Crack ILI Response: Maximum Depth and Failure Pressure Ratio

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Contents

Figures

Tables

Crack ILI Response: Maximum Depth and Failure Pressure Ratio

1 Scope

This technical report is related to the Pipeline Research Council International (PRCI) project NDE-4-20[1]. This technical report justifies the failure pressure ratio (FPR) and depth elements of reasonable and prudent crack ILI response criteria, to be applied in combination with other best practices of API RP 1176[2] and consideration of advancements in ultrasonic crack ILI technologies and performance.

2 Normative References

There are no normative references in this document.

3 Abbreviations

CL	crack-like
c/w	considered with
FPR	failure pressure ratio
ILI	in-line inspection
IMP	integrity management plan
MOP	maximum operating pressure
NDE	nondestructive examination
PAUT	phased array ultrasonic test
SCC	stress corrosion crack(ing)
TT	tool tolerance
UTCD	ultrasonic tool crack detection
w/o	without
WT	wall thickness

4 General

The recommended response to crack ILI information, which is expected to become a normative annex to the revision of API RP 1176, is shown in Table 1. The criteria shaded in green were examined as part of the NDE-4-20 project.

While some of the findings can inform gas transmission pipelines and corrosion ILI response, the focus of NDE-4-20 and this technical report is axial cracking in hazardous liquid pipelines.

1 C. Macrory et al., “Considerations for Crack ILI Response in Hazardous Liquid Pipelines,” PRCI, PR727-213904-R01, 2022.

2 API RP 1176, *Recommended Practice for Assessment and Management of Cracking in Pipelines*, First Edition, July 2016.

Table 1—Recommended Crack ILI Response Criteria

Description	FPR or Depth	Timing
Saturated	Unknown	Priority
Depth	>70% WT	Priority
FPR w/o TT	1.10	Priority
FPR c/w TT	1.10	Near-term
FPR w/o TT	1.25	Near-term
Growth (next ILI)	1.1 c/w TT or >80% WT	Scheduled

5 Analysis

The crack ILI response criteria shaded in green in Table 1 were examined through the following lenses:

— data-driven incident-avoidance metrics;

— data-driven ILI-NDE pair and safety factor analysis;

— trajectory of UTCD performance;

— purpose and intent of engineering safety factors.

In particular, the criteria values were assessed to determine if incremental changes were appropriate. The values in Table 1 were found to be effective, efficient, prudent, and sustainable, as well as aligned to the best interests of the public while properly protecting the environment.

5.1 Maximum Depth

Fifty percent (50 %) WT has historically been the standard response threshold for corrosion and SCC features in gas pipelines. But is 50 % WT justified for hazardous liquid pipelines? Or are there enough differences in threats, crack management methods, and historical performance to substantiate a value other than 50 % WT?

NDE-4-20 completed an in-depth review of crack incidents since 2007 and found that none of the 13 incidents with crack ILI sizing information available had ILI-reported depths greater than 50 % WT. Therefore, from a historical viewpoint, no incidents could have been avoided through implementation of a crack ILI response threshold of 50 % WT. Similarly, examination of ~7000 ILI-NDE matched pairs demonstrates that implementing the depth criterion of 70 % WT, in conjunction with the FPR criteria of Table 1, is holistically effective. During one operator interview conducted as part of the NDE 4-20 project, it was noted that hundreds of seam-weld imperfections with reported depths between 50 % and 70 % WT were being monitored for continuing fitness-for-service and growth over time with UTCD. None of the operators interviewed suggested a maximum depth response greater than 70 % WT.

It was concluded that, for liquid pipelines, a 70 % WT maximum depth crack ILI response, when deployed together with the other FPR criteria of Table 1, is reasonable, proven, and prudent. An incremental decrease in depth response would not measurably reduce incidents and is not recommended.

