

# **A Risk Based Approach to Leak Survey Optimization**

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## **Abstract**

The approach to asset management for gas distribution systems is rapidly evolving. Utilities, prompted by multiple drivers, are moving towards proactive risk-aware or risk-based asset management approaches. Such risk-based asset management approaches can provide the opportunity for significant risk and cost reductions and can also provide for significant improvements in long-range planning of maintenance activities. This paper demonstrates the development and trial of a risk-informed approach for planning leak surveys of vintage Aldyl piping within a gas distribution system, based primarily on statistically-derived projections of the likelihood of failure. Simulations comparing the model to the current prescriptive inspection schedule indicate that the LDC can achieve significant risk reductions within its current inspection budget.

## **Introduction**

The approach to asset management for gas distribution systems is rapidly evolving. Utilities, prompted by multiple drivers, are more and more moving towards proactive risk-aware or risk-based asset management approaches.

## **Benefits of a Risk-Aware Asset Management Approach**

There have been numerous recent developments in the area of risk-based asset management, such as the development and introduction of the PAS 55 asset management standard: *Specification for the Optimized Management of Physical Assets* and the broad movement towards statistical risk assessment methodologies. As highlighted in PAS 55, there are four critical stages in the life cycle of any asset—(1) Acquisition, (2) Operation, (3) Maintenance and (4) Disposal—and statistical risk assessment methodologies are starting to be applied to all four.

The primary benefits of risk-based asset management are:

- The development of a clear overall risk picture for the asset
- The ability to make risk decisions on an informed basis
- The ability to compare risks based on the same base measure across a variety of assets with different potential for failure and consequences
- The ability to set clear desired risk targets
- The ability to reduce risk in the asset base in the most cost-effective manner

As the list above shows, risk-based asset management requires conscious and informed decisions regarding asset risk based on a clear assessment of that risk within the asset base. Critical to this is ensuring that the risk assessments upon which risk decisions are made are reflective of the true system risk. This has led to a drive towards probabilistic risk assessment (PRA) where statistical models are developed to create an accurate, probabilistic picture of asset risk. These probabilistic statistical models are rapidly replacing outdated approaches such as risk indices and prescriptive maintenance and inspection practices.

## **Optimizing Maintenance Activities Based on Risk Benefit**

A key component in the development of risk-based asset management technologies is Risk-Based Inspection (RBI). RBI, as with other risk-based asset management approaches, is gaining increasing popularity because of the significant reductions in both system risks and the costs of the inspection process that result from this approach. In the RBI approach, asset inspection plans are developed based on prioritizing the inspection of the highest risk assets in the system on an individual component basis.

This is in contrast to the commonly applied approach of prescriptive inspection, where assets are inspected based on predefined schedules. While prescriptive programs are typically based on inspecting higher risk components on a more frequent schedule (e.g. inspecting vintage plastics on a five-year cycle and new plastics on a 10-year cycle), specific prioritization of the individual assets within each inspection category is often not conducted. It has been demonstrated that getting to a higher level of differentiation of risk among assets, up to assessing risk on an individual component basis, can provide the opportunity for significant risk and cost reductions and can also provide for significant improvements in long-range planning of maintenance activities.

### **Evaluating the Risk of Failure of Gas Network Assets**

RBI programs are developed based on looking at both the probability of failure of the components in the system and the potential consequences of failure. This reflects the traditional definition of risk as the probability of failure times the consequence of failure. While there are many potential approaches to estimating both probability of failure and consequences, the state-of-the-art approach is to use probabilistic modeling tools. In this approach, the probability of failure of each individual asset component is determined based on statistical modeling, typically utilizing past performance data for the asset and ideally incorporating an understanding of the specific mechanisms of failure. For example, vintage plastic pipelines manufactured from the same material installed in the same year could have significantly different probabilities of failure based on the end-use operating pressures, with higher failure probability for the higher pressure systems.

