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A RISK BASED APPROACH TO PRIORITIZING ALDYL PIPING REPLACEMENTS IN GAS DISTRIBUTION SYSTEMS

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ABSTRACT

Managing aging pipeline infrastructure is an important part of overall pipeline risk management. The critical risk management questions for an aging infrastructure are: how quickly should replacement occur and what parts of the system should be prioritized for replacement. To answer these questions it is necessary to characterize the expected future performance of the pipeline and the more accurately this is done the better risk can be managed. This paper examines the use of mechanistic-probability models for prioritizing Aldyl piping replacements in gas distribution systems based on segment by segment leak rate forecasts tied to the specific pipe segment materials and operating conditions. The general modeling approach is reviewed and the resulting models are tested for predictive capability versus actual field leak rates. The results show that mechanistic-probability models can accurately predict leak rates across all the generations of Aldyl piping materials under a broad range of end-use operating conditions, providing the utility operator with a powerful tool to determine required replacement levels to achieve risk targets, optimize replacement programs and optimize leak survey plans.

INTRODUCTION

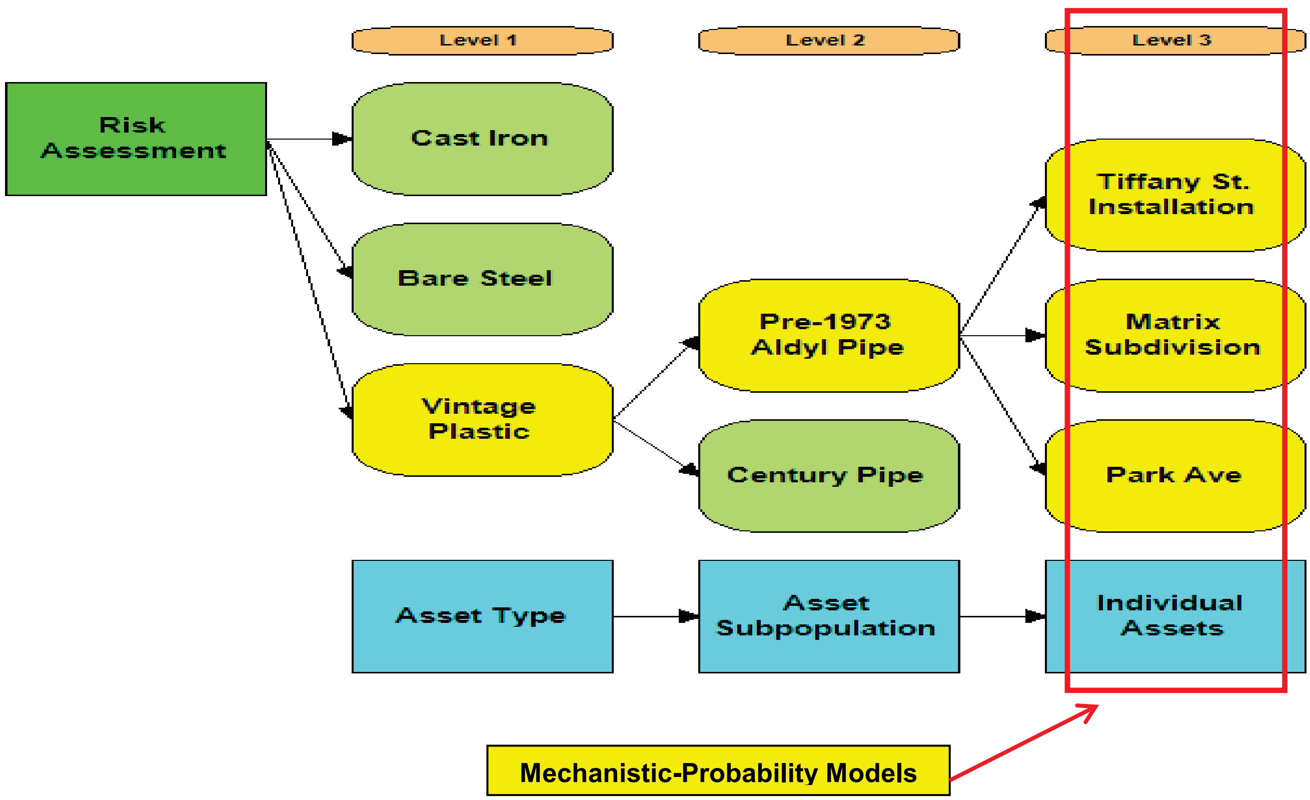
The introduction of polyethylene (PE) piping materials into gas distribution was a major technological breakthrough. Their ease of installation, the absence of corrosion and their fusability have resulted in highly robust piping systems with the net result being that PE is now the material of choice in gas distribution piping. While the service record for PE piping has generally been excellent, there have been some known issues with some of the earlier generation PE materials. In particular, some Aldyl piping materials have experienced in-service piping leaks and have been targeted for replacement programs by a number of utilities.

