Development of a High-Resolution Hard Spot Specification for Reliable Inline Inspection and Threat Management

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Abstract

A hard spot is defined in the 2024 PRCI hard spot susceptibility review as "localized area in the body of the pipe having elevated hardness levels compared with normal hardness levels prevalent in the rest of the pipe body. They are, in most cases, the result of unintended rapid cooling (quenching) of the steel while in a hot condition in the plate or hot strip mill, or during the forming or forging process for seamless pipe or fittings, with or without benefit of subsequent annealing or tempering." When stressed, they can be subject to failure from mechanisms such as hydrogen-stress cracking or fracture cracking. Industry experience in managing the hard spot threat paired with the recently published operator susceptibility review have raised awareness to the importance of a reliable inline inspection (ILI) hard spot specification to detect and classify hard spots. Validation data is key for developing a robust specification.

This paper describes how, in collaboration with Enbridge and other industry partners, an enhanced solution for hard spot detection and reporting with a robust POD, POI, and POS specification has been demonstrated. Using a three-pronged approach, applied to an established Hardspot ILI technology, a rigorous re-validation was conducted comprising testing of essential variables in three design environments. Extensive pull tests, existing and historical dig data, and FEA modeling in the comprehensive development program utilized multiple data streams to establish an enhanced specification and refine classification techniques to ensure confident hard spot identification – and, therefore, efficient dig programs. Using sample data provided by Enbridge, the enhanced hard spot assessment process was applied to historical inline inspection data to add further optimization and confidence in the derived specification.

Furthermore, the paper will describe how the program not only considered all essential variables in the process and certified an analysis process for the classification of the various hard spot feature types but then how it was effectively extended to three MFL platforms. The result - a broad range of opportunities for combination inspection with standard, planned corrosion inspections.

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Introduction

Pipeline hard spots have become a key integrity threat for operators to manage, and it is critical for Inline Inspection technology to address this threat with reliable and robust specification and classification.

Recent increased awareness and shared industry learnings have resulted in a published 2024 PRCI susceptibility review[1] where several operators were surveyed on individual susceptibility and developed programs to manage the hard spot threat. This review found that hardspot program management had two key challenges when compared to other integrity threats. "Limitations in ILI performance in hard spot detection" and "limitations in field nondestructive examination (NDE) techniques" have resulted in a call to action for enhancement in technology offering and industry collaboration to advance performance of hardspot detection and sizing in ILI.[1] Hard spot susceptibility was identified by several operators for the manufacturers summarized in Figure 1 below detailing 88 reported types (vintages) in total from the 2024 completed PRCI review.

Manufacturer	PRCI 2024	INGAA 2005
A.O. Smith	58	20
Bethlehem	7	2
National Tube	3	
Republic Steel	3	3
Youngstown Sheet & Tube	5	3
Kaiser	4	1
Consolidated Western	2	
US Steel	1	
Welland Tube	1	
Other[65]	1	
Not reported	3	
TOTAL	88	29

Figure 1: *PRCI Susceptibility Review- Manufacturers of Pipe in Hard Spot Failures*

Focused efforts in developing programs and guidance for managing the hardspot threat resulted in a published PHMSA advisory bulletin in November 2024 that "alerts operators of advancements in knowledge of hard spot susceptibility, most notably that what was once considered to be an issue confined to a single manufacturer (A.O. Smith) of specific, limited manufacturing years, is now understood to include potentially other manufacturers and manufacturing years."[2] A key outcome of this bulletin is continued action by operators to complete a thorough hardspot susceptibility review within their programs that now includes review for other manufacturers and manufacturing years on vintage pipelines outside of the initial scope of understanding that the threat was previously linked to a single manufacturer. These findings have consequently resulted in a renewed focus on hard spot assessment methodologies as well as the abilities and specifications of ILI. Considering these recent developments, Baker Hughes has deployed a new enhanced performance specification for its hard spot service, developed with multi-modal methodology and rigorous validation supported by industry collaborations.

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1. ILI Specification for hard spots

A hard spot is a localized area of increased hardness, defined in 49 CFR Part 192 as "an area on steel pipe material with a hardness greater than or equal to Rockwell 35 HRC (Brinell 327 HB or Vickers 345 HV10)". They are typically introduced during the manufacturing process and can lead to an increased risk of cracking due to brittleness. For the purposes of ILI tool validation, a hard spot is considered to be any area with an elevated hardness above the base material as it is important to use all available data including low level features (below specified POD of 250 BHN) to validate detection, classification and sizing.

The API1163 standard describes a performance specification as "*a written set of statements that define the capabilities of an ILI system to detect, classify (identify), and characterize features*."[3] Each of these capabilities should be accompanied by a range of conditions under which the specification is valid – known as **essential variables**. For each valid range, the performance should be qualified by supporting data and a validation methodology. The supporting data can be: verified historical data, full-scale tests from real or artificial anomalies, and small-scale tests, modelling, and/or analyses. This supporting data is then used to quantify the performance of the ILI inspection system across the working range of essential variables, typically focusing on feature detection (POD), identification (POI) and sizing (POS).