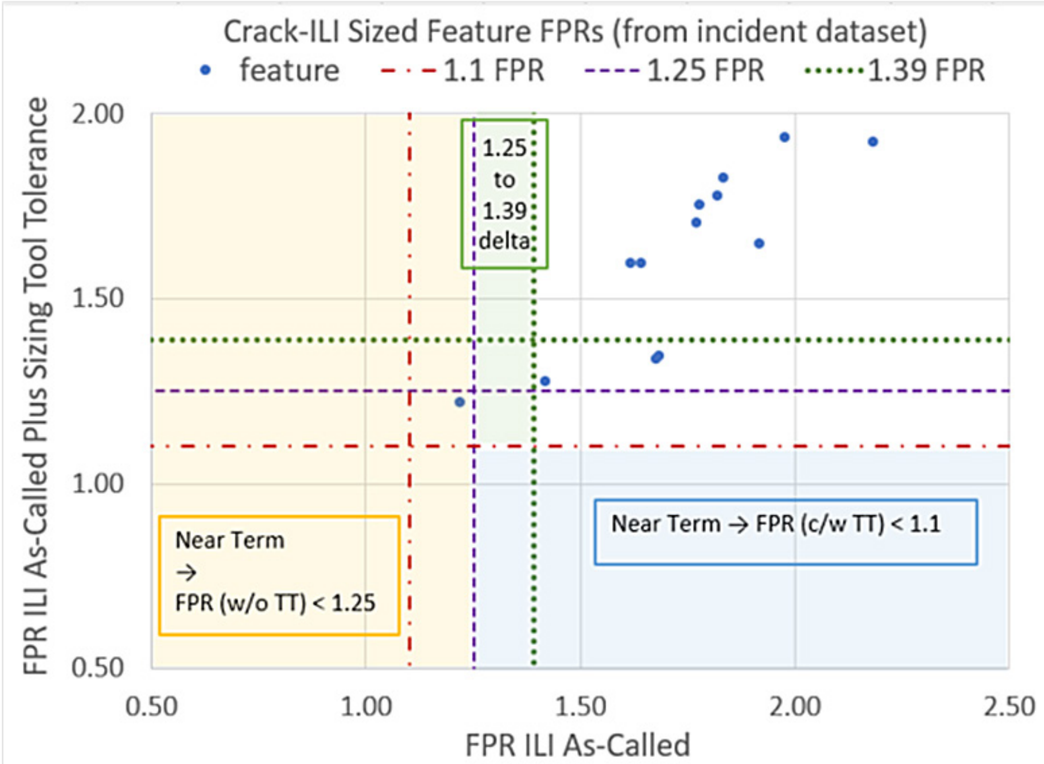

Figure 1—Incident Outliers, Crack ILI FPR c/w TT vs w/o TT (feature depths are all less Than 50 % WT

5.2 Maximum Failure Pressure Ratio

With millions of crack-like ILI features being reported to operators, outliers are expected[3] . Addressing the outliers was a focus of project NDE-4-20. The 13 outliers that caused incidents are plotted in Figure 1 with ILI as-called FPR w/o TT on the X-axis and FPR c/w TT on the Y-axis. Boundary lines and area highlights have been added for the recommended ILI near-term response and the difference between 1.25 and 1.39 FPR.

The most important characteristic illustrated in Figure 1 is the wide scatter of incident FPR with no centric bias.

Examination of the near-hit[4] data from the ILI-NDE pairs shows a similar characteristic: there is no notable clustering of near-hit FPRs between 1.25 and 1.39 FPR, as shown in Figure 2[5] .

3 In this context, an "outlier" is defined as an instance of crack ILI reporting that contributed to an incident (leak or rupture), a near-hit (potential failure of near-critical feature avoided by the timely discovery), or a corrective action on the part of the ILI vendor or the IMP of the operator.

4 "Near-hit" is the potential failure of a near-critical feature avoided by the timely discovery and, in the case of the ILI-NDE study, features with a field NDE FPR less than or equal to 1.0.