As in any replacement program, two key questions arise: At what rate should I replace the Aldyl piping in my system?, and What piping should be prioritized for replacement? These are typical asset management decisions common to a wide variety of industries and asset management best practices dictate that these types of decisions are based on sound risk assessments. Within risk assessment there are a variety of approaches that can be applied, ranging in complexity and effectiveness from simple index models based on point scales attributed to factors deemed relevant to risk (now falling out of favor), to probabilistic modeling to mechanistic-probability models. This paper examines the application of mechanistic-probability models, arguably the most complex yet most effective of the modeling approaches, to the Aldyl piping replacement question and examines their effectiveness and key advantages.

RISK ASSESSMENT FOR GAS DISTRIBUTION SYSTEMS

Risk in the pipeline industry is typically defined as the likelihood of failure times the potential consequences of failure. There is a general hierarchy of risk assessments that are conducted in prioritizing pipeline asset management decisions, moving from the overall system to greater levels of detail (**Figure 1**). An initial general assessment of the overall distribution system is used to develop a risk ranking by asset type; for example, identifying cast-iron, bare steel and vintage plastic as key targets for asset management activities. A second level of risk assessment is then conducted on each of these priority asset types to identify the most at-risk subpopulations within the general asset class. For example, for the vintage plastic asset class, the subpopulation of pre-1973 Aldyl piping can be identified as a more at risk subpopulation. The third, and generally final, level of assessment is the ranking of individual assets within the subpopulation, identifying, for example, specific pipeline segments of pre-1973 Aldyl to be targeted as risk priorities such as specific installations or sections of the network (e.g. a specific subdivision). It is this final level of risk assessment that is addressed by the mechanistic-probability models examined in this paper. Specifically, the overall objective is to develop relative pipeline risk scores for the Aldyl plastic piping assets in the gas distribution system that enables risk ranking specific to each pipeline segment. The intent of this is to enable efficient and effective direction of resources in prioritizing repair / replacement decisions to minimize overall pipeline risk.

Figure 1: Position of Mechanistic-Probability Models in the Overall Risk Assessment Process



This paper is focused on the development of likelihood of failure forecasts in the form of leak rate models (which can be combined with consequence projections through, for example, liking the leak rate projections to GIS-based consequence tools). The leak rate models are focused on the prediction of leak probabilities due to the slow crack growth mechanism (SCG). Slow crack growth is the primary failure mechanism, aside from third-party damage, for older generation polyethylene piping materials in gas distribution systems. It is failure of the pipeline components due to this mechanism that needs to be modeled in order to assess the relative expected performance of plastic gas distribution piping. The more accurately the risk of SCG failure in specific segments of a plastic gas distribution network can be assessed, the more effective risk management strategies will be. The developed mechanistic-probability models provide the ability to risk rank the Aldyl asset base on a pipeline segment basis, providing the ability for targeted risk management activities.

THE DIFFERENT GENERATIONS OF ALDYL PIPING

There are a total of five different generations of Aldyl piping materials, each with its own specific performance characteristics. As the performance of the different generations varies widely, mechanistic-probability models need to be developed for each. The specific generations, and the years of their manufacture, are provided in **Table 1**.