Consequence modeling is also based on a probabilistic approach, where the probability of consequences of different magnitudes are developed based on the specifics of the system and failures that are occurring. For example, a rupture of a high-pressure gas pipeline in a high density urban setting has the potential for significantly higher consequences than a slow leak that develops in a rural area. The specific consequences for each of these events can be measured in a probabilistic way based on consideration of factors such as distribution of potential leak size, distribution of potential gas release volumes, potential for ignition sources, etc.

### **Trial Simulation of Optimized Leak Surveying Based on Risk Benefit**

Many utilities, as part of their overall adoption of the emerging state-of-the-art risk-based asset management approaches, are looking to explore the use of RBI tools to support and enhance their prescriptive inspection programs for assets in their networks. Most prescriptive inspection programs are based on the idea of inspecting assets at a higher risk of failure at shorter inspection intervals; a more fully-developed RBI program will help enhance system safety and reliability. The approach documented in this paper was subjected to a trial simulation to compare its risk outcomes to those of a five year prescriptive leak survey schedule.

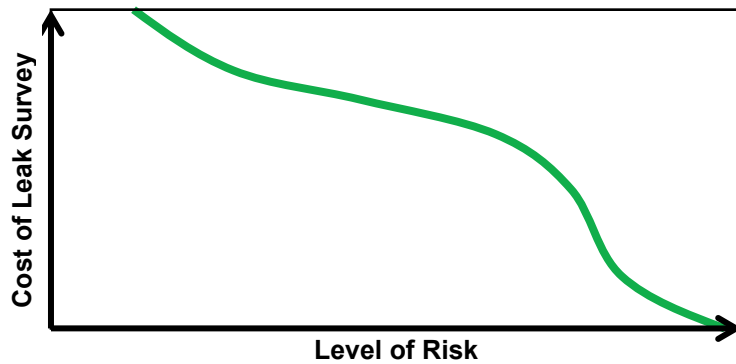
### **Leak Survey Optimization Framework**

As the obvious goal of absolutely minimizing risk is achieved with continuous surveying, there are two realistic optimization goals: (1) minimization of risk given a certain level of leak surveying resources and (2) minimization of the leak surveying resources required to achieve a certain level of risk in the network. In addition to these two optimization goals, the basic methods for producing an optimized leak survey plan can be used to generate a Pareto Set<sup>1</sup> of the optimum achievable risk-cost combinations, permitting asset managers to balance cost and risk as appropriate for the assets under their care, as illustrated in **Figure 1**. The method presented here can be applied to any asset that experiences hidden failures – those that do not affect the primary functioning of the asset and, hence, are typically not found until they are looked for or cause a problem other than loss of service – in a gas distribution network, including both linear assets and fixed plant, where past leak survey data and asset failure record data may be used to construct probability of failure models for the asset.

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<sup>1</sup> The Pareto Set, for this project, is the set of risk-cost combinations where a certain level of reliability is achieved at minimum cost, or conversely a certain cost of leak surveying achieves maximum reliability. All other possible risk-cost combinations can be improved to offer a higher level of reliability at a lower cost.

**Figure 1: Illustration of Pareto Set of Network Risk for Levels of Leak Survey costs**



Note: The green line represents a potential Pareto Set - the minimum level or risk achievable with a certain level of Leak Survey resources. All non-efficient risk-cost pairs lie to the right of the line.

### Information Needed to Prioritize Assets for Leak Surveying

To prioritize assets for leak surveying there must be some knowledge of the likelihood of failure (i.e. leaking) or, at a minimum, an estimate or assumption of this likelihood<sup>2</sup>. Ideally there would be an estimate of the failure rate for each asset, an estimate that incorporates all information that is known to have an effect on the reliability of the asset from installation factors to operating conditions and maintenance information.