5 No NDE uncertainty considered in this plot.

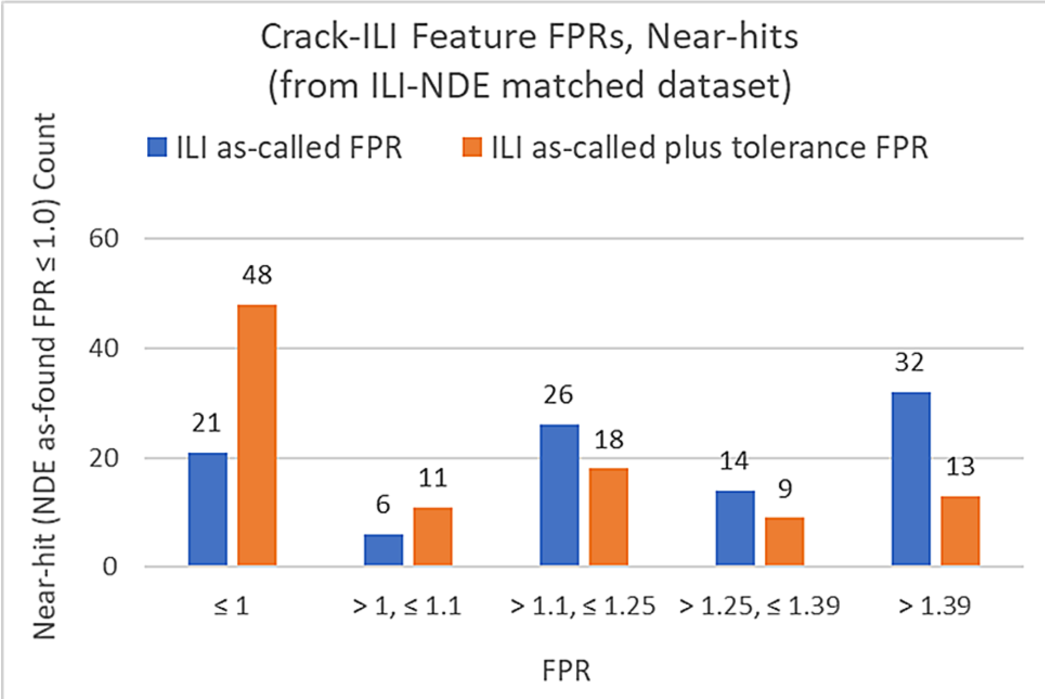

Figure 2—Near-hit Feature Counts by FPR Ranges

The large majority of the near-hits would be addressed with 1.25 FPR (w/o TT) and 1.1 FPR (c/w TT). Those with FPRs greater than 1.25 are considered outliers. Since the aim of best-practice recommendations is to efficiently reduce incident rates, it is apparent that an incremental increase beyond the recommended values of 1.25 FPR w/o TT and 1.1 c/w TT would not measurably reduce incidents and is not sustainable in reducing near-hit outliers.

It was concluded that outlier root causes cannot practically be addressed by enforcing an increase in FPR. Perhaps more importantly, an attempt to increase FPR beyond 1.25 would divert resources away from addressing incident root causes (Table 2) and implementing more effective preventative measures. However, it was recognized that a response criterion of greater than 1.25 FPR could be appropriate given certain circumstances, such as: low %SMYS operation, non-conservative tool bias (or unproven tool performance), and field-identified outliers with low FPR.

Table 2—Incident Summary and Corrective Action Linkages

Defect Description	Service Failure/ Near-hit	Years from Crack ILI	FPR w/o TT	FPR c/w TT	Corrective Action Linkages
SCC, base material w/ growth	in-service	5	1.22	1.22	[a], [b], [c]
crack in/near girth weld	near-hit	0	1.42	1.27	[c]
mfg. defect with growth	in-service	1	1.62	1.59	[a], [b], [c], [d]
mfg. defect	near-hit	1	1.64	1.59	[b], [c]
mfg. defect	in-service	1	1.68	1.34	[a], [b]
mfg. defect	in-service	3	1.69	1.35	[a], [b]
mfg. defect with growth	near-hit	1	1.77	1.70	[b], [c]
mfg. defect	in-service	1	1.78	1.75	[a], [b]
mfg. defect with growth	near-hit	1	1.82	1.78	[b], [c]
mfg. defect with growth	near-hit	7	1.83	1.83	[b], [c]
mfg. defect	in-service	1	1.92	1.65	[a], [b]
mfg. defect	in-service	1	1.98	1.94	[a], [b]
mfg. defect	in-service	1	2.18	1.92	[a], [b]

[a] PRCI projects (NDE-4E and NDE-4-7).
[b] Operator-vendor collaboration, detection and sizing algorithm revisions, and validation.
[c] Augmented API RP 1176 refresh interacting threat and data integration guidance (NDE-4-20).
[d] Augmented API RP 1176 refresh fatigue susceptibility guidance (NDE-4-20).

The application of the standard response criteria, coupled with corrective actions cited in Table 2, already shows a downward trend for leak and rupture incidents (33 % lower in 2020 than 2014) and more 'near-hit' IMP successes as shown in Figure 3.

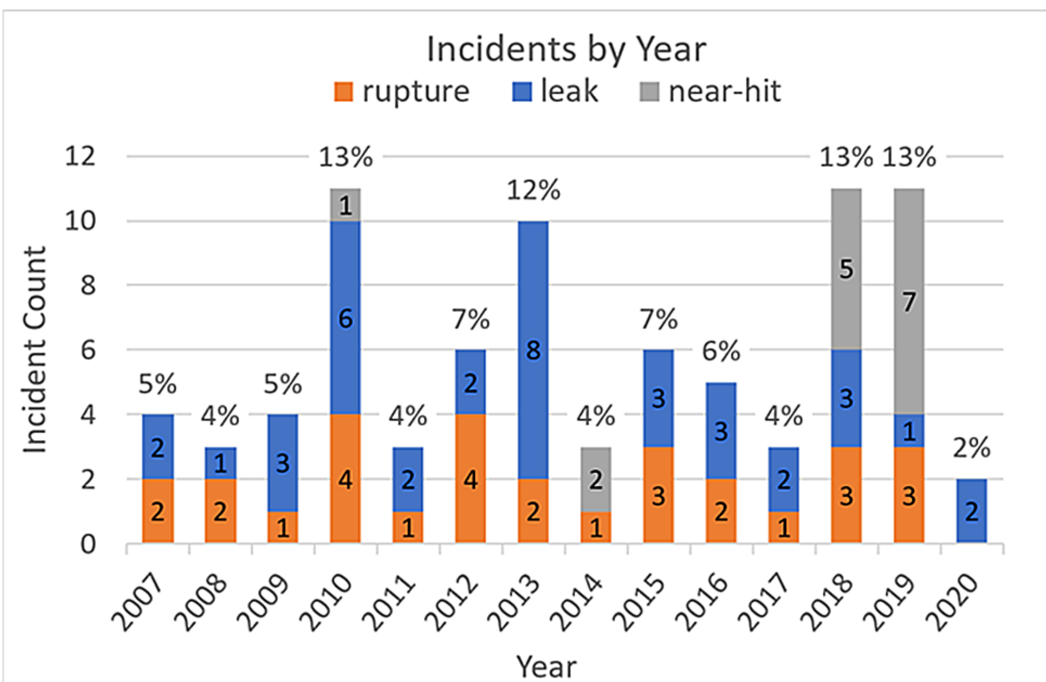

Figure 3—Incident and Near-hit Trends

NDE-4-20 derived an expected remediation cost based on NDE-ILI pairs, increasing the FPR criterion from 1.25 to 1.39 and arriving at ~2.5 times the number of excavations, as illustrated in Figure 4. The confidence level by such FPR criterion increase, however, only marginally grows by 4.5 %.