2. Understanding the importance of essential variables in development of a robust hardspot specification.

The first step in creating a specification is to identify all essential variables.
During the development of the enhanced specification, the entire ILI system and process were analyzed to identify the essential variables associated with each stage of an inspection and subsequent analysis, while ensuring any potential interactions were understood. Experiments are devised to understand the effect of each essential variable, ideally by isolating that variable and keeping all others static. All essential variables were documented, some variables such as sensor design were unchanged over all experiments while some key variables were the focus of the testing such as wall thickness and run speed.

Figure 2 shows the interactions between key essential variables, grouped into categories showing the different aspects of the features or inspection process which could potentially affect the results.

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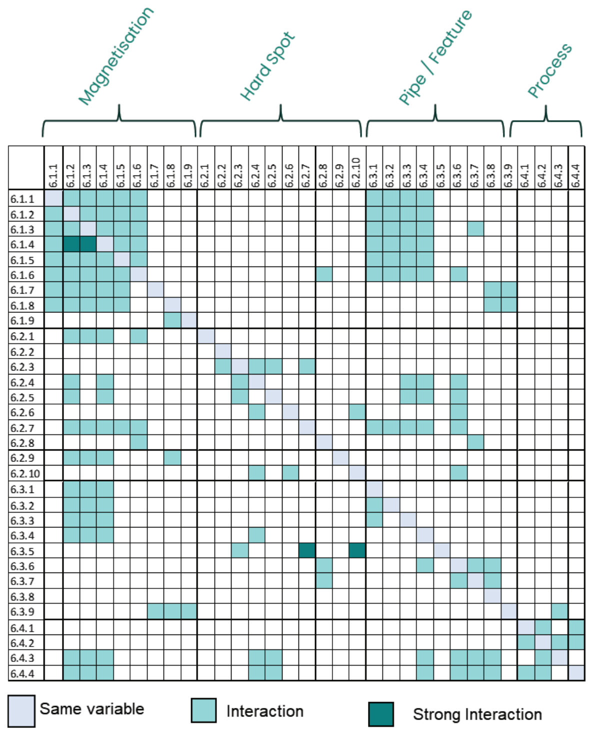

Figure 2: *Interaction Between Essential Variables*

3. Hard Spot Inline Inspection- Low Field and No Field

There are different approaches to detecting hard spots with two common approaches - magnetizing the pipe wall using a standard MFL vehicle then analyzing the residual field or comparing signals from high and low field ILI vehicles.

The same essential variables will apply to different approaches but in different ways. This paper details the qualification and deployment of an enhanced hardspot specification of an ILI system based on analysing the residual magnetisation - or a no-field approach.

Alternatively, application of a magnetic field lower than one typically used in an MFL inspection could be used. However, both techniques result in visibility of material changes such as hard spots in the ILI data collection. The key difference in a no-field approach is that it does not require a quantitative comparison between visible hard spot data and corrosion data as the no-field approach renders corrosion data essentially invisible.

4. Development of Enhanced Specification

To evaluate each essential variable, data must be available that spans the expected operating range of that variable.

Each source of the available data has limitations that were acknowledged in this completed specification development.

- **Operational hard spots** are the most representative, but there is no control over feature dimensions and often only a single run. Also, the number of completed digs for validation data is very limited compared to metal loss.
- **Pull tests** provided much more controllable run parameters but were limited in ability to control hardness of features.
- **FEA modelling** was utilized and proved to be a very flexible data source with the type of features that can be modelled.

One example of this flexibility in the FEA modelling data source was the use of variation in through wall hardness and isolation of variables such as pipe diameter. This project acknowledged that this variation may not reflect reality perfectly, but the design of experiments and utilization of a multi-modal provided a robust methodology across a full range of variables needing validation.

Addressing the full range of variables, experiments across all three modalities (See Figure 3) were required and results were duplicated across experiments wherever possible.

Figure 3: *Multi-modal Testing Methods for Specification Development- FEA Modelling, Pull Tests, and Dig Data*

The results of the experiments into variation with respect to essential variables were consistent across all modalities and showed the residual field approach is a robust inspection technique. The hard spot signals and predicted dimensions were consistent across different tool types and when varying wall thickness and run speed, allowing the specification to be established across these essential variables. Sensor stand-off and hard spot through wall variation did show a significant effect on signal characteristics, and applicable limits could be established in the specification.

