.

Regardless of the method used, the area to be evaluated must be defined. One approach is to evaluate the entire lined area. Another approach is to evaluate a portion of the lined area and extrapolate the outcome from the evaluated area to the entire lined area. Evaluating the entire area is more costly and imposes greater risk, but the outcomes are free of the uncertainty associated with "missing" defects that are present in areas that are not evaluated. In this section, the uncertainty associated with drawing inferences about the condition of a liner by evaluating a fraction of the area is described. A statistical method is described to quantify the uncertainty associated with estimating the presence and number of defects based on data collected from the fraction of the area that was evaluated.

3.1 Methodology

The Monte Carlo method was used to describe and quantify the uncertainty associated with detecting defects when a fraction of the area is evaluated. The Monte Carlo method consists of generating a series of "realizations" - possible scenarios in which the characteristic of the scenario (number of defects, location of defects) is generated by random sampling from probability distributions representing the type of uncertainty associated with each characteristic. This process is repeated many times and the collection of outputs is analyzed to describe the probabilistic characteristics of the phenomenon of interest (e.g., % missed defects). In this study, outcomes from Monte Carlo simulations were used to describe the uncertainty in the number of defects when the outcome of an evaluation is extrapolated to the entire area.

The area of secondary containment was described as a rectangle, approximating the shape of a secondary containment area used for oil storage tanks at VMT (Fig. 3.1) as described in Golder (2017). The rectangle approximating the lined area (Fig. 3.2) is 315 m long (L) and 120 m wide (W), with a total surface area (A = L x W) of 3.7 ha. A fraction of the area (0.9 ha) within the rectangle is covered by tanks (and not liner) and does not require evaluation.

Thus, the rectangle representing the entire area of secondary containment was reduced in length to account for the tanks, resulting in a rectangle representing the “effective area” of secondary containment with L = 240 m and W = 120 m (Fig. 3.2). This representation simplifies the analysis without loss of generality of the outcomes.

The methodology consists of generating a random set of defects, both the total number of defects and their locations, and a random set of sampling locations. The overlap of sampling locations with defects (“detections”) is then computed, with the number of detections recorded for each realization. The fraction of defects missed is computed and the total number of defects is estimated by extrapolating the number of defects detected to the entire area based on the fraction of the area evaluated. Statistical inferences are then made regarding the area of evaluation required to achieve an acceptable number of missed defects or acceptable error in the extrapolated number of defects.

3.1.1 Number and Location of Defects. The number of defects in the lined area was described with a Poisson distribution, which expresses the probability of a given number of events occurring in a fixed interval of time or space when these events occur with a constant mean rate that is independent of time or space (Ang and Tang 1975). The probability density function (pdf) for the Poisson distribution is:

$$f_d = \frac{N_d^n \, e^{-N_d}}{n!} \tag{1}$$

where (f_d) is the probability density, n is the number of defects per unit area in a given realization, and N_d is the mean number of defects per unit area. A typical histogram of number of defects is shown in Fig. 3.3 for a case where N_d = 15 defects/hectare (ha) for a simulation conducted with 20,000 realizations.