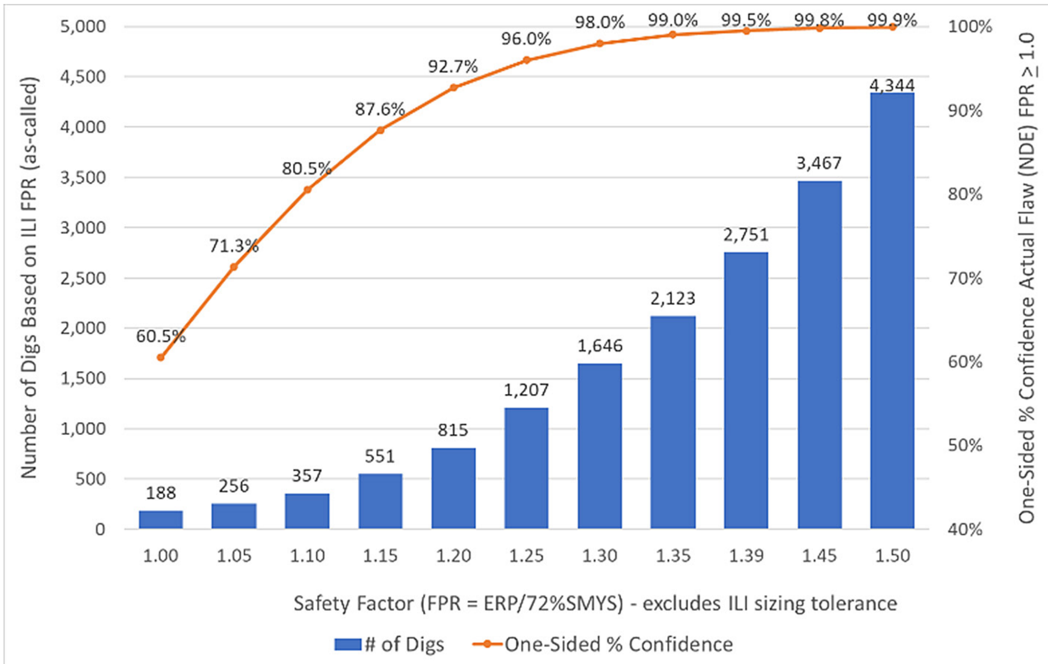

Figure 4—Dig Counts for Crack ILI As-called FPR, ILI-NDE Pairs

For additional context, a sample pipeline segment taken from the Figure 4 data set, with estimated burst pressure plotted for each crack ILI feature by mile marker, is shown in Figure 5. If the crack ILI response was increased from 1.25 to 1.39 FPR, the dig count would increase from 11 to 201 (11+190) with no tangible safety benefit. Additionally, this would not be a one-time cost. Due to the population density in close proximity to the 1.39 MOP line, each subsequent ILI would have a significant number of crack features below the 1.39 MOP line due to tool tolerances and commodity variation. Maintaining a 1.39 FPR on this asset is not viable or sustainable.

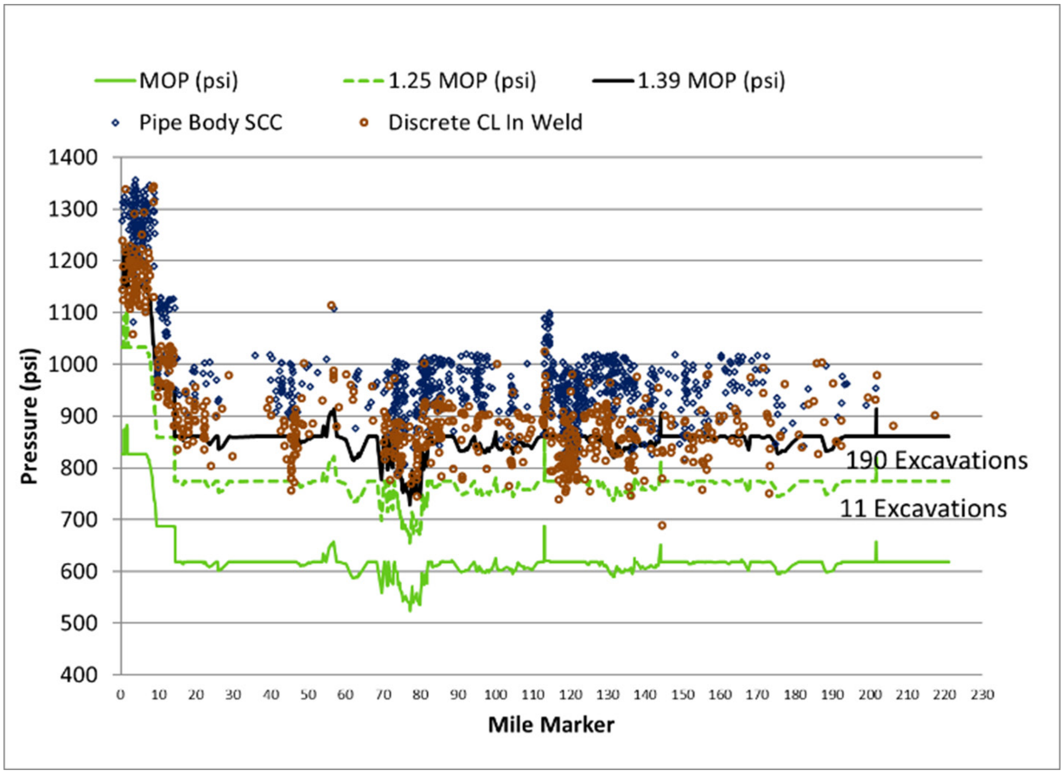

Figure 5—Fitness-for-Service Plot for an Operating Pipeline, Dig Count to Achieve As-called FPR Levels 1.25 and 1.39