In addition to the five different generations of Aldyl pipe, there was also a time from 1971 to 1972 where Low Ductile Inner Wall (LDIW) pipe was produced. This was a processing issue affecting thirty to forty percent of the pipe produced during this period. The performance of this material, and the associated issues, are well known within the industry.

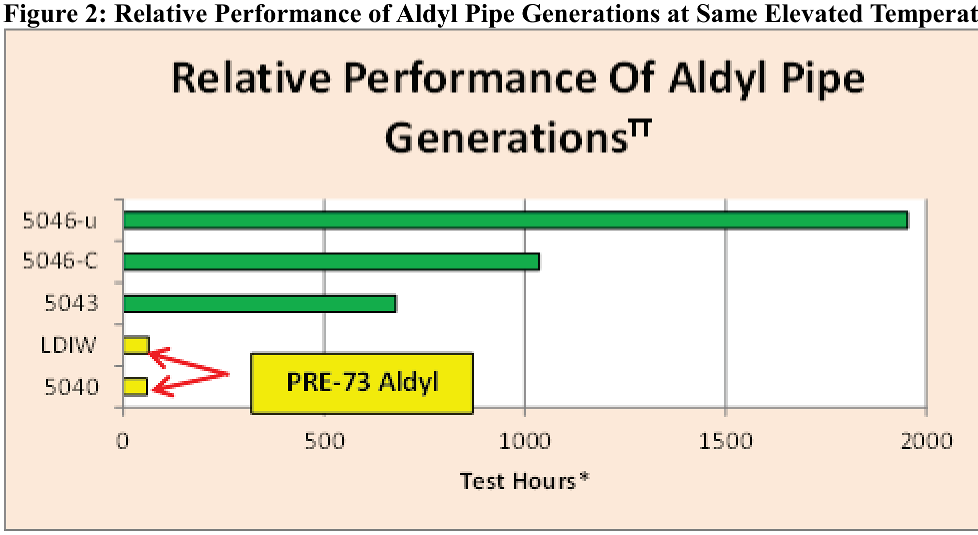
Table 1: Generations of Aldyl A Piping in Gas Distribution

Generation	Aldyl Resin[1]	Years of Manufacture		Color	Comment
1st	**5040**	1965-1971		Tan	Original Alathon Resin
2nd	**5043**	Standard	1971-1983	Tan	Density Increased
		LDIW[2]	1971-1972	Tan	Manufacturing Issue
		'AAAA'	1975-1980	Green	DR 9.3 for Class 4 Areas
3rd	**5046c**	1983-1986		Tan	Co-monomer Changed
4th	**5046u**	1986-1989		Tan	Co-monomer Increased
5th	**5046o**	After 1989		Tan	Co-monomer on HMWT[3] Fraction

Notes: [1]All resins marketed as Aldyl A, [2] Low Ductile Inner Wall, [3] High Molecular Weight

A relative comparison of the performance of the Aldyl generations is provided in **Figure 2**. The chart provides a simple comparison of time to failure in accelerated laboratory testing of straight pipe at a single accelerated temperature and pressure condition. Of key importance is the significant difference between the pre-1973 Aldyl materials and those that follow; overall, there is an order of magnitude difference in performance between the lowest (pre-1973 Aldyl) and highest (Aldyl 5046u) test lifetimes.