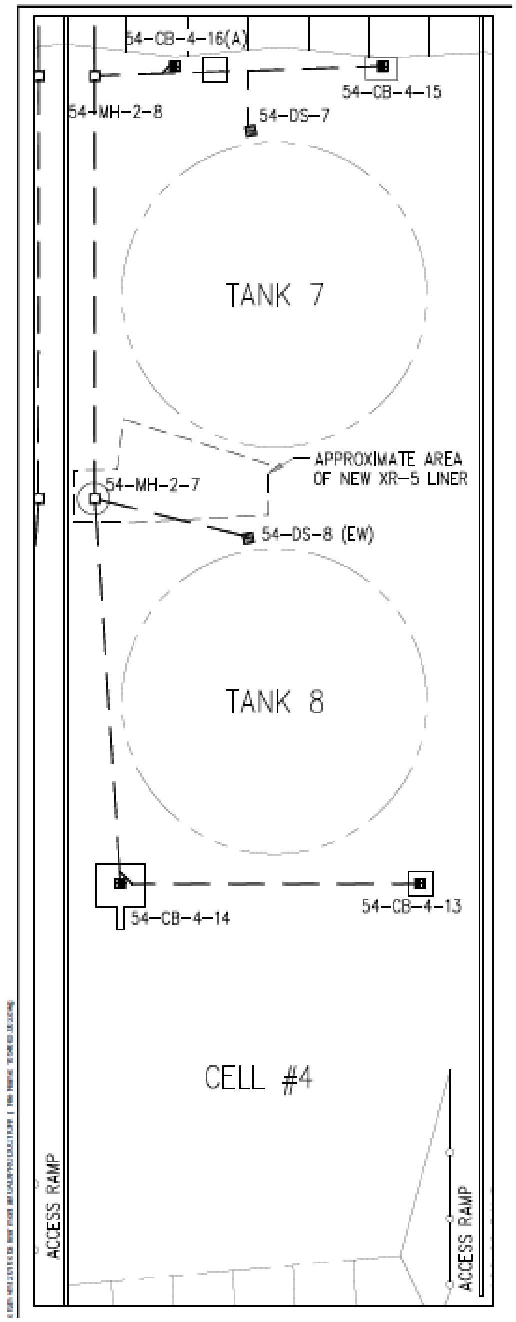
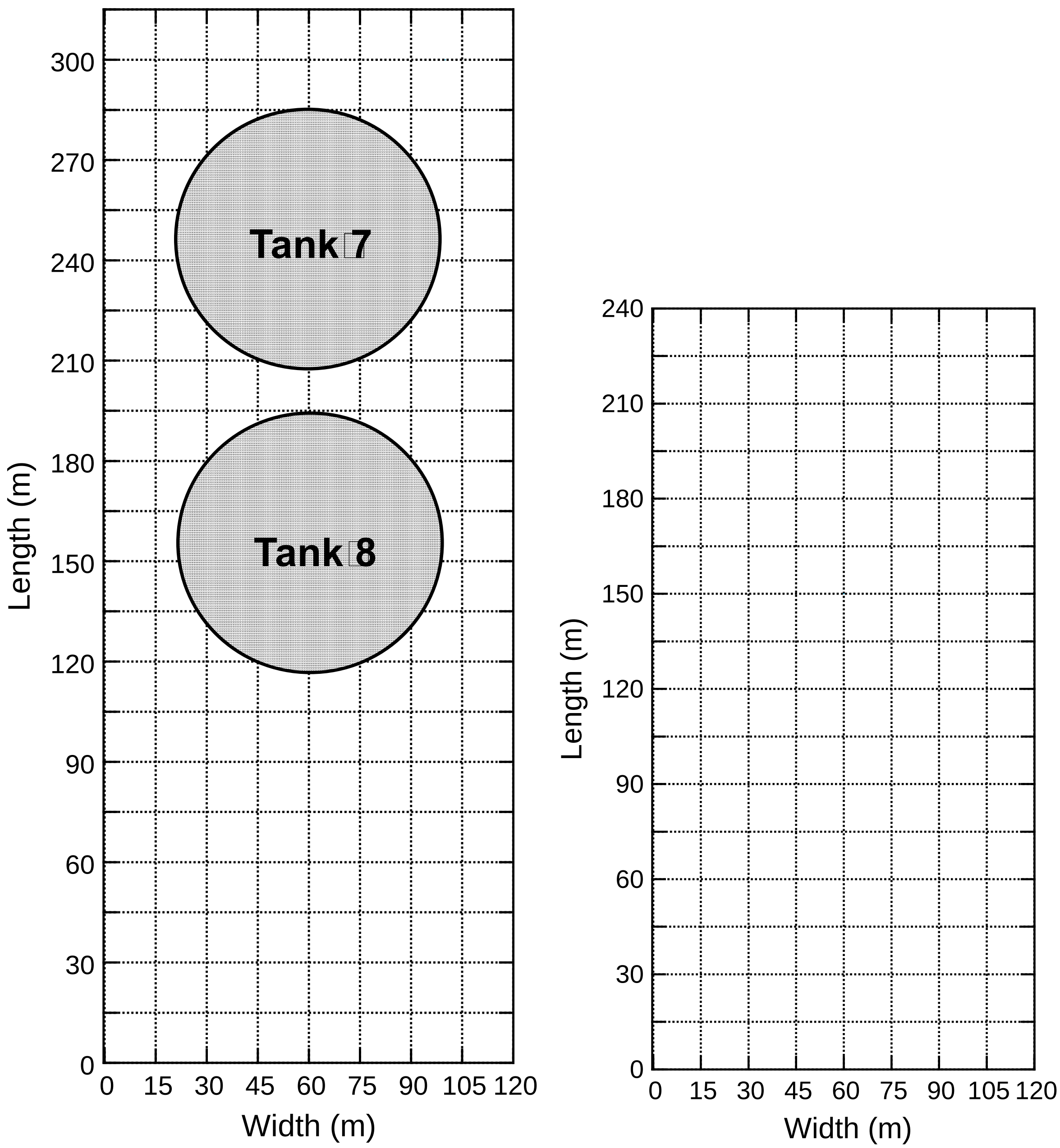


Fig 3.1. Typical secondary containment area with two storage tanks at the Valdez Marine Terminal (from Golder 2017).



(a) (b)

Fig 3.2. Actual area of secondary containment showing locations of tanks (a) and effective area of secondary containment used in analysis (b).