An accurate reliability model is needed to prioritize assets for leak surveying. Further, the proportion of leaks that are found via the leak survey as compared to other methods must be known. The usefulness of a leak survey depends on there being leaks for it to find that would not otherwise be found.

In addition to a reliability model, any statutory or regulatory leak survey requirements must be accommodated in any proposed leak survey program. While such requirements may not necessarily permit an optimized level of risk to be achieved, they must be respected as constraints. It is often the case that regulatory bodies will modify such requirements if it can be demonstrated that an alternative course of action offers greater net benefit, in economic or risk terms, to the public; thus, a well-documented leak survey program that achieves lower risks to the public for the same cost level will likely be well-received.

### Optimization Criteria and Methods Available for Leak Survey Prioritization

With a reliability or probability of failure model for the network's assets known, a leak survey program may be designed to optimize either the risk level in the network or the cost of the leak survey. It is assumed here that the cost of conducting a leak survey on an individual asset is identical to that of other assets and that there is a constant proportion of leaks that are reported without being detected by a leak survey. These methods may also be performed effectively on groups of assets that are convenient "units" for an individual survey (e.g. a specific geographic survey region, or block, etc.)—this simply requires that the failure rate of the individual assets within the group be aggregated together.

### Notation Used

The following notation is used in this section:

$z$	Proportion of leaks identified by means other than a leak survey.
$\vec{x}_i(t)$	Vector of relevant information about asset $i$ at time $t$ ; some information may depend on time.
$t_i$	The time of the last leak survey on asset $i$ .
$t_E$	The time of the end of the survey period under consideration.
$h_i(t; \vec{x}_i(t))$	Estimated hazard rate of asset $i$ at time $t$ , accounting for information in $\vec{x}_i(t)$ .

<sup>2</sup> For example, a current prescriptive schedule of 5- and 10-year leak surveys may be based on the assumption that older assets require a shorter inspection interval due to higher failure rates, while younger assets are sufficiently reliable to need only a 10-year leak survey.

$H_i(t; \vec{x}_i(t), t_i)$	Estimated number of leaks experienced by asset $i$ by time $t$ , given that it was last inspected at time $t_i$ .
$N_i(t; \vec{x}_i(t), t_i)$	Estimated number of leaks experienced by asset $i$ by time $t$ , given that it was last inspected at time $t_i$ , that may be found by leak surveying.
$R_i$	Risk reduction achieved by inspecting asset $i$ in the survey period.
$L$	Estimated number of leaks that exist in the network following the leak survey.

### Minimizing Network Risk with Given Leak Surveying Resources

Overall risk within any gas distribution network is effectively determined by the functional requirement of the asset to deliver natural gas safely. This is comprised of financial and other risks caused by loss of supply to customers that might occur without a leak of gas and the health and safety risk caused by a leak of gas. It is this latter risk that is addressed by the leak survey program, whose intent is to find leaks and repair them prior to more significant negative consequences. As such, minimizing the level of risk in the network may be achieved by selecting the leak survey program that minimizes the number of leaks in the network at the end of the survey.<sup>3,4</sup>

To minimize the number of leaks in the network requires first estimating the risk benefit of surveying each asset in a particular year of analysis. This is done by first determining  $N_i(t_E; \vec{x}_i(t), t_i)$ , the estimated number of leaks experienced by asset  $i$  by the end of the survey period, given that it was last inspected at time  $t_i$  (which is assumed to be before the survey period under consideration). This is calculated by first integrating the hazard rate of the asset from the time of its last survey to time  $t_E$ , that is:

$$H_i(t_E; \vec{x}_i(t), t_i) = \int_{t_i}^{t_E} h_i(T; \vec{x}_i(T)) dT, \quad (2-1)$$

then scaling that number by the estimated proportion of leaks that were identified by means other than a leak survey to find  $N_i$ , the number of leaks that might exist in the assets covered by the program absent the leak survey<sup>5</sup>:

$$N_i(t_E; \vec{x}_i(t), t_i) = (1 - z) \cdot H_i(t_E; \vec{x}_i(t), t_i). \quad (2-2)$$