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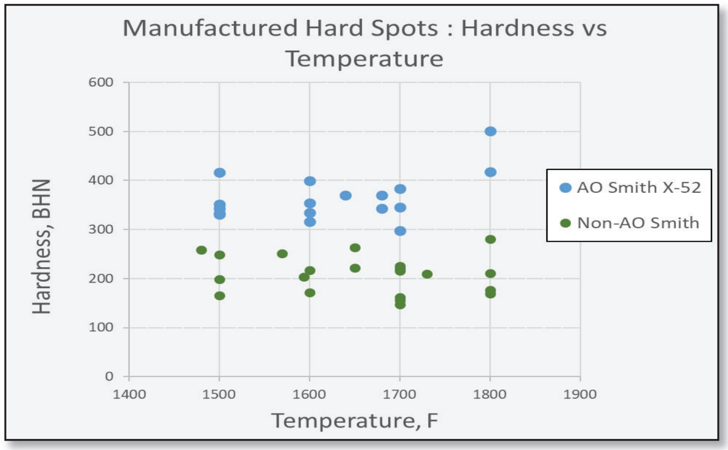

Figure 4: *Variation of Hardness and Temperature in Manufactured Hard Spots for Validation of Specification*

The hard spot manufacturing process was duplicated with identical parameters across different pipe spools. Findings from this validation effort show that the same process created higher hardnesses in a vintage AO Smith spool than in a similar more recent spool. This indicates that the AO Smith pipe steel may be more susceptible to the creation of higher hardnesses.

Figure 4 shows the population of hard spots across two spools and the hardnesses achieved compared to the temperature applied, with the separation in hardness across the two spools evident.

Using the methodology described above for developing the robust specification, creation and validation of POD, POI, and POS as well as acceptable ranges for the essential variables were achieved.

5. POD, POI, and POS

Pipeline data from the three sources were compiled into the validation evidence and final specification. The validation evidence was derived from experiments designed carefully to cover all the identified essential variables relating to the ILI inspection tool and run parameters and many relating to the hard spot itself, which resulted in the delivery of a robust specification across a wide range of hard spots, ILI tools and run conditions.

Through the process of deconstructing the hard spot ILI inspection system, identifying the essential variables for each step, devising the experiments, and evaluating the data from each source, the data science and analysis teams have gained invaluable insights to the influences on signal responses from varying conditions and scenarios. The quality of the data obtained directly contributed to the quality of this specification and continued optimization opportunities underpinning a best-in-class hard spot inspection service.

Figure 5 summarizes the hardspot performance specification achieved through detailed experimentation and validation process.

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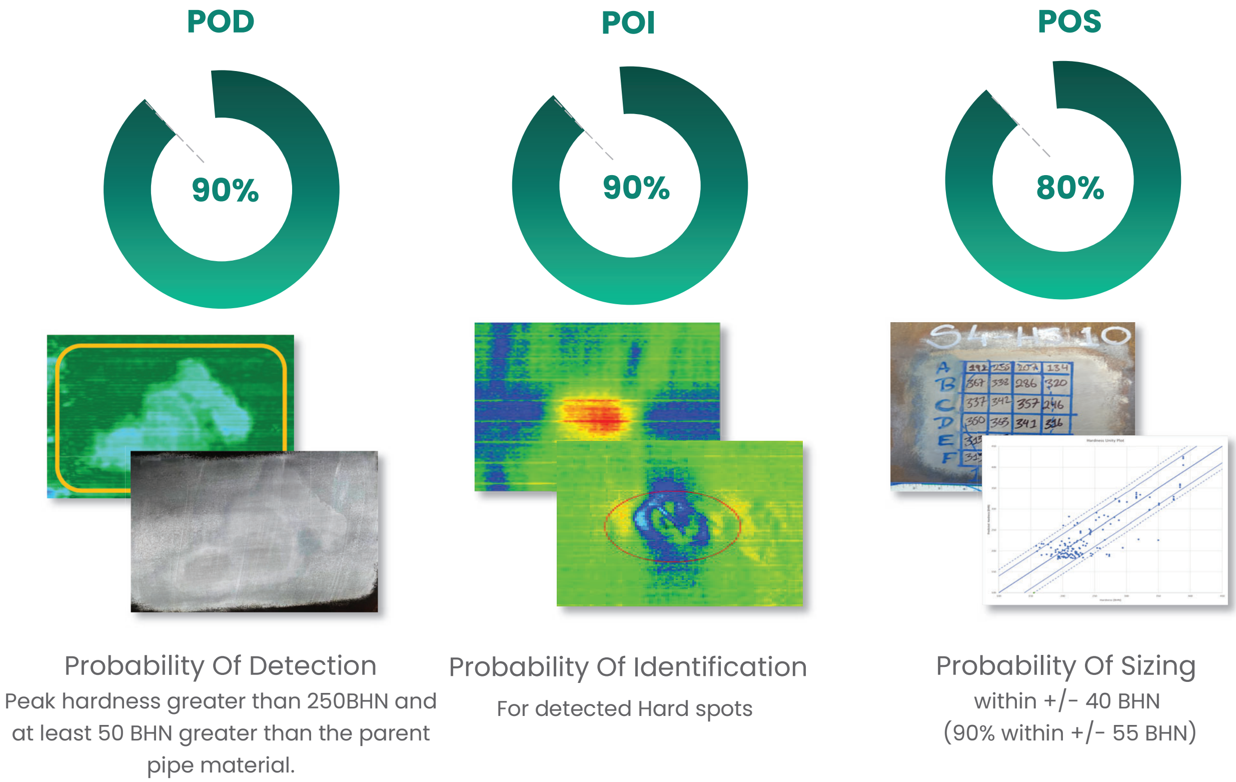