6 Crack ILI Advances

Crack ILI, referring particularly to UTCD in context here, is relatively new to industry—it emerged in the 1990s, rapidly developed through 2005, and supplanted hydrostatic testing as the preferred crack-management method for many large operators by 2010. With larger operator investment, more field data correlation opportunities, and free-market competition, ILI vendors have scaled up and made notable advancements. Operators noticed a shift to the better in UTCD tool performance in the 2012–2014 time frame, with commensurate improvement in tool performance specifications. Given this landscape and context, the scope of NDE-4-20 has been structured to focus on recent incidents.

In the last decade, metallurgical cutouts began showing that "inside the pipe" ILI information was often superior to "outside the pipe" NDE information; by 2020, this was by a large margin. To continue to advance ILI, better NDE was needed, and was made a priority for PRCI project NDE-4E. Many operators are now realizing improved NDE by migrating to methods such as PAUT and encoded PAUT, prescribed calibration requirements, and mandatory NDE technician training and certification.

A partial list of evolutionary advancement in UTCD with approximate timing (sourced from four ILI vendor inputs) is shown in Table 3.

Table 3—UTCD Advancement Summary

UTCD Advancement	Time Frame
Bucket sizing	2003
Initial crack profiles	2005
SCC mapping	2005
First-generation phased array	2005
Absolute depth reporting	2007–13
Sensor diameter optimization	2010
Weld misalignment analysis	2010
Mechanical arm optimization for girth weld	2010+
Sensor circumferential spacing optimization	2011
SCC identification algorithm optimization	2011
Metadata confidence correlation development	2011+
Electronics modernization	2013+
Improved profile accuracy	2013
SCC interlinking length algorithm	2014
Onboard sensing corrections	2014+
NGL (propane) capability expansion	2015
Multiple technology integration	2016+
Pitch/catch technology deployment	2017
Indirect crack echo analysis/sizing	2017+
Second-generation phased array w/local WT	2019+
Tip diffraction direct measurement sizing	2019
Sensor diameter optimization for NPS<20 in.	2019
Artificial intelligence—feature classification	2021
Artificial intelligence—weld type ID	2021

6.1 Crack ILI Shrinking Uncertainty

Philosophically, the FPR is intended to account for uncertainty in the overall assessment, which can be visualized with the demand and capacity curves shown in Figure 6. The demand distribution is pressure during operation, generally below MOP with rare exceedance during surge[6] . On the other side, the estimated pressure-containing capacity is generally close to the lower bound of real pipe pressure-carrying capacity due to a combination of conservatively assumed pipe property and model built-in conservatism. The difference between the estimated failure pressure and MOP is represented by FPR or safety factor, as shown in Figure 6. If there is more uncertainty in the ILI information, the blue capacity distribution spreads and flattens, which in turn increases the small red area (the overlap). The overlap represents the possibility of failure. As a result, a larger safety factor is needed to push the demand and capacity distributions apart and maintain the overlap area within an acceptable size. Conversely, as uncertainty in capacity or demand diminishes, the separation safety factor may be reduced while maintaining a constant small overlap area.

[6] Maximum pressure during surge cannot exceed 110 % MOP per CFR 195.