The number of leaks that would exist in the network if the asset is surveyed at time  $t$  is then determined:

$$N_i(t_E; \vec{x}_i(t), t) = (1 - z) \cdot H_i(t_E; \vec{x}_i(t), t) = (1 - z) \cdot \int_t^{t_E} h_i(T; \vec{x}_i(T)) dT. \quad (2-3)$$

The difference between  $N_i(t_E; \vec{x}_i(t), t_i)$  and  $N_i(t_E; \vec{x}_i(t), t)$  provides a measure of the risk benefit,  $R_i$ , for all of the assets under consideration for leak surveying. By surveying those assets that have the highest  $R_i$  for a given survey period, a leak survey program is developed that minimizes the number of leaks in the assets covered by the program. It should be noted that, all else equal, this method will rank more highly those assets that were less recently surveyed.

<sup>3</sup> For this initial model, the potential consequences of a leak are not differentiated. However, consequences of failure may be easily included in this model for a more accurate risk-based optimization.

<sup>4</sup> This method is usually equivalent to maximizing the number of leaks found by the survey, though in some cases a different survey program will be generated with these two methods.

<sup>5</sup> It should be noted that, if planning for the leak survey is done close to the date of the actual survey, one may directly use the number of leaks found by means other than a leak survey on the asset being considered for surveying,  $N_{Observed,i}(t_E, t_i)$ , viz.:

$$N_i(t_E; \vec{x}_i(t), t_i) = H_i(t_E; \vec{x}_i(t), t_i) - N_{Observed,i}(t_E, t_i).$$

However, due to other constraints, such as regulatory survey requirements, the procedure for selecting the assets for a given year or season of leak surveying is somewhat more involved. The overall procedure is as follows:

1. Identify the number of assets,  $M$ , that may be surveyed in the coming time period using the available leak survey resources
2. Identify those  $Q$  assets that must be surveyed this time period due to regulatory requirements
3. Calculate the risk benefit  $R_i$  for those assets not identified in (2.); order the assets by  $R_i$
4. Select the top  $(M - Q)$  assets by  $R_i$  for inclusion in this time period's leak survey

After completing this procedure, the estimated number of leaks,  $L$ , may be determined in the assets covered by the program by summing  $N_i(t_E; \vec{x}_i(t), t)$  for those assets that were selected to be surveyed in this time period and adding it to the sum of the  $N_i(t_E; \vec{x}_i(t), t_i)$  for those assets that were not included, or:

$$L = \sum_{\substack{\text{Assets} \\ \text{Selected} \\ \text{for Leak} \\ \text{Surveying}}} N_i(t_E; \vec{x}_i(t), t) + \sum_{\substack{\text{Assets} \\ \text{Selected} \\ \text{for Leak} \\ \text{Surveying}}} N_i(t_E; \vec{x}_i(t), t_i). \quad (2-4)$$

Longer-range leak survey planning may be considered on a similar basis; however, the overall goal is to minimize the number of leaks that exist within the network at any given time.

#### Minimizing Leak Surveying Resources Given Level of Network Risk

The calculations required to minimize leak survey resources for a given level of risk in the assets covered by the program are similar to those detailed in the previous section. In this method it is assumed that the level of risk is determined by selecting some critical number of leaks in the network,  $L_{required}$ , which must be met. The overall procedure is as follows:

1. Identify those  $Q$  assets that must be surveyed this time period due to regulatory requirements; add these assets to the **Survey List**
2. Calculate the risk benefit  $R_i$  for those assets not identified in (1.); order the assets by  $R_i$  and include in the **Risk Benefit List**
3. Calculate the value of  $L$  assuming that only those assets currently on the **Survey List** are surveyed
4. Select the top asset by  $R_i$  on the **Risk Benefit List** for inclusion in this time period's leak survey; remove this top asset from the **Risk Benefit List** and include it in the **Survey List**
5. Recalculate the value of  $L$  assuming that only those assets currently on the **Survey List** are surveyed
6. If the value of  $L$  calculated in (5.) is lower than  $L_{required}$ , use the current **Survey List** for this year's leak survey program. Otherwise, return to (4.) if there are assets remaining on the **Risk Benefit List**

This method will provide a list of assets to be surveyed that will ensure that a maximum specified level of risk is present in the assets covered by the program, while meeting regulatory requirements.

#### **Generating a Pareto Set of Efficient Leak Surveys**

To generate a Pareto Set of efficient leak survey programs, a similar procedure is followed but is run continually with an  $L_{required}$  that ranges from unbounded to zero. Equivalently this may be expressed as follows:

1. Identify those  $Q$  assets that must be surveyed this time period due to regulatory requirements; add these assets to the **Survey List**
2. Calculate the risk benefit  $R_i$  for those assets not identified in (1.); order the assets by  $R_i$  and include in the **Risk Benefit List**
3. Calculate the value of  $L$  assuming that only those assets currently on the **Survey List** are surveyed

4. Select the top asset by  $R_i$  on the **Risk Benefit List** for inclusion in this time period's leak survey; remove this top asset from the **Risk Benefit List** and include it in the **Survey List**
5. Recalculate the value of  $L$  assuming that only those assets currently on the **Survey List** are surveyed. Include this value of  $L$  and the current size of the **Survey List** as a risk-cost pair for inclusion in the **Pareto Set**
6. Return to (4.) if there are assets remaining on the **Risk Benefit List**; otherwise, report the **Pareto Set**

### **Supporting Information for Leak Survey Optimization**

Fundamental to any effective asset management plan is an understanding of the risk of failure of the assets covered by the plan, particularly of the probability of failure. This understanding may come from direct observation of the current state of the asset through actions such as inspection or condition monitoring, by analysis of the statistical patterns of the failures of similar assets in service, or by some combination of both.

As many gas distribution utilities have devoted significant resources to tracking the service histories of the components of their networks, statistical analysis of such network assets is now highly practicable; advanced analyses of the times to failure of distribution network piping assets are now commonplace. These analyses can be used to predict the failure rates of assets through time and support improved reliability of gas distribution systems while helping direct efficient deployment of limited maintenance resources, hence optimizing management of distribution system assets.

#### *Reliability Analysis and Supporting Information Required*

An asset's reliability is the probability that it will perform its expected or desired function over a certain time, given a certain set of operating conditions. A useful mathematical description of an asset's reliability is given by its reliability function, which can incorporate knowledge about how its probability of failure changes as it ages. The reliability function,  $R(t)$ , provides the proportion of the population that has not failed by time  $t$  and is expressed mathematically as:

$$R(t) = \Pr(T \geq t), \tag{3-1}$$

where  $T$  is the typically random time to failure of an asset. The reliability function for an asset is a representation of the distribution of times to failure of that asset, and so its reliability may be equivalently expressed in terms of the probability density function<sup>6</sup> (PDF, often written as  $f(t)$ ), the cumulative density function<sup>7</sup> (CDF, often written as  $F(t)$ ), or the hazard rate ( $h(t)$ ) of the asset, the expected rate at which an individual asset will fail given that it is operating at time  $t$ .

The reliability of an asset may be dependent on its age and other operating factors. Thus, to effectively model mathematically the reliability of assets in a gas distribution network, information on installation times, failure and/or repair times, operating parameters and construction parameters are required, among other sources of information. Using these parameters, a general reliability model may be constructed and used to predict the risk of failure of the components in the installed asset base.