Figure 5*: Performance Specification on POD, POI, and POS*

POD of 90% was achieved for features with hardness greater than 250 BHN and a minimum of 50 BHN greater than the parent pipe material. In pull tests, a good correlation between the shape and extent of the Nital Etching, EddyFi Spyne signal, and the ILI signal was observed. The detection plot in Figure 6 below shows the blue line as the detection threshold specified in the POD with respect to hardness and length. Base hardness averaged between 160 and 170 BHN and 100% of features above specification were detected.

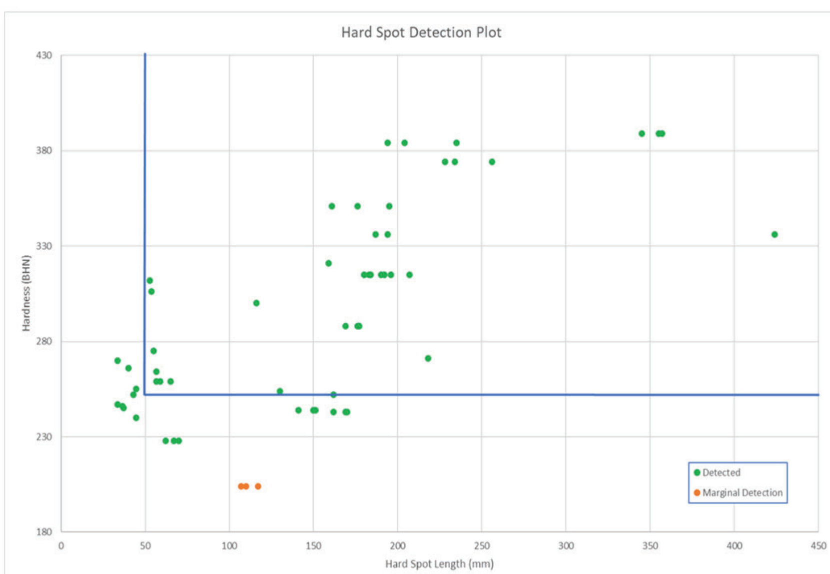

Figure 6*: Enhanced Specification Hardness Detection Plot*

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POI was tested and validated for five different hard spot feature type classifications shown in Figure 7 below.

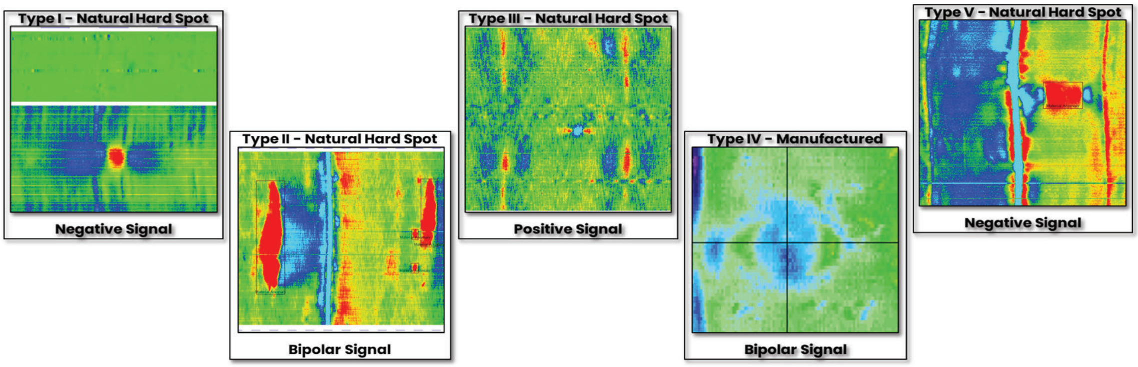

Figure 7: *Enhanced Specification Hardspot Feature Classification Types*

Five feature classification types were developed: Type 1, Type II, Type III, Type IV, and Type V. Type I hard spot features are classified as natural hard spots that can have either positive or negative signals in ILI data. They are consistent in shape and area characteristics and align most commonly with the main feature type seen operationally. Type II hard spot features are classified as non-uniform hard spots with large and complex, hard spot areas. These feature types can be associated with expansion marks and other manufacturing processes. Type III hard spot features are classified as Cad weld type and are defined as a small area and uniform shape. They also typically show uniform hardness, and MFL data can be utilized to assess if there is any attachment associated. Type IV hard spot features have an appearance similar to manufactured hard spots, resulting from the effects caused by boundaries of the manufacturing process. Lastly, Type V hard spot features are classified as material anomalies that are low predicted hardness features most commonly resulting from manufacturing origin. Some examples of these can be grinds or arc strikes. POI of 90% was calculated by applying the updated classification rules to all available non-manufactured hard spot data.