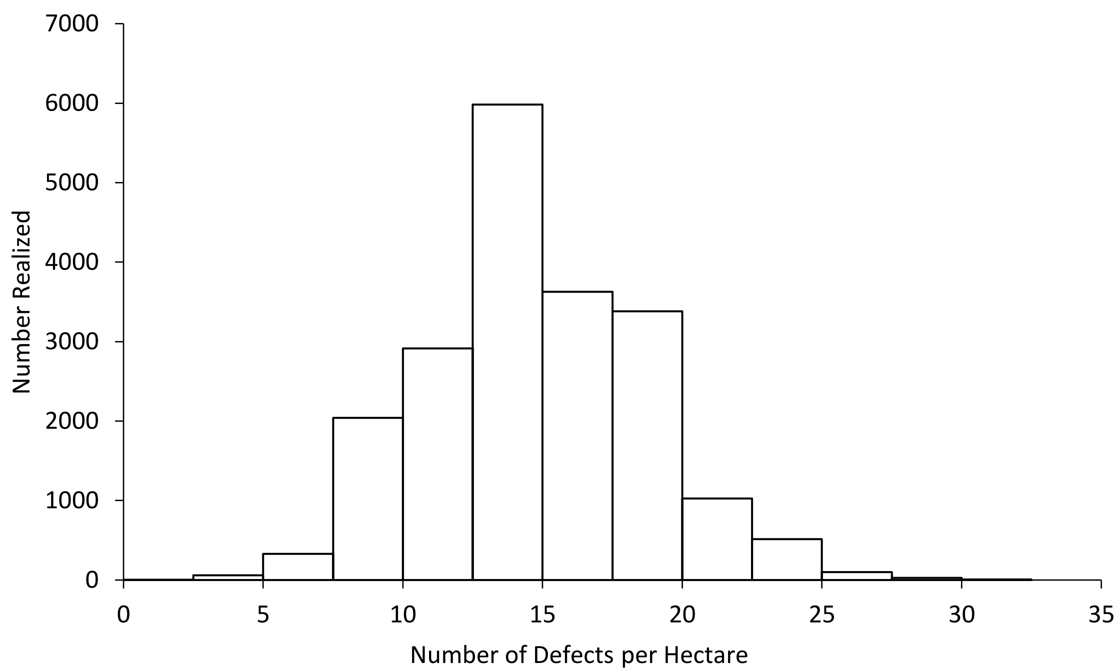


Fig. 3.3. Histogram of number of defects per ha for simulation with mean number of defects = 15 per ha and simulation with 20,000 realizations.

Defects were assumed to exist at any location within the rectangular area of secondary containment with equal probability, which was described by the two-dimensional uniform distribution with pdf:

$$f_{x,y} = \frac{1}{L\,W} \tag{2}$$

An example is shown in Fig. 3.4 of a realization of a set of 26 defects (blue dots) randomly distributed throughout the “effective” area of secondary containment that was generated for a case with N_d = 10 holes/ha.

3.1.2 Evaluation Areas. Evaluations were conducted over square regions having dimension L_e. The area being evaluated was assumed to be fully exposed for visual inspection without damaging the liner or evaluated non-destructively (e.g., leak location survey) with a method that identifies any and all defects present in the area of evaluation. Simulations were conducted for a single square region representing a small fraction of the total area (L_e^2/LW), the entire area, and a range of areas in between. The location of each square evaluation region was selected randomly from a grid partitioning the entire area of secondary containment (Fig. 3.4) to represent a random evaluation strategy. Each evaluation region had equal probability of being assigned to any location in the grid but could not occupy a region previously evaluated within a realization. The number of regions was assigned deterministically (e.g., by the evaluator).

3.1.3 Number of Detections or Misses. For each realization, locations of the defects were compared to locations of the evaluation regions, with a “hit” defined as a defect existing within an evaluation region. The total number of hits was determined for a given realization, and the total number of defects was extrapolated based on the number of hits and the fraction of the secondary containment area that was evaluated. The percent missed was computed as the number of missed defects (= total number of defects – number of hits) relative to the total number of defects.

The example shown in Fig. 3.4 represents a realization with 10 test areas (orange squares) each 15 m x 15 m in size that were randomly assigned from a uniform distribution to locations on the grid partitioning the rectangle defining the effective area of secondary containment. Five defects are “detected” (i.e., # hits = 5) in three of the 10 evaluation areas, with two of the evaluation areas having two defects. The percentage of defects missed by the evaluation is 80.8%. The extrapolated number of defects in the secondary containment area is 64 or nearly 2.5 times the actual number of defects (26).