Figure 2: Relative Performance of Aldyl Pipe Generations at Same Elevated Temperature Test Condition



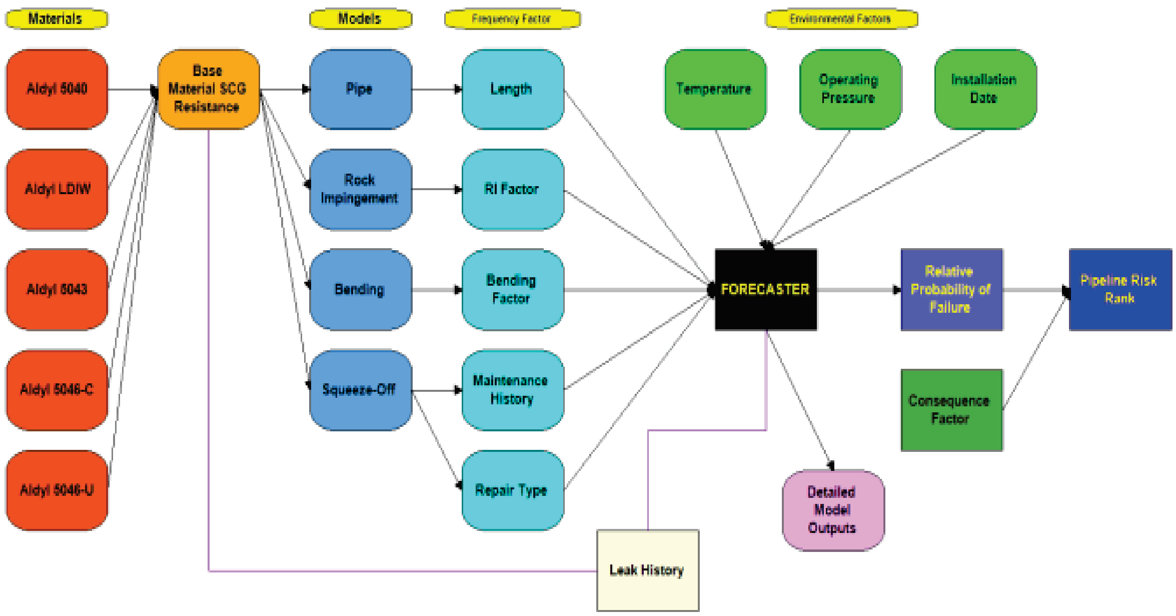
Note: $^{\pi}$Based on testing at single condition. For more detailed performance characterizations see section on Performance Comparison of Aldyl Materials. *Testing conducted at 80°C on 2" Pipe at nominal test stresses of 450-470 psi with Water internal/Water external. All failures were SCG failures initiating at the inner pipe bore.

In this paper the different Aldyl generations and the LDIW pipe are characterized. For each of the materials, mechanistic-probability models were developed to predict performance of straight pipe, pipe with rock impingement, squeezed pipe, deflected pipe and fittings.

MODELING ALDYL PIPING LEAK RATES

Figure 3 provides an overview of the mechanistic-probability risk rank model process used in the development of the Aldyl A risk ranking models. The output of the model is a Relative Probability of Failure score for each Aldyl pipeline segment in the utilities system based on the input of the specific material and pipeline segment details. The general process involves (1) characterization of SCG resistance for the specific plastic pipe materials under study, (2) development of models for forecasting the performance of the pipe and pipe with rock impingement, deflection stresses, squeeze-off damage and fittings, (3) development of an overall forecast module and (4) tuning and confirmation of the models based on actual field data.

Figure 3: Overview of the Mechanistic-Probability Risk Rank Model Process



Performance forecasting models were developed based on the Jana Shift-Extrapolation (JSE™) methodology and Weibull statistical reliability analysis. The JSE™ provides the ability to take laboratory SCG test data and shift the test times to projected lifetimes at a given end-use condition (temperature and pressure). These data are then analyzed using Weibull model-based statistical techniques to develop performance projections under end-use conditions. The models developed using the JSE™ were then tuned using field failure data.

JSE™ Models

Based on testing of Aldyl piping samples under accelerated laboratory conditions, models for shifting test times under these accelerated conditions to end-use conditions were developed for each generation of Aldyl piping for straight pipe, bent pipe, pipe with rock impingement and pipe with squeeze-off prior to testing. The resulting JSE™ models were based on the key parameters impacting the SCG failure mechanism.