These classifications and characterization of hardspot signals into feature types help to better understand potential nature or origin of hardspots. It will also be valuable to further develop sizing methodologies and improve peak hardness definition. This specification details five feature types, and these will be optimized with future industry collaboration opportunities for alignment with best practices in characterization of hardspot threat assessments.

POS was calculated at 80% confidence for hard spots to be predicted within +/- 40 BHN of actual hardness, and 90% of hard spots will be predicted within +/- 55 BHN of actual hardness. In the unity plot below (Figure 8), a range of features around the detection level are shown. Lines in the plot illustrate the published POS performance for features greater than 250 BHN and within +/- 50 BHN. All features in Figure 8 below includes all non-manufactured hard spots that were available. This includes a majority of Type I hard spots.

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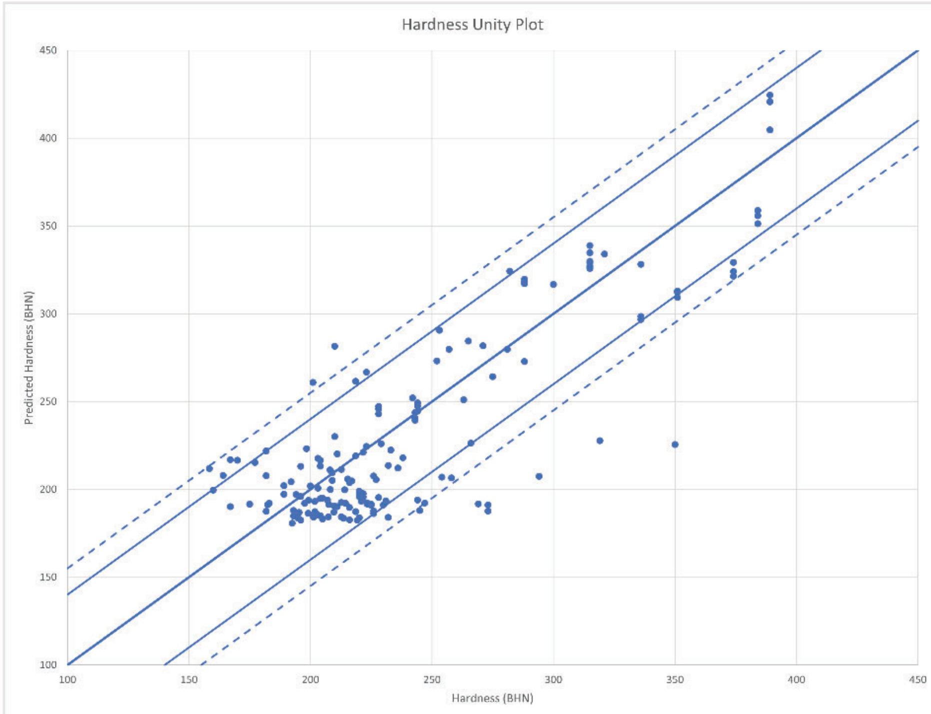

Figure 8: *Enhanced Specification Hardness Unity Plot*

Figure 9 below shows the length prediction performance. Hard spot lengths will be predicted within 1"/25mm, or 2"/50mm if the hardspot is longer than 4"/100mm, at an 80% certainty and widths will be predicted within 2"/50mm at an 80% certainty.