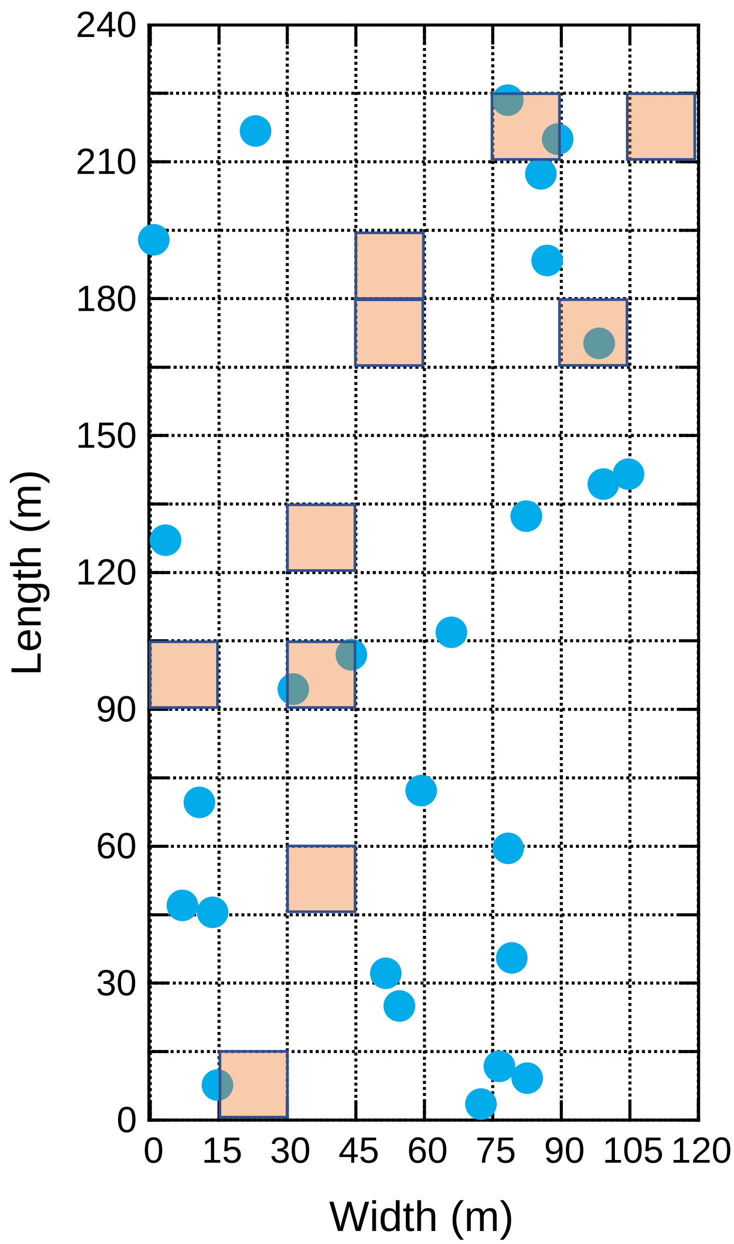


Fig. 3.4. Example illustrating realization of defect locations (blue dots) for case with 26 defects randomly distributed across the effective area of secondary containment along with 10 randomly assigned evaluation areas (orange squares). Defects detected in three of 10 evaluation areas. Five of the 26 defects were detected in this evaluation.

3.1.4 Monte Carlo Simulator. Simulations were conducted within Microsoft Excel (v16.64) using the SimVoi add-in (v3.11, TreePlan 2022). SimVoi is a Monte Carlo simulation package that includes a variety of different probability distributions and uses a deterministic Excel spreadsheet as the basis for conducting a simulation, with the number of realizations defined by the user. Each Monte Carlo simulation in this study employed 20,000 realizations (i.e., the analysis for each case was conducted 20,000 times with a different set of conditions (random samples of the number of defects, location of defects, number of evaluation areas, location of evaluation areas) defined by SimVoi for each of the 20,000 realizations).

The histogram in Fig. 3.3 illustrates the number of defects generated from the Poisson generator with N_d =15 defects/ha. A histogram of percentage of defects missed by an evaluation is shown in Fig. 3.5 for the case with N_d =15 defects/ha and sampling conducted over 35% of the effective area of secondary containment. A large fraction of defects is missed despite sampling more than one-third of the total area of containment. In some rare cases, all the defects are missed and detecting at least 50% of the defects is highly unlikely.

The histogram in Fig. 3.6 illustrates the extrapolation error, defined as the difference between the actual number of defects and the extrapolated number of defects for a case with 35% of the area evaluated. The error in this example varies widely from over-estimates exceeding 80 defects and under-estimates as large as 60 defects.

Simulations were conducted for four frequencies of defects: N_d = 5, 10, 15, and 20 defects/ha. The case with N_d = 5 defects/ha represents a typical condition after installation with good quality control but without a leak location survey conducted to identify and repair defects in the as-built installation (Giroud and Bonaparte 1989a,b). The case with N_d = 20 represents a large number of defects due to very poor installation quality, damage incurred post installation, and/or defects induced by weathering or degradation.

3.2 Results and Discussion

3.2.1 Minimum Area of Evaluation. Outcomes from the simulations are shown in Fig. 3.7 in terms of percent of defects missed in an evaluation. The graphs in Fig. 3.7 depict the minimum percentage of area that must be evaluated for an acceptable maximum percentage of missed defects with a defined probability of mistakenly missing a greater percentage of defects than stipulated. For example, Fig. 3.7a illustrates that at least 59% of the secondary containment area must be evaluated if at least 50% of the defects must be detected with a 25% probability of missing more defects (i.e., there is a 25% chance that less than 50% of the defects will be detected).

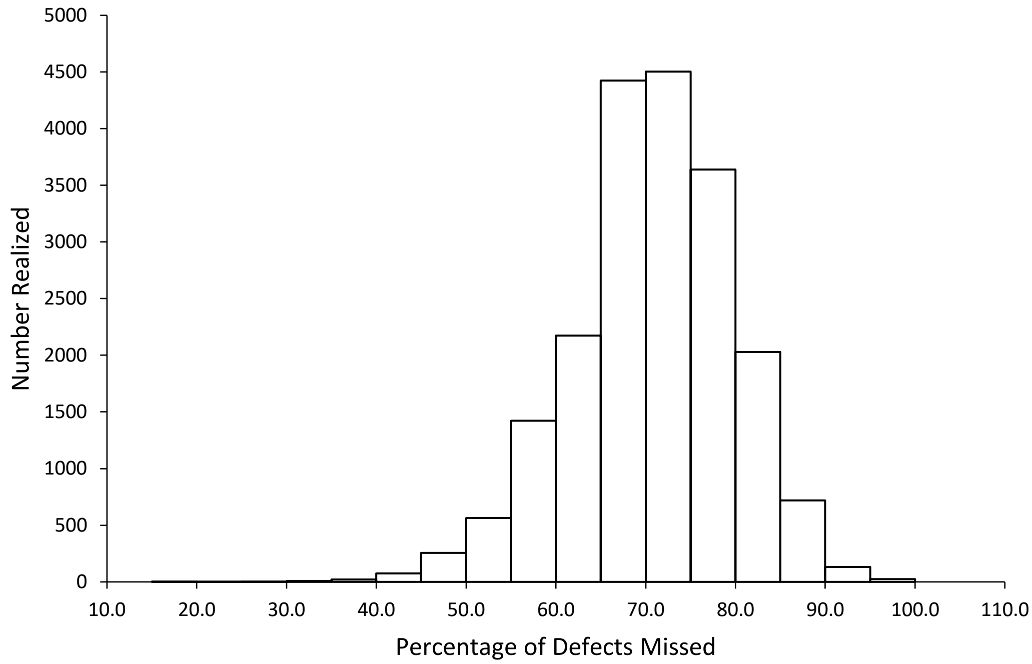


Fig. 3.5. Histogram of percentage of defects missed by evaluation distributed across the liner area for mean of 15 defects/ha and sampling over 35% of area of secondary containment. Based on simulation with 20,000 realizations.