The laboratory data was translated to initial leak rate models by fitting a three-parameter Weibull model to JSE™ shifted failure data. The Weibull model is commonly used in reliability analysis to estimate the risk or rate of failure of engineered systems and components, largely due to its flexibility in fitting a wide variety of failure time distributions. Parameters were generated for a two foot segment (to correspond with the length of pipe tested in the laboratory testing) of each Aldyl A pipe material at each set of operating temperatures and pressures, as well as external factors such as rock impingement, bending moments or the presence of squeezed-off sections in each segment. The initial model required inputting estimates of the average proportion of segments that would be affected by external factors; i.e. the number of segments affected by rock impingement or bending moments, which were derived based on past field failure data.

The mechanistic-probability models produce an associated hazard function for each two foot segment, a measure of the risk of a segment experiencing its first failure as a function of time. Research has shown that for linear assets, such as pipelines, the failure intensity or crude rate of occurrence of failures of a pipeline consisting of many segments may be calculated by aggregating the hazards of the segments. The resulting mechanistic-probability failure intensity estimate can be used to calculate both the expected number of failures that a pipeline will experience by a certain age and the average number of failures that a pipeline will experience in a year of a certain age.

Tuning the JSE™ Models

In order to optimize the accuracy of the model predictions, the initial leak projections from the laboratory generated data were 'tuned' to the observed field performance. The tuning process involved adjusting the JSE™-derived parameters and the estimated incidence of rock impingement, deflection stresses and squeeze-off damage to improve their accuracy in predicting the number of historical field failures experienced in the Aldyl A asset base, with a goal of minimizing the difference between overall predicted and experienced number of failures. Using the calculation of the expected number of failures that a pipeline will experience by a certain age, the predictions made by the mechanistic-probability models were compared against the actual number of failures experienced by each pipeline segment. The gas utility data used represented over 50,000 pipeline segments covering all the Aldyl generations and operating under a broad range of end-use conditions (temperature and pressure). For a more accurate statistical assessment, comparisons were made between the predicted number of failures experienced by groups of pipelines determined by operating condition; i.e. all pipelines of the same material installed in the same year and operating at a certain temperature and pressure (termed 'bin segments' in this paper).

The tuned models provide segment by segment leak rate projections based on the specific local operating conditions of the segment that are closely aligned with the observed field behavior. **Figure 4** provides a comparison of the model projected leak rates after tuning to the observed leak rates in Aldyl mains. The data is a composite of all Aldyl piping generations and operating conditions in the system. The R^2 value of 0.91 (91% of the data is described by the model) indicates excellent alignment between the model projections and observed behavior.