#### *Weibull Proportional Hazards Model*

An effective statistical reliability model is the Weibull Proportional Hazards Model (Weibull PHM). This model uses the Weibull function, commonly used in Reliability Engineering, to model the effects of age on reliability and assumes that functions of operating or construction parameters have a proportional effect on the hazard rate of the assets modeled. The Weibull PHM, expressed in its reliability model form with non-time-varying operating parameters, is given as:

<sup>6</sup> The probability density function (PDF) describes the proportion of a [statistical] population that will experience an event of interest **at** time  $t$ .

<sup>7</sup> The cumulative density function (CDF) describes the proportion of a [statistical] population that will experience an event of interest **by** time  $t$ .

(3-2)

$$R(t) = \exp\left(-\exp[\vec{z} \circ \vec{\gamma}] \cdot \left(\frac{t - t_0}{\eta}\right)^\beta\right),$$

where:

- $R(t)$  Reliability function, the proportion of the population that has not failed by time  $t$   
 $t_0$  time before which no failures occur  
 $\eta$  eta, the characteristic life or time at which 63.2% of the population has failed, when the information vector,  $\vec{z}$ , is zero. In a standard Weibull analysis this is the “typical” life of a member of a population.  
 $\beta$  beta, the shape parameter<sup>8</sup> of the distribution  
 $\vec{z}$  a vector of information about the operating or construction parameters of the asset being modeled  
 $\vec{\gamma}$  the vector of parameters determining the effect of the operating or construction parameters on the asset’s reliability

The Weibull PHM can also be expressed in terms of the probability density function (PDF) of failures in the population, i.e. the observed fraction of the population that will fail at a given age  $t$ , which is given as:

(3-3)

$$f(t) = \frac{\beta}{\eta} \left(\frac{t - t_0}{\eta}\right)^{\beta-1} \cdot \exp[\vec{z} \circ \vec{\gamma}] \cdot \exp\left(-\exp[\vec{z} \circ \vec{\gamma}] \cdot \left(\frac{t - t_0}{\eta}\right)^\beta\right).$$

Another convenient form of the model is as a hazard function, which is the failure rate at time  $t$  of members of the population that have not yet failed by time  $t$ . The hazard function has the form:

(3-4)

$$h(t) = \frac{\beta}{\eta} \left(\frac{t - t_0}{\eta}\right)^{\beta-1} \cdot \exp[\vec{z} \circ \vec{\gamma}].$$

### Aldyl Reliability Analysis

As an example of the application of the method described above, the reliability of Aldyl pipe that was installed into a local gas distribution company’s (LDC) network was characterized based on analysis of the data contained within the LDC’s asset tracking system. This reliability evaluation was used to support the simulated trial of an optimized leak survey program covering these assets. The failure and installation histories of the Aldyl service lines were provided and analyzed using standard statistical reliability analysis techniques, implemented through spreadsheet software.

The Weibull PHM applied to the Aldyl lines has the following form when written as a hazard function:

(3-5)

$$h(t; P) = L \cdot \frac{\beta}{\eta} \left(\frac{t - t_0}{\eta}\right)^{\beta-1} \cdot \exp[\alpha \cdot P].$$

As no information on the length of each service line was provided, the data analysis provided here is based on a Weibull PHM analysis containing only pressure as an explanatory covariate (i.e. L was set to 1 (one) in the analysis calculations). The Weibull PHM model was fit using the method of likelihood maximization to the failure histories of the Aldyl services, with the values of the parameters identified as beta ( $\beta$ ) = 2.4±0.2, eta ( $\eta$ ) = 60±6 years,  $t_0$  = 18±2 years and  $\alpha$  = 0.02±0.01 psig<sup>-1</sup>.

### **Risk Ranking Method and Leak Survey Optimization**

There are two risk ranking methods available for prioritizing the leak survey. The first method is based on surveying those assets that have the highest probability of failing in the coming year—that is, based on expected failure rate—while the second method is based on the optimized leak survey method and

<sup>8</sup> The shape parameter, Beta, provides an indication of the nature of the failure time distribution’s behaviour through time: for  $\beta = 1$  there is a constant failure rate, for  $\beta > 1$  the failure rate is increasing and for  $\beta < 1$  the failure rate is decreasing.

prioritizes those assets that have had the greatest probability of failing since they were last surveyed. The former method may be useful if there is a desire to set a new cyclic leak survey schedule; however, the latter method, based upon the framework outlined above, is recommended for use as it will provide the greatest risk reduction benefit.

#### Failure Rate-Based Prioritization

To prioritize the assets based upon predicted failure rate, the current value of the hazard function must be calculated for each asset in the year of interest. A higher hazard rate indicates a greater likelihood of failure in the coming year.

For the Aldyl Services, the risk rank is calculated with:

$$h(t) = \frac{\beta}{\eta} \cdot \left(\frac{t - t_0}{\eta}\right)^{\beta-1} \cdot \exp[\alpha \cdot P], \quad (4-1)$$

with  $t$  being each asset's age in the year of interest, and the parameters  $\beta$ ,  $\eta$ ,  $t_0$ , and  $\alpha$  set as appropriate.

#### Optimized Method

To prioritize the assets based upon probability of having failed since they were last surveyed, the cumulative hazard function for each asset from the last survey year to the year of interest is calculated.

For the Aldyl Services the risk rank is calculated with:

$$N(t, T) = \exp[\alpha \cdot P] \cdot \left[ \left(\frac{t - t_0}{\eta}\right)^\beta - \left(\frac{T - t_0}{\eta}\right)^\beta \right], \quad (4-2)$$

with  $t$  being each asset's age in the year of interest,  $T$  being the year it was last surveyed, and the appropriate values of  $\beta$ ,  $\eta$ , and  $t_0$ . A higher cumulative hazard rate indicates a greater likelihood of detecting a leak during the survey.

#### **Trial of Prioritization Tool with Aldyl Services Asset Base**

An evaluation of the prioritization method was simulated and compared to the current 5-year prescriptive schedule. This evaluation was conducted on a simulated set of assets with reliability performance based on the reliability analysis of the systems in the asset base.

#### Assumptions Used

There were several assumptions made to simplify the calculations required for the comparative analysis provided here; these assumptions do not affect the quality of the resulting comparison.

1. Approximately 70% of the leaks that occur in the network are found by leak survey<sup>9</sup>
2. The reliability of the assets in the simulated asset base has the reliability features as modeled above
3. The level of survey resources available is only sufficient to maintain a 5-year survey schedule on the asset base; as these assets fail and are not replaced with like assets, this assumption implies a constantly-decreasing level of survey resource availability
4. The leak survey occurs on the last day of a year, and all assets were installed at the beginning of their installation year

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<sup>9</sup> This number was derived through discussion with personnel from a variety of LDCs and a review of leak history and leak survey data provided.



### Methods Used in Analysis

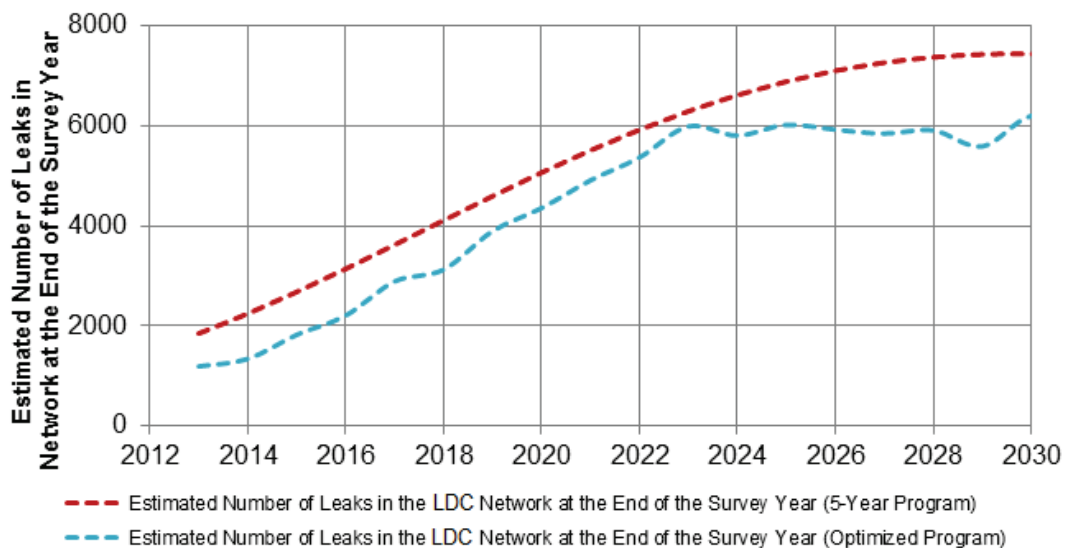
For the base case of the current 5-year leak survey schedule, the number of leaks,  $L$ , expected to exist in the network at the end of each year from 2013 until 2030 was calculated as described in the Leak Survey Optimization Framework section of this paper.

For the optimized leak survey schedule, the method used in *Minimizing Network Risk with Given Leak Surveying Resources* was used, with the number of assets surveyed in the base case used as the upper limit on available survey resources. Due to the size of the groups as detailed in assumption above, this assumption results in a simulation that provides fewer resources to the optimized case; that is the simulation is biased against the optimized case.

### Trial Results and Discussion

The trial simulation results are presented in **Figure 2**, showing the number of assets surveyed and estimated risk in LDC network at the end of each survey year.

**Figure 2: Results of Trial Simulation of Optimized Leak Survey Method**



Note: The graph shows the estimated risk in LDC network at the end of each survey year. (The number of assets surveyed decreases every year due to assets failing out of the population; the number of assets surveyed drops from approximately 63,000 in 2013 to 50,000 in 2030.)

As can be seen in **Figure 2** the optimized leak survey program results in a lower level of risk in network at the end of every survey year, while consuming the same level of leak survey resources. It is also seen that the level of risk continues to increase every year, as the asset base is experiencing a strongly increasing level of failure. It is clear that an optimized risk-based inspection regime can significantly reduce the level of risk present in the LDC network for the asset base. The simulation demonstrates that implementing an RBI program will reduce the level of risk in the network by approximately 20%, as measured by leaks present in the system at any time; this risk reduction is achieved with no increase in surveying resources beyond some additional planning effort.

The model also shows increased survey levels and an associated replacement plan would be needed to maintain the current level of risk in the network. Additional projects to improve the knowledge of the risk present in the LDC network, and the application of such knowledge to asset management tactics used at LDC, would be useful in further reducing risk throughout the network.

## **Conclusions**

A procedure has been developed for optimizing the effectiveness of leak surveys based on probability of failure (reliability) models. The optimization methodology provides operators with a general method to implement risk-based inspection (RBI) of their assets for any asset for which similar probability of failure models are or can be developed. This method was developed with the assumption that all leaks in a distribution system are of equivalent consequence; however, the method may be easily extended to incorporate different levels of consequence for leaks on different assets or different types of leaks.

A simulation of the effectiveness of this optimized leak survey was conducted for vintage Aldyl piping systems and compared to the effectiveness of a current 5-year prescriptive leak surveying method. The simulation projects that the optimized leak survey program will result in a lower level of risk in the network at the end of every survey year while consuming the same leak survey resources compared to the current prescriptive 5-year survey program, demonstrating the benefit of a risk-based inspection in improving the reliability of an asset base. The simulation demonstrates that implementing a RBI program will reduce the level of risk in the network by approximately 20%, as measured by leaks present in the system at any time; this risk reduction is achieved with no increase in surveying resources beyond some additional planning effort.