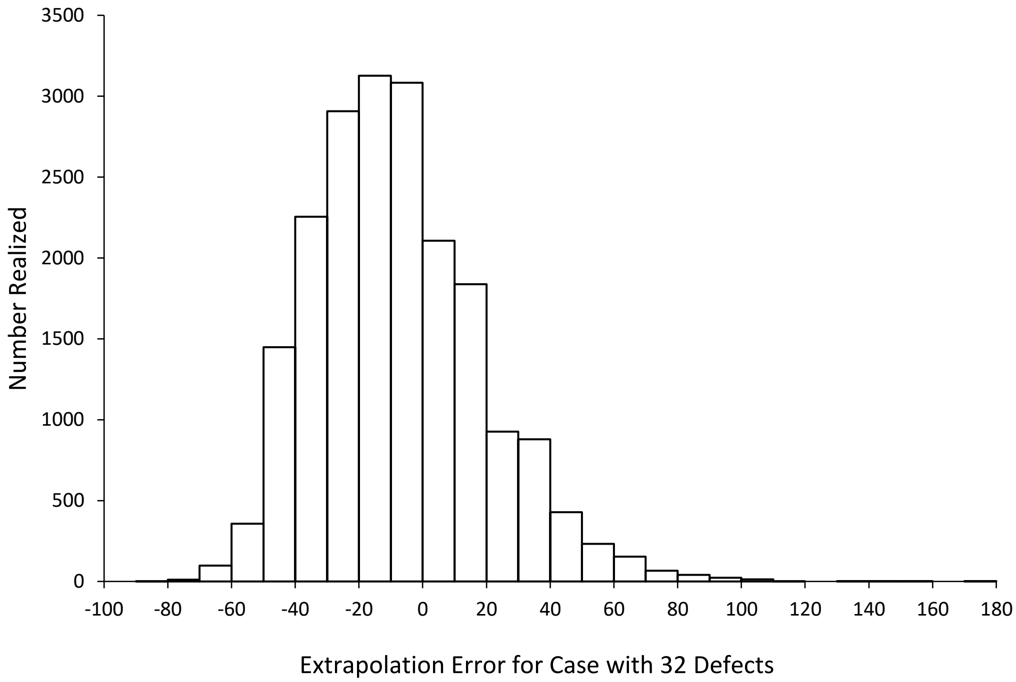


Fig. 3.6. Histogram of extrapolation area based on partial evaluation of the effective area of secondary containment for case with 32 defects randomly distributed across the effective area of secondary containment. Based on simulation with 20,000 realizations.