Figure 4: Comparison of Observed and Model Predicted Leaks for Gas Mains

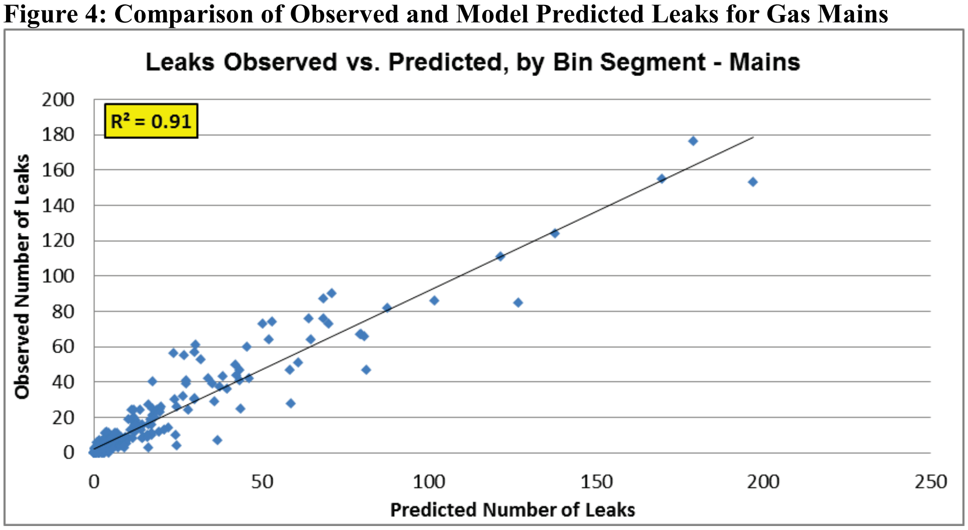
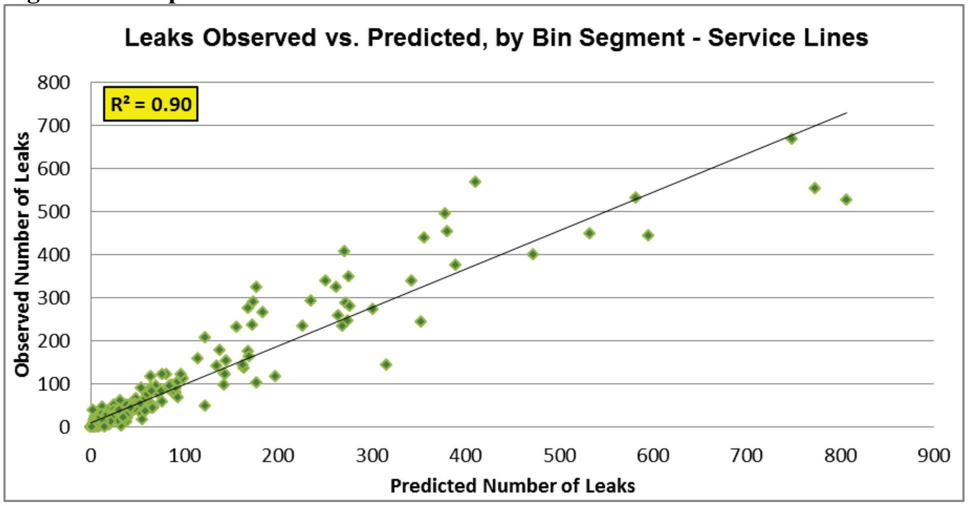


Figure 5 provides the same comparison for Aldyl service lines. Again excellent agreement in observed between the model and actual leak history, with an R^2 of 0.90. Overall, therefore, the mechanistic-probability models are seen to provide a good fit to historical field failure data and describe the performance of the different Aldyl generations across a broad range of operating conditions.

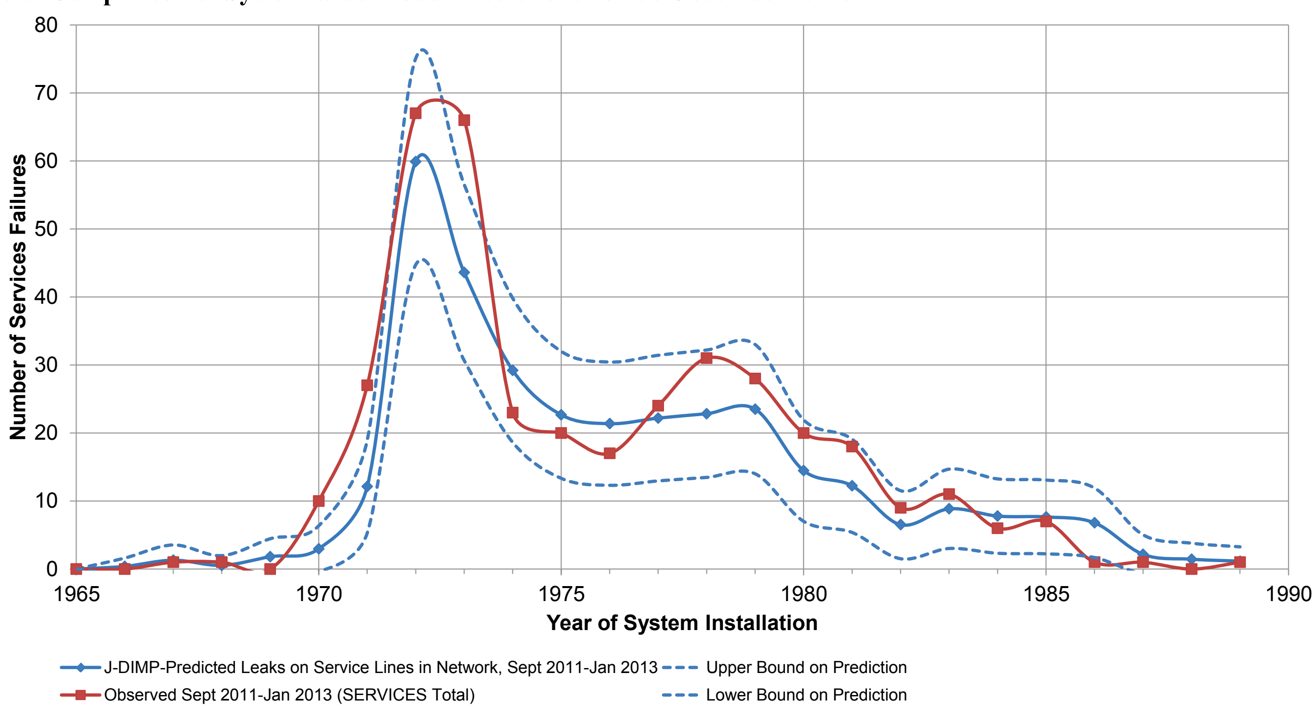
Figure 5: Comparison of Observed and Model Predicted Leaks for Gas Service Lines