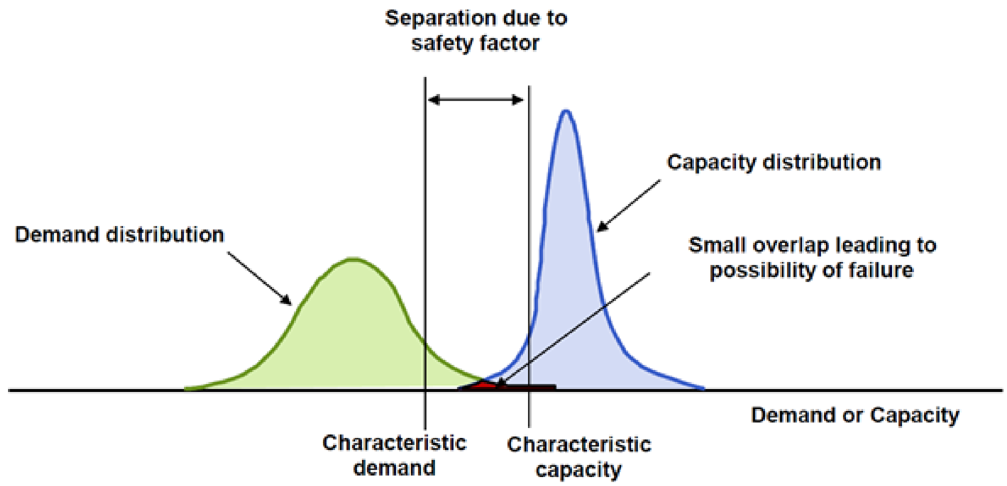

Figure 6—Role of Safety Factor (FPR)

Over time, the capacity distribution gets tighter, justifying a smaller safety factor (FPR) separation between the demand and capacity curves. This is based on crack ILI advances and supported by NDE advances. The shrinking probability of failure over time is conceptually illustrated in Figure 7.

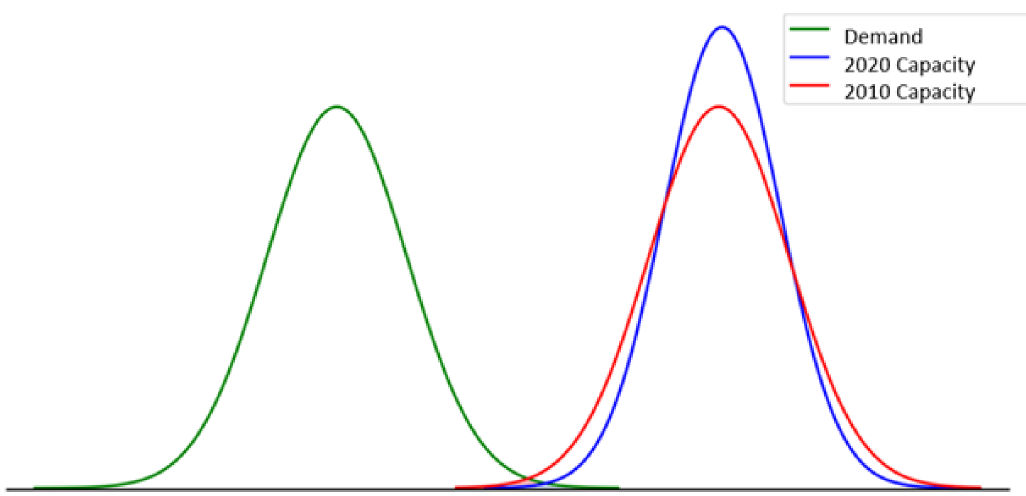

Figure 7—Uncertainty Shrinkage and Effect on Probability of Failure

It was concluded that the crack ILI response criteria in Table 1—which is based on aggregate legacy industry performance—is conservative for future implementation, given that the capacity distribution dispersion decreases over time.

6.2 Novel UT Signal Analysis

In addition to the expected natural advance in electronics, sensor density, mechanical experiential learnings, and more (see Table 3), new UT signal analysis methods are propelling UTCD forward faster than expected after starting just a few years ago.

One element of this advance, which is eliminating the prior depth “saturation” limit, is the analysis of a greater number of time of flight reflections, also referred to as “indirect crack echo” analysis (Figure 8).

Another signal-analysis enhancement is to not only quantify the reflected wave energy, but also the amount of energy attenuated in the pitch/catch scenario, where counterclockwise sensors “listen” for pulses from the clockwise sensor shots and vice versa. If a sound attenuation occurs, this is an indication of a possible crack, which constitutes a sound impedance. This is conceptually illustrated in Figure 9.

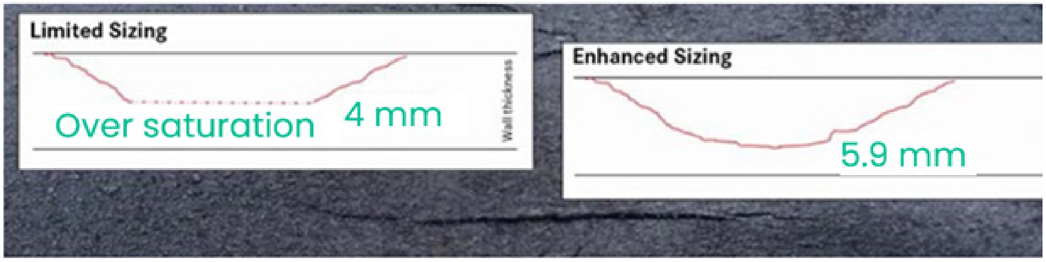

Figure 8—Enhanced Sizing from Indirect Crack Echo (courtesy of NDT Global)

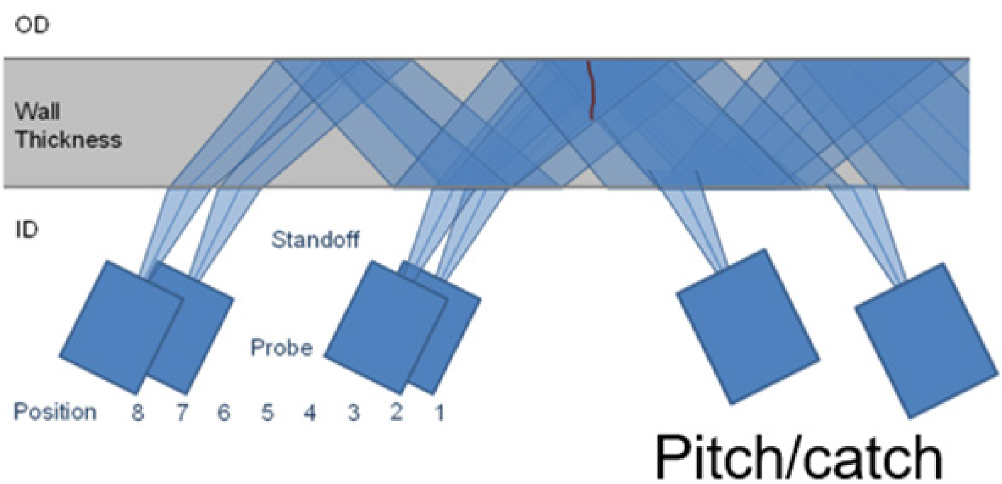

Figure 9—Pitch/Catch Signal Analysis

Advancements realized with NDE PAUT, using multiple and variable shear wave angles, begged the following question: Why not use a similar approach from inside the pipe? This approach has come to fruition with an emerging generation of ultrasonic tools that collect an unprecedented volume of information during an inspection. Integrating the signal analysis, and optimization of algorithms for detection, identification, and sizing of crack features, is ongoing.

7 Conclusion

The crack ILI response criteria shown in Table 1 were found to be effective, efficient, prudent, and sustainable. They were also found to be aligned to the best interests of the public while properly protecting the environment.

For liquid pipelines, a 70 % WT maximum depth crack ILI response is reasonable, proven, and prudent. An incremental reduction in the maximum depth response was found to be ineffective in reducing incidents.

It has been demonstrated that an incremental increase beyond the recommended values of 1.25 FPR w/o TT and 1.1 c/w TT would not measurably reduce incidents. Crack outlier root causes cannot practically be addressed by an increase in FPR; other remedial actions are needed and are already bearing fruit for incident avoidance. Increasing FPR beyond 1.25 would divert resources away from resolving cracking incident root causes and is not sustainable.

The ceiling for continued development and improvement of UTCD is high. Uncertainty in UTCD ILI data is shrinking over time; uncertainty levels of 10 years ago have been measurably reduced in current inspections.

Adopting the proven response criteria in Table 1 is viewed as conservative as ILI technology advancement continues.

Continuous improvement toward unprecedented liquid pipeline transport reliability can be amplified and accelerated as desirable operator behaviors are reinforced through reasonable and judicious rules and guidance.

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