Development of ILI hard spot assessment in an era of change

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Abstract

Managing the threat of hard spots has been on the agenda of pipeline operators for several years. It is fair to say that the industry understanding of what hard spots are, how they are formed and how we can manage them has advanced rapidly but is still evolving. The industry knowledge has been recognized by PHMSA and an Advisory Bulletin was issued discussing the threat of hard spots. Industry now has a good feel for the susceptibility of different pipe types and vintages, and there is good appreciation that not all hard spots are the same and variations in morphology result in different types of hard spots and different ILI signal patterns. The current status is predicated on the significant amount of validation work that operators are performing in response to ILI. However, the industry is not standing still, and since the last PPIM conference more information has become available that has led to further improvements. This paper discusses the recent experience, bringing together the latest results from ILI, non-destructive testing and research activities to continually advance assessment methods for managing the threat of hard spots.

Nomenclature

BHN	Brinell Hardness Number
BW	Butt Welded
CP	Cathodic Protection
EC	Eddy Current
ERW	Electric Resistance Welded
FEA	Finite element analysis
FBW	Flash Butt Welded
FW	Flash Welded
HSC	Hydrogen Stress Cracking
ID	Inner diameter
ILI	In-Line Inspection
IM	Integrity Management
NDE	Non-Destructive Examination
OD	Outer Diameter
POD	Probability of Detection
POI	Probability of Identification
RIN	Regulatory Information Notice
SAW	Submerged Arc Welded
UCI	Ultrasonic Contact Impedance

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1. Introduction

With the introduction of regulations around hard spots in RIN 1 and RIN 2 in 2020 and 2023 respectively and more recently, the issuance of the National Transportation Safety Board (NTSB) report PIR-22-02 [1] regarding the hard spot failure in Danville, Kentucky, industry awareness around hard spots has increased significantly. Two papers presented at IPC in 2024 [2] [3] discuss recent experience from operators on managing the threat of hard spots. One paper from IPC 2024 discussed the process by which hard spots ILI vendors were evaluated and qualified in accordance with API 1163 for a hard spot inspection program [4]. A further paper [5] presented the use of probabilistic HSC models to predict rupture using a Bayesian network accounting for factors such as material properties, reported hard spot characteristics (hardness, length) and ILI tolerances in addition to other factors.

One of the key missing pieces of the puzzle over the last few years has been hard spot susceptibility. Whilst there has been some industry awareness around specific manufactures with hard spot failures (AO smith & Bethlehem steel), an overview of all historic failures and why certain pipe types (diameters, seam type etc.) are more susceptible to the presence of hard spots and failure, had not been undertaken, until very recently through the work performed by PRCI [6]. The industry now has a good level of understanding in how to manage the threat of hard spots which is based upon the following major components.

1.1 Understanding hard spot susceptibility

Understanding what types of pipes in the network are susceptible to hard spots is the first step to identifying where you may have a risk of hard spot threat. Secondly, understanding the failure mechanisms of hard spots (HSC and the relationship between crack length and hardness) forms the basis for the next component.

1.2 Develop an effective Integrity Management (IM) program

Developing risk models to guide decision making prior to ILI is discussed in reference [5]. In the post ILI phase, understanding which features may be potentially injurious is key. Building in CP data, coating degradation, hardness and length into risk models to determine dig prioritization is critical. However, without an accurate indication of how many may exist, the orientation (internal vs external), the absolute hardness and the size of these hard spot features, an effective integrity management program will be ineffective.

1.3 Confidence in the ILI technology

Perhaps the most critical component to managing the threat of hard spots is ensuring there is adequate confidence around the ILI technology to detect, identify and size hard spots. Work

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presