Pipeline Variable Uncertainties and Their Effects on Leak Detectability

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Introduction

General

Software-based leak detection systems (LDS), often loosely referred to as computational pipeline monitoring (CPM) rely upon field measurement and instrumentation. Systematic procedures are needed to allow rational design of CPM systems by providing an estimate of the sensitivity that can be expected given a CPM type and instrumentation, and given the engineering factors and operational environment of the pipeline.

CPM methods for LDS are not new, and early applications appeared almost as soon as useful computing power became available to the industry in the 1970's. It was realized very early on that a large number of factors contribute to the effectiveness of CPM. For a given pipeline, it is essential to understand the uncertainty in the prediction made by the CPM algorithm in use regarding the existence, or absence of leaks.

Modern internal LDS collects field data using supervisory control and data acquisition (SCADA) systems and provide the analysis in real time. There are a number of physical principles that can be used as the basis for a LDS technique. These can range from a simple monitoring of the rate of change of a single pressure reading, to the detailed computation of the complete physical state of the pipeline. Taken as a whole, including all the physical inputs, SCADA readings, and engineering assumptions, a modern, internal, CPM-based LDS is a complex system. Relating the uncertainties inherent in the inputs, configuration, and the technique itself to the uncertainty in the prediction of a leak is an equally complex task.

The first accepted industry publication for the numerical assessment of uncertainty in CPM techniques is the API 1149 (first published in 1993). This publication remains valid and extremely valuable within its range of applicability. Generally speaking, it is designed for crude oil and refined products pipelines. It also focuses on (while also discussing other ancillary issues) single, straight pipelines and on the material balance method of CPM, particularly under steady state conditions.

Purpose

This revision of procedures for the assessment of uncertainty in CPM techniques was undertaken in light of a number of recent technological developments and operational requirements. It is also directed at engineering uncertainty factors that prove, in practice, to have a significant effect on LDS uncertainty but that were not thoroughly addressed in the 1993 version.

While the 1993 API 1149 has proven to be useful to the industry, it is incomplete and has several shortcomings and gaps in justifying the sensitivity estimation metrics. The project team has identified these shortcomings and gaps that need to be addressed in the 2015 revision of the publication to improve the industry's ability to qualify sensitivities estimations of many CPM applications.

1) *The need to cover the complete range of CPM methods in current, practical use.* The original API 1149 only covers volume balance internally based CPM systems and not some of the other related CPM systems mentioned in the API 1130 (first published in 2002, revised September 2007, and reaffirmed in 2012).

   A list of the techniques cited in API 1130 and covered in this document is provided in Table 1.

2) *The need to extend the assessment to highly volatile liquids (HVL) and natural gases*. In part because the uncertainties related to CPM in HVL and gas pipelines are not covered by the 1993 revision of API 1149, CPM is often dismissed too readily as a viable form of leak detection. The review therefore explicitly covers these two common pipeline fluids, in addition to low volatility liquids (LVL). The calculation of density—or, equivalently, the computation of volumes at standard conditions—is central to a number of lead detection (LD) techniques that rely on the principle of conservation of mass. Therefore, especially for these kinds of LD methods the equations

of state, and the calculation of density/standard volumes, are important. This is discussed in much more detail under the subsection on the reference model.

3) *Alignment of the definitions and approach to uncertainty with those used systematically in instrument and measurement engineering*. The intention is to provide a systematic and universally recognized framework for the definitions related to uncertainty. Specifically, the procedure refers to the American Society of Mechanical Engineers (ASME) *Validation and Verification Procedure* (*V&V*) number 20 (2009). A similar framework is used throughout metering and measurement engineering, including the API *Manual of Petroleum Measurement Standards* (*MPMS*) (2013), where far more technical detail can be found. The basic measures of uncertainty are bias and precision, and these are discussed at length.

   This framework recognizes that there is no one fixed numerical value for uncertainty. Rather, it regards uncertainty as being fundamentally statistical in nature. Therefore, whatever threshold for detection is set using a given technology there remains a statistically defined probability that it will produce false alarms and miss actual leaks. The framework addresses and formalizes a number of issues, including:

   — how to specify the uncertainties in the input variables and provide guidance on the uncertainties present in different types of sensors and measurement systems;

   — how the presumed normally distributed errors in source measurement translate to strongly non-normal distributions in the uncertainty of the final leak alarm;

   — issues related to the impossibility of systematically estimating false alarm rates by considering just the statistical measures of bias and precision.

   The reader is also referred to the existing API 1130 as well as the 1993 API 1149 for discussion of the complex relationship between alarm sensitivity, alarm confidence, and false alarms. It is also discussed in Section 13.

4) *Recognition of the nonlinear and strongly time-dependent nature of certain engineering factors*. The motion of fluids in pipes, particularly with constantly and randomly variable boundary conditions, is difficult to predict systematically using simplified equations of motion. One of the most common and difficult issues in a pipeline is to estimate the impact of a fluctuating temperature of the fluid at its inlet. A simplified, steady state model of the flow tends to over-estimate, often by several orders of magnitude, the total effect on the fluid properties. Because of non-ideal thermal effects, the only effective approach is to use a full transient computation of the pipeline state with accurate inputs and boundary conditions.

   There are a number of quasi-steady operations that vary with time due to the movement of temperature fronts, drag reducing agent (DRA) concentration variations, or product property variations (including those caused by batching) through the line. Again, the recognition that these effects can yield inaccurate results when simplified models are used makes the use of computer software for their assessment essential.

   The 1993 API 1149 only produces an estimate curve for steady state conditions, limited to the impact of flow, pressure, and temperature. This approach aims to include any source of uncertainty within a consistent framework, including fluid properties, operational affects, and instrumentation analysis. It also addresses the implementation of the software to be used or developed.

   Refer to Figure 7 and Figure 8 for example *overall* tornado diagrams that illustrate the relative impact of various engineering factors on the uncertainty of a LDS, for liquids and gas systems respectively.

5) *Inclusion, in detail, of a number of engineering factors that occur regularly in pipeline operations*. These are listed in detail, and represent issues that are addressed only at a fairly high level in the original 1993 API 1149 estimation procedures. In addition, the 1993 publication only quantifies the uncertainty effects of measured variables like flow, pressure, and temperature. The document examines in detail the calculation for uncertainties

in other fluid properties and their uncertainty affects, such as density, viscosity, bulk modulus, and thermal expansion coefficient.

Similarly, it aims to quantify the typical operational transient conditions experienced on a pipeline, including startup, shutdown, slack (channel flow) operations, and the effects of fluid properties from steady state to transient operations.

6) *Inclusion of the major telemetry (SCADA) uncertainties in measurement.* The procedure takes into account scan rate, communications, loss-of-data, data-time skew, and latency within the uncertainty calculation. Section 7 addresses these issues with an instrumentation guideline that couples the compounded effects of the scan rate, communications, loss-of-data, data-time skew, and latency on overall uncertainty.

   Refer to Figure 9 for an example Tornado diagram that illustrates the relative impact of various SCADA factors on the uncertainty of a LDS.

7) *Section 7 provides update and improved guidance on the source uncertainties present in different types of sensors and measurement systems*. It also discusses what happens to the presumed normally distributed errors, pertaining to forecasting false alarm estimates, given that these alarms occur due to a failure in the telemetry system, which in turn would be outside of a normal statistical probability. In addition, it addresses the issues related to how this does not readily relate to false alarm rate, particularly with consideration of these statistical outliers.

Annex A is a high-level summary of the procedure, which can be used as a standalone document for non-technical readers, or for readers who only require an overview.

Annex B includes a set of worked examples that use actual operating pipeline data to illustrate the use of the procedure, with a range of engineering and operational factors present.

The reader is advised that a sound knowledge of basic fluid mechanics [appropriate to performing pipeline hydraulic modeling (see for example Wylie, Streeter, and Bedford, 2010 or Lurie, 2008)] as well as a knowledge of basic statistical theory [appropriate to performing instrument and measurement analysis (see for example Cox, 2006 or the 2013 API *MPMS* and references therein)] are pre-supposed in the presentation of these advanced LDS uncertainty assessment techniques.

Pipeline Variable Uncertainties and Their Effects on Leak Detectability

1 Scope

This document describes procedures for *predicting* uncertainties in the detection of leaks in pipelines using computational methods based upon physical hydraulic state measurements. This class of pipeline leak detection methods is commonly called computational pipeline monitoring (CPM).

Generally, CPM methods take physical measurements from a pipeline as an input, and calculate a *metric* that is used to assess whether a leak is likely to have occurred. The *uncertainty* in the CPM method is a fundamentally statistical measure of how likely an alarm is to be valid; equivalently, how often an alarm may be due to routine operational conditions or lie within the realm of known input uncertainty.

2 Normative References

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies. A list of other documents associated with API 1149 is included in the Bibliography.

API Recommended Practice 1130, *Computational Pipeline Monitoring for Liquids,* 1st Edition

API Publication 1149, *Pipeline Variable Uncertainties and their Effects on Leak Detectability*, 1993

3 Terms, Definitions, Acronyms, Abbreviations, and Symbols

3.1 Terms and Definitions

For the purposes of this document, the following definitions apply.

3.1.1
accuracy
Used to denote a standard deviation of an estimator of the mean uncertainty. If the sample mean is used, this is also the standard error $\sigma/\sqrt{n}$ of all the errors in the readings. This can itself be estimated by $\sqrt{S^2/n}$.

3.1.2
calibration
Process used to reduce the systematic bias to zero. A calibrated measurement has zero average error.

3.1.3
estimator
A function of a number of samples, used to estimate statistical parameters related to the distribution of U. Note that it is itself a random variable.

3.1.4
harmonic average/sum/product
The inverse of the average/sum/product of the inverses of a set of numbers.

3.1.5
mean uncertainty
The mean (unknown) of U.

NOTE In most statistical theory publications this is called the accuracy of the measurement.