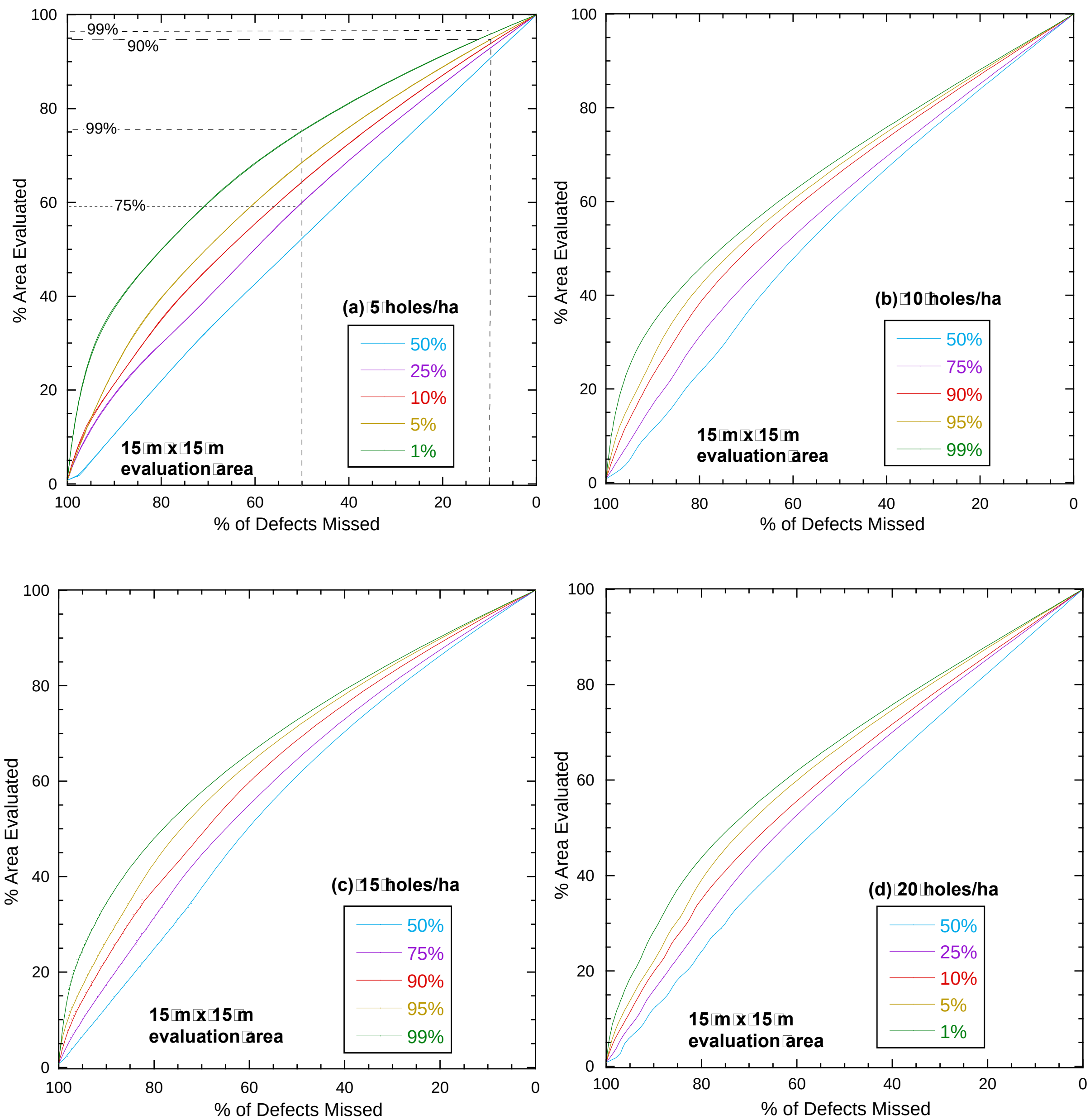


Fig. 3.7. Percentage of defects missed in evaluation as a function of the percentage of the liner area evaluated for an average number of holes per area of (a) 5 holes/ha, (b) 10 holes/ha, (c) 15 holes/ha, and (d) 20 holes/ha.

If the probability of missing more defects is reduced to 1%, a typical threshold in environmental analysis, then at least 76% of the area must be evaluated if missing no more than 50% of the defects is stipulated. That is, the minimum area of evaluation increases as the percentage of defects to be detected increases and the acceptable probability of mistake diminishes.

Comparison of the graphs in Fig. 3.7 shows that as the number of defects per area (N_d) increases, an increasingly larger percentage of secondary containment liner must be evaluated for a given minimum percentage of defects detected. Requirements to detect only 50% or 75% of defects, as described for illustrative purposes in the context of Fig. 3.7a, are not typical. These examples were selected because they could be readily interpreted from the graphs. A more realistic criterion for evaluating a containment system liner is detection of at least 90% of defects (or higher) with an acceptable probability of mistake of 5% or less. This more stringent requirement necessitates evaluation of at least 95% of the secondary containment liner for N_d = 5 defects/ha (Fig. 3.7a).

An increasingly larger percentage of area must be evaluated as the defect frequency increases, with at least 95% of a secondary containment liner needing to be evaluated to achieve fewer than 10% defects missed in all cases. From a practical perspective, direct evaluation of the liner (i.e., uncovering and inspection) over a small fraction of the area has limited value in terms of identifying defects. Non-destructive methods that can evaluate the entire surface of the liner are more appropriate.

3.2.2 Extrapolating and Extrapolation Error. An estimate of the total number of defects in a secondary containment liner (N_{te}) can be estimated by extrapolating the number of defects detected (N_{dd}) in the portion of the area that is evaluated by the following:

$$N_{te} = N_{dd} \frac{A_t}{A_e} \tag{3}$$

where A_t is the total area of the secondary containment liner and A_e is the area of evaluation. The error in the estimated total number of defects (ε) can be computed as:

$$\varepsilon = N_{te} - N_t \tag{4}$$

where N_{te} is the extrapolated total number of defects and N_t is the actual number of defects.

The standard deviation in the extrapolation error (σ_ε) is shown in Fig. 3.8 as a function of the percentage of secondary liner that was evaluated. In Fig. 3.8, σ_ε is normalized by the average number of total defects anticipated ($N_d A_t$). Extrapolations based on a limited area of evaluation have large σ_ε, indicating considerable uncertainty in the extrapolation. The standard deviation decreases appreciably as the percentage of area increases, with σ_ε diminishing to zero when the entire area is evaluated (no extrapolation and no uncertainty). The greatest reductions in σ_ε occur as the area evaluated is increased to 20%, with gradual reductions with increases in area beyond 20%. This implies that the area of evaluation should comprise at least 20% of the area of secondary containment to achieve the maximum practical reduction in uncertainty.

Uncertainty in the extrapolated number of defects can be estimated from the curves in Fig. 3.8 recognizing that the extrapolated number of defects is approximately normally distributed. Confidence intervals around the extrapolation can be set using multiples of σ_ε in accordance with principles of the normal distribution ($N_{te}\pm\sigma_\varepsilon$ captures 67%, $N_{te}\pm1.6\sigma_\varepsilon$ captures 90%, and $N_{te}\pm2\sigma_\varepsilon$ captures 95%; Cressie 1991). For example, if 40% of the secondary containment area was evaluated and yielded 22 defects, then N_{te} would be computed as 22÷0.4 = 55 defects. The standard deviation would be estimated from Fig. 3.8 for 40% area evaluated recognizing that N_d is approximately equal to 22÷(0.4×2.88 ha) = 19 defects/ha, which yields $\sigma_\varepsilon/N_d A_t$ = 0.2 (from Fig. 3.8) or σ_ε = 0.2×19×2.88 = 11. Thus, the upper bound confidence interval on the total number of defects would be 66 defects (= 55+11) for the 67% confidence interval (σ_ε), 73 defects (= 55+18) for the 90% confidence interval ($1.6\sigma_\varepsilon$), and 77 defects (= 55+22) for the 99% confidence interval ($2\sigma_\varepsilon$).