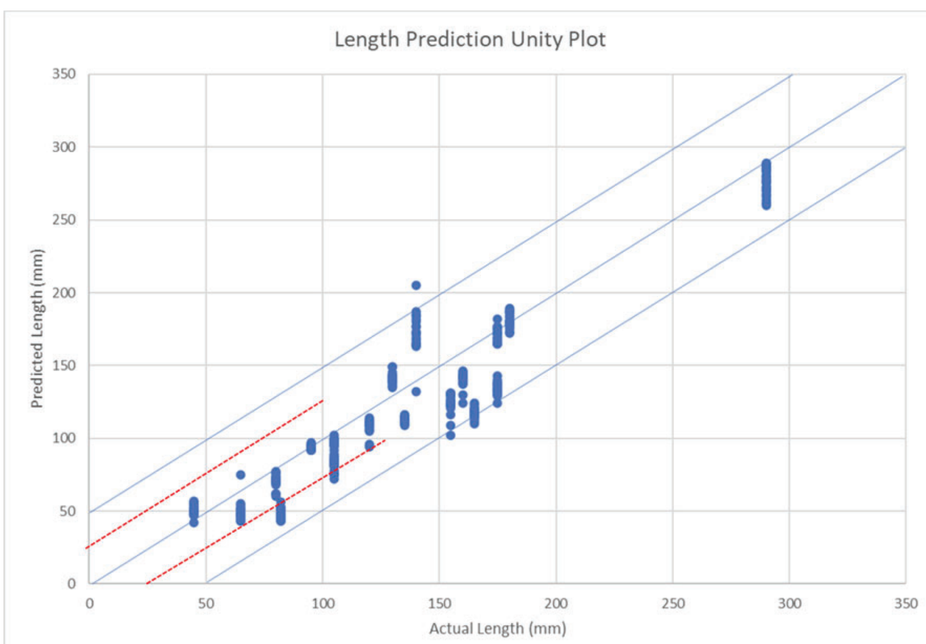

Figure 9: *Enhanced Specification Length Unity Plot*

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Dig data can be used to corroborate the validation test discussed above where the data points coincide and is of particular use in improving POS and POI. Examples of different types of a hard spot and more than one feature type results in a residual field signal and can be misinterpreted as hard spot. POI is one of the more challenging aspects for ILI inspections of hard spots as the ILI tool records residual field, not hardness directly, and hard spots are not the only type of feature to show an increased residual field. Pipeline features such as dents, metal objects, arc strikes, and CAD welds could be possible false positives. This developed POI allows for informed report delivery to operators for improved threat management.

6. Application and Deployment of an Enhanced Specification and Hard Spot Assessment

ILI tool validation is not a one-time process. For the purpose of this study, Enbridge hard spot dig information is reviewed and added to the Baker Hughes dig database, where the performance across all technologies, including hard spots, is tracked on an ongoing basis. Availability of additional dig data is expected to lead to new learnings and optimization opportunity in performance which will lead to future improvements to the published specification.

As a result, Baker Hughes has engaged in industry collaboration with Enbridge to re-assess historical ILI inspection and corresponding dig data validated with NDE. The performance validation is shown in Figure 9 below.

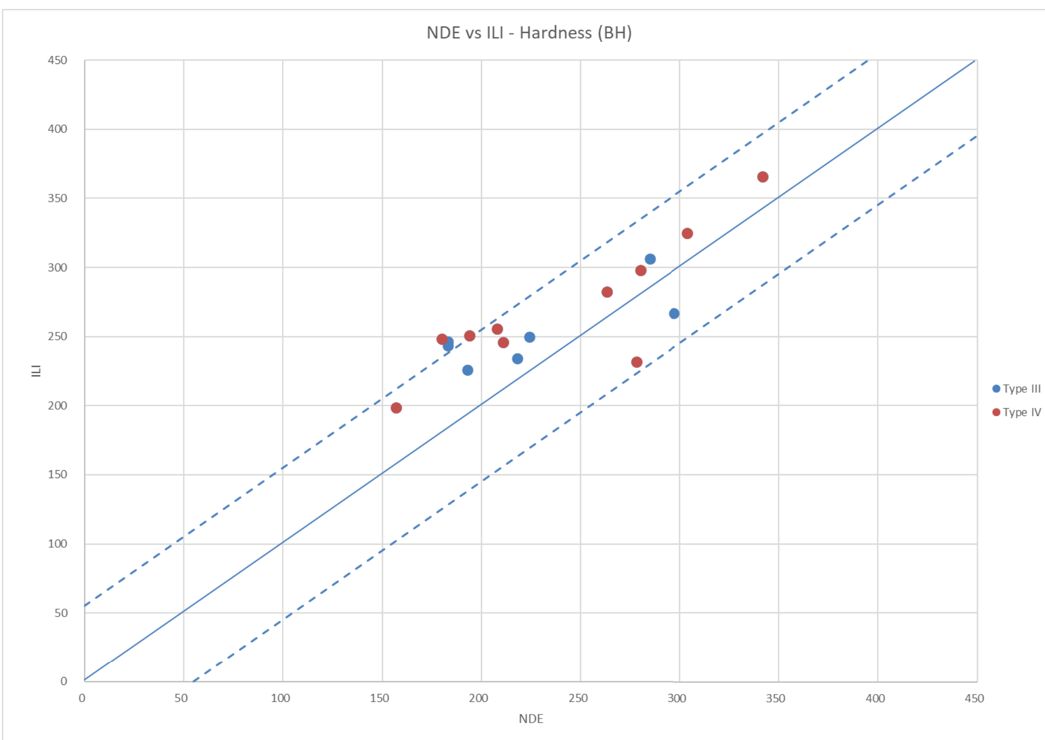

Figure 10: *Hardspot Validation Dig Data from Deployed Enhanced Specification*

17 hard spot features from validated dig data shown in Figure 10. The performance on this sample is demonstrative that the enhanced specification can be met in practice. Following API 1163 methodology, the Clopper-Pearson upper confidence limit at the 90% confidence level specification is equal to 93.2%. The specification will be further validated and optimized with increased dig data availability offering a larger data set for future projects. It is important to also note that this unity plot did not account for potential variation in NDE tolerances due to different equipment used, and that may have an impact to those that appear slightly overcalled which could have been within spec if NDE tolerances were taken into consideration.