ASSESSING MODEL PERFORMANCE

While the comparison of the model projections to the data used to tune the models indicates that the model fits the data well, it is not a true test of the predictive capability of the model. To assess this predictive capability, the tuned models were used to forecast leak rates for a gas distribution system over an eleven month period. **Figure 6** provides a comparison of the observed and projected leak rates through that period by Aldyl vintage. The red line represents the observed number of field failures by installation year of the Aldyl piping systems. The solid blue line represents the model projected number of leaks along with the 95% confidence limits (dashed blue lines). The model closely projects the total number of leaks within each installation year across all the Aldyl generations. In addition to the specific leak rate projections, the confidence limits provide for the ability, through Monte Carlo simulation, to examine the expected range of performance for the gas system in a given year to provide a more complete risk picture than just a single point projection.

Figure 6: Comparison of System-wide Model Predictions versus Observed Leaks



USING THE ALDYL MECHANISTIC-PROBABILITY MODELS TO OPTIMIZE ASSET MANAGEMENT

The mechanistic-probability models developed for Aldyl piping materials provided leak frequency projections in good agreement with observed performance throughout the different Aldyl generations. The projections, therefore, provide guidance on answering the two fundamental replacement questions: At what rate should I replace the Aldyl piping in my system? and What piping should be prioritized for replacement?

The future leak rate forecasts, providing accurate projections of the total future number of leaks and how those leaks are projected to change over time into the future, can be used to set target replacement levels based on the risk criteria – for example, what level of pipe needs to be replaced to maintain a constant leak rate in future years? These overall projections can also be used for planning maintenance activities.

The models also allow for true risk prioritization of the replacement program. Once accurate leak forecasts based on the specific materials and operating conditions in a system are developed, a true risk ranking of the Aldyl piping in the network can be obtained. Because the operating parameters (pressure and temperature), in addition to the Aldyl vintage, can exert a significant influence on the leak rate, this ranking is often very different from a simple age based replacement program.

Accurate leak rate forecasts also allow for optimization of leak survey programs by targeting the higher risk Aldyl segments. Combined with pipe replacement program optimization, the operator has the opportunity to significantly reduce system risk in an informed way while managing the remaining Aldyl piping in their system.

CONCLUSIONS

Mechanistic-probability models were developed for Aldyl piping materials that were shown to provide accurate projections of future leak rates. This allows for optimization of asset management decisions based on sound projections of future system performance. The amount of Aldyl piping requiring replacement to achieve specific risk objectives can be determined along with the priority with which different segments within the overall network should be replaced.