3.3 Summary and Implications

This section has presented a statistical methodology to interpret an evaluation of a secondary containment liner in which only a portion of the liner is evaluated. A Monte Carlo method was developed to simulate defects in a secondary containment liner and to evaluate the likelihood of detecting defects when only a portion of the liner is evaluated. A method is described by which the total number of defects in the secondary containment liner can be extrapolated from the number of defects observed when inspecting only a portion of the liner. The uncertainly in the total number of defects can also be quantified with the methodology that is presented.

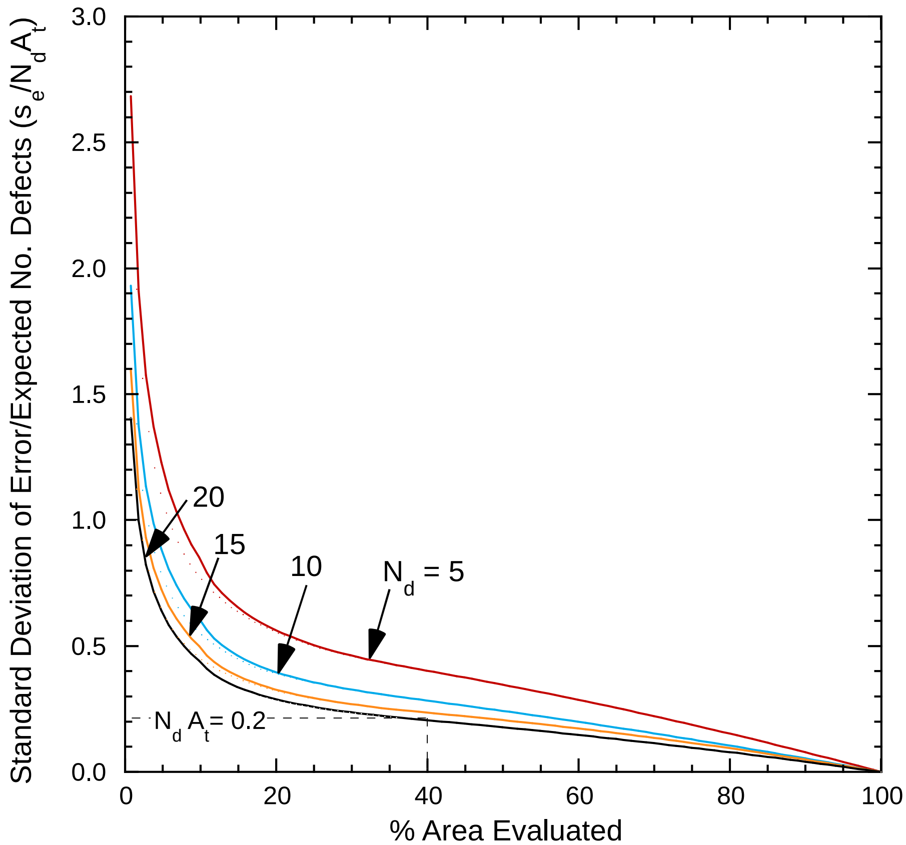


Fig. 3.8. Normalized standard deviation of extrapolation area as a function of percentage of area of secondary containment that was evaluated for 5, 10, 15, and 20 defects/ha.

Outcomes of the analysis demonstrate that a substantial number of defects are likely to be missed when an evaluation is conducted over only a portion of a secondary containment liner. An increasingly larger fraction of the liner must be evaluated as the acceptable percentage of missed defects increases, the acceptable probability of mistakenly missing defects diminishes, or the average number of defects increases.

For typical scenarios where at least 90% of the defects must be detected and the acceptable probability of mistakenly missing more defects is less than 5%, the area of evaluation exceeds 95% of the total area. Thus, for practical purposes, methods that can evaluate the entire area of secondary containment are needed if the objective is to identify the presence and location of defects.

A method to estimate the total number of defects in a secondary containment liner is presented that is based on extrapolating the number of defects encountered when evaluating a fraction of the area of the secondary containment liner. A method to quantify the uncertainty in the estimated total number of defects obtained by extrapolation is also presented. The uncertainty in the estimate diminishes greatly as the fraction of the area being evaluated increases to 20%. For further increases in evaluation area, the uncertainty diminishes more slowly. Thus, if the objective is to estimate the total number of defects with acceptable uncertainty, the evaluation area should include at least 20% of the area of secondary containment liner. Larger areas could be selected to reduce the uncertainty in the estimated total number of defects.

4. SUMMARY AND CONCLUSIONS

This report has described methods that can be used to evaluate the CBA liner in the secondary containment systems at VMT and provides recommendations on the most suitable methods for assessment. The report also describes a statistical method that was developed to evaluate how to compute the number of defects in a secondary containment liner with a specified degree of statistical confidence based on outcomes from inspection over a portion of the liner. The statistical methodology was also used to demonstrate how much area of liner needs to be inspected to draw inferences regarding the condition of the liner. Charts are provided that can be used to determine the minimum area of evaluation to obtain an assessment of liner defects with an acceptable percentage of missed defects and an acceptable probability of mistake.

The following conclusions are drawn based on the outcomes of the study:

- Leak location and electrical resistance tomography surveys are recommended for evaluating the CBA liner at VMT. These established and commercially available methods are highly sensitive to the contrasts in electrical conduction that are present when defects exist in a non-conductive material (e.g., CBA liner) placed adjacent to more conductive earthen materials. Both methods can be used to locate defects directly, can be used to create a map of defects, and do not require disturbance of materials directly above the liner.