Methods of measuring hardness in field can have quite high tolerances and performance in field can have an impact on hardspot feature classifications especially like a Type III classification where you could miss the peak hardness on certain NDE equipment and processes. This highlights future collaboration opportunity to utilize the NDE equipment variation and effects in a future study to expand understanding on any potential impact to ILI performance and specification of hard spots.

The re-assessment allowed for additional validation of performance in classification of Type III features (Figures 11, 12, and 13) and Type IV features (Figures 14 and 15). Prior to this work, available dig data and industry reports mostly shared Type I hardspot types.

Figures 11, 12, and 13 demonstrate the successful detection, identification, and sizing for reporting a Type III Cad weld hard spot feature. This feature was a localized small area with peak hardness of 342 BHN with a very clear signal for ILI reporting. Previously, these feature types were not classified and could have been reported as a material anomaly due to limited information for classification. Ultimately, prior to definition of the Type III classification most operators would have previously considered it's reporting a false positive for hardspot inspection.

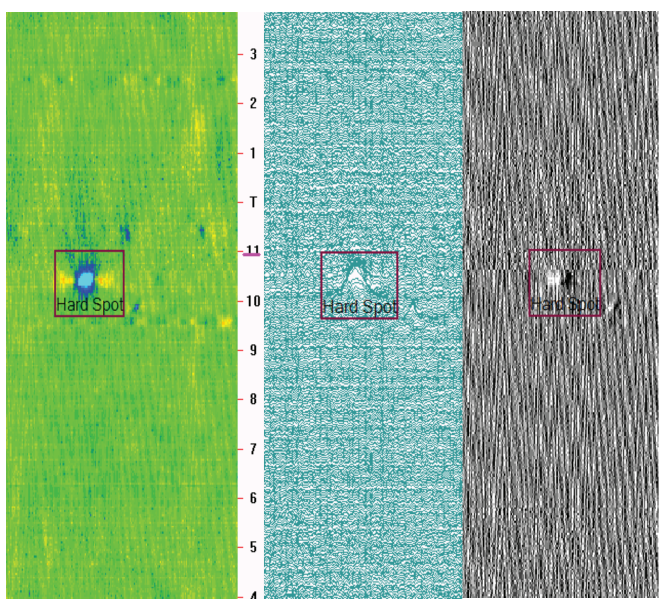

Figure 11: *Hardspot Data from Spool with Validated Operational Type III Hardspot*

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0	16	15	14	13	12	11	10	9	8
16	169	178	146	158	159	153	158	153	151
15	171	183	153	164	152	169	178	174	175
14	165	166	164	161	167	166	161	162	170
13	OBST.	OBST.	OBST.	OBST.	OBST.	OBST.	OBST.	OBST.	OBST.
12	162	136	147	156	161	151	155	149	161
11	156	157	155	154	153	151	151	147	146
10	155	164	157	165	164	158 159 180 342	155 156 145 136	155	156
9	153	157	153	147	153	327 209 148 208	212 174 195 192	153	153
8	160	160	143	151	140	155 158 155 154	246 160 147 155	158	159
7	142	142	142	148	151	151	146	146	145
6	140	137	149	155	154	150	138	142	142
5	135	135	137	140	137	141	144	141	140
0.4	137	136	140	141	149	151	150	145	143
3	141	153	153	143	145	147	140	141	145

Figure 12: *Hardness Readings for Figure 10 Spool*

Figure 13: *Nital Etching for Figure 10 Spool*

Figures 14 and 15 below align with industry reported features with a signal concentration around the edge. This aligns with the Type IV classification and a structure to the signal where quite often there is not amplitude in the middle, but hardness which results in the signal concentrated on the outside edges. The hardness grid in Figure 15 illustrates good alignment to the ILI signal and detected hardness as well further validating POI.

Hardspot feature correlating to hardness grid in Figure 15.

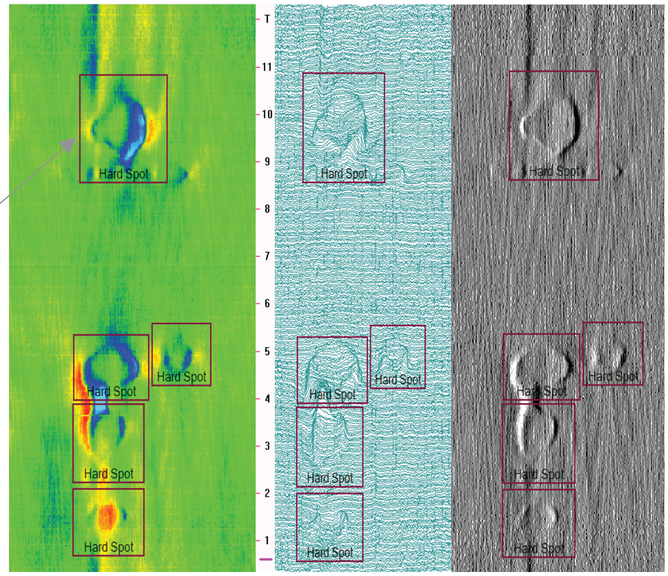

Figure 14: *Hardspot Data from Spool with Validated Operational Type IV Hardspots*