- Inferences based on evaluating only a fraction of a CBA liner are subject to considerable uncertainty, with a high probability of missing a significant fraction if not a majority of defects. The minimum area of liner to assess depends on the acceptable fraction of defects missed and an acceptable probability of a mistaken inference. For a typical statistical threshold in environmental analysis (e.g., 99% probably of detection of defects), essentially all of the liner area needs to be evaluated if the objective is to detect the presence and location of all defects.

- If the objective is to estimate the total number of defects (not location or size) by extrapolating outcomes obtained by evaluating a fraction of the area, at least 20% of the liner area should be assessed. Using at least 20% of the liner area will reduce the uncertainty in the estimated number of defects considerably. Larger areas will have much less impact on reducing uncertainty.

- A pilot study should be conducted in the West Tank Farm area to evaluate the leak location and electrical resistance tomography methodologies, especially the ability of both methods to detect defects with the thick layer overlying the CBA liner. Surveys with both methodologies should be applied over at least 20% of the lined area, with maps made of the defects made based on the outcomes of the surveys. The same area should be evaluated with both methods. Direct visual inspection of the CBA liner should be conducted afterwards on the entire area evaluated with the leak location and electrical resistance tomography methodologies to ground truth outcomes of the surveys. The direct visual inspection will also provide an opportunity to correlate defect size and shape with the signals recorded by the leak location and electrical resistance tomography methods.

5.0 AUTHOR'S BIOGRAPHY

Craig H. Benson is a geoenvironmental engineer with deep expertise in waste management, waste containment systems, recycling and beneficial reuse, and sustainability. He served as Dean of Engineering at the University of Virginia (UVA) and as Department Chair and Director of Sustainability Research and Education at the University of Wisconsin-Madison, where he was appointed as Wisconsin Distinguished Professor. Benson has a BS from Lehigh University and MSE and PhD degrees from the University of Texas at Austin, all in Civil Engineering with an emphasis in geoenvironmental engineering. He is a member of the US National Academy of Engineering (NAE) and the National Academy of Inventors (NAI), as well as a Fellow in the American Association for the Advancement of Science (AAAS).

Benson has been conducting research related to protection of the environment for three decades, with primary focus on environmental containment of solid, hazardous, radioactive, and mining wastes; beneficial use of industrial byproducts; and sustainable infrastructure. He is recognized as a foremost international authority on waste containment systems, and is widely sought after for his expertise in design, operation, and performance assessment of waste disposal facilities. His expertise includes municipal solid waste (MSW), hazardous waste (HW), coal combustion residuals (CCR), mining and mineral processing wastes, low-level radioactive waste (LLW), mixed radioactive waste (MW), uranium mill tailings, and bauxite residuals. Benson leads the Landfill Partnership for the US Department of Energy's (DOE) Consortium for Risk Evaluation with Stakeholder Participation (CRESP), which provides research and technical support on issues related to performance assessments for LLW and MW disposal facilities as well as evaluation of the performance of existing and historic DOE disposal facilities. He was co-Principal Investigator on USEPA's Alternative Cover Assessment Program (ACAP) and authored the USEPA guidance on design, evaluation, construction, and monitoring of water balance covers (*aka* ET covers). Benson also developed the seminal guidance on the engineering properties of final covers for waste containment for the US Nuclear Regulatory Commission (Engineered Covers for Waste Containment: Changes in Engineering Properties & Implications for Long-Term Performance Assessment, NUREG/CR-7028). He served as co-Principal Investigator on the Bioreactor Partnership, an industry-government-academic partnership to develop principles for optimal operation of MSW landfills as bioreactors, and as co-Principal Investigator on the Elevated Temperatures Landfill (ETLF) project, which developed the key principles to manage and avoid highly elevated temperatures in MSW landfills. Benson is currently developing principles and practices regarding the hydrology and geochemistry of coal ash disposal facilities relevant to final closure strategies, developing guidance on managing landfill gas and odor issues and quantifying the physical and social correspondence between landfill odors and odor complaints, and evaluating the efficacy of plastic waste recycling and upcycling. He frequently consults as an expert in waste containment systems and sustainability.

Benson's research experience involves laboratory studies, large-scale field experiments, and computer modeling. He has published more than 300 refereed articles based on his research and has received numerous research awards, including the Karl Terzaghi Award, Ralph Peck Award, Huber Research Prize, Alfred Noble Prize, Croes Medal (twice), Middlebrooks Award (twice), Collingwood Prize, and Casagrande Award from the American Society of Civil Engineers and the Award of Merit, Ivan Johnson Award for Outstanding Achievement, and the Best Practical Paper Award (twice) from ASTM International. Benson has a distinguished record of public service, having served as Editor-in-Chief of the *Journal of Geotechnical and Geoenvironmental Engineering*, President of the ASCE Geo-Institute (GI), Chair of the GI Geoenvironmental Committee, Vice Chair of the Executive Committee of ASTM Committee D18 on Soil and Rock, and Chair of ASTM Committee D18.04 on Hydraulic Properties and Barriers. He currently serves as Chair of Section 4 of the National Academy of Engineering.

Benson's research has been funded by a diverse set of sources including industry, local and state government, and federal agencies. His recent research has been funded primarily by the US Department of Energy through the Office of Environmental Management, the Nuclear Regulatory Commission, the Electric Power Research Institute, and the Environmental Research and Education Foundation. Early in his career, Benson was awarded the Presidential Young Investigator Award from the National Science Foundation and the Distinguished Young Faculty Award from the US Department of Energy to support his research.

Link to Benson's CV: CV for Craig H. Benson

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