0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1	142	140	142	142	143	141	142	140	144	139	130	137	136	137	127	127	143	121	129
2	155	133	139	142	134	146	142	143	142	151	139	141	135	134	138	140	140	142	142
3	140	142	143	143	144	145	147	133	135	143	137	139	127	148	139	127	124	135	137
4	135	145	145	150	144	143	146	146	145	153	141	143	144	137	141	136	134	140	145
5	131	146	148	172	175	161	150	148	147	137	148	138	141	143	142	140	134	143	131
6	139	141	142	223	243	244	202	169	183	169	142	140	142	135	137	141	141	135	143
7	140	138	160	212	255	234	252	247	220	165	148	136	136	140	143	126	138	138	136
8	131	139	193	265	281	272	270	271	243	243	178	138	136	140	141	123	133	148	150
9	138	159	233	268	281	284	288	297	279	262	197	162	158	126	116	145	138	153	145
10	142	147	178	238	277	283	289	285	272	203	193	159	138	187	134	136	111	130	128
11	147	136	175	240	265	263	267	215	232	189	151	143	141	139	140	135	135	140	145
12	147	138	172	221	257	262	217	185	185	144	134	142	134	133	139	138	140	138	137
13	141	147	147	165	198	216	191	148	143	136	131	144	138	138	146	142	130	141	147
14	127	146	152	167	167	154	144	142	146	148	146	132	119	133	99	132	94	114	130
15	159	170	169	171	169	156	155	146	153	145	134	143	136	140	144	152	135	130	141
16	163	172	164	189	199	146	192	160	141	143	170	139	145	149	171	164	136	119	124
17	209	220	222	220	225	185	165	182	179	175	166	179	150	148	137	117	108	100	134

Figure 15: *Hardness Readings for Figure 13 Spool for Top Hardspot Feature*

Type III and Type IV feature types were included in the Figure 10 unity plot and sample size. Through this collaboration, Type III and Type IV feature discrimination were validated from existing dig data provided and contributes to further validation of the published specification for POI and POS.

After applying the specification to the Enbridge features in the scope for re-analysis, the resulting validation and confirmation of performance and classification of feature types enable this technology offering to continue to deliver to the industry with confidence.

7. Hardspot Inspection Technology Capability Across Three Platforms

This enhanced specification has been validated across three Baker Hughes tool technologies in the VECTRA™ GEMINI and MagneScan™ platforms. Variation of tool technology platforms tested was proven to have no effect on the residual field retained within the pipe-wall which is a primary essential variable that

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determines specification performance. Run to run repeatability was tested and validated to conclude that the hard spot signals using the residual field approach in the scope of this project were invariant to tool type and diameter as well as wall thickness and speed above the minimum magnetization threshold.

Figure 16: *Hardspot with Axial MFL Single Pass Inspection*

Hard spot inspection can be performed in a single pass run with Axial MFL and the hardspot module in one combo configuration. It can also be performed in a two-pass configuration where the Axial MFL tool is run first and followed by a second run for the hardspot tool. In the case of two pass runs the second run is completed within 24 hours of the first run to mitigate impact to hardspot performance due to any potential decay of residual field. Harder pipe steel will retain a higher level of residual magnetization than the surrounding pipe following a magnetic ILI inspection. The residual field signal can be detected and measured by a subsequent vehicle with the appropriate sensors. Inspection can be performed in single or dual pass configurations. Both MFL and residual field data sets with multiple sensor types are used for analysis and classification of hard spot features.

Conclusion

Industry awareness and dedicated effort to effectively managing the hard spot threat has driven the industry call to action for enhanced specification and performance of ILI technology for hardspot assessment. This paper describes the development and deployment of an enhanced specification from completed validation and multi-modal tested data from multiple sources to cover all essential variables. Utilization of residual field methodology with this specification is robust to ILI tool design, magnetic history, run speed, pipe diameter, and wall thickness.

Independent verification of the improved specification through re-assessment of prior inspection results in collaboration with Enbridge has showcased the benefits and shared industry learnings that will result in better management of hardspot threats. Future continuation projects to consider to further enhancement include utilization of NDE equipment and tolerance testing and validation with ILI technology for hardspot reporting. Baker Hughes hardspot inspection service with enhanced specification efforts will continue to be optimized through these future opportunities to continue to deliver best-in-class service for hardspot threat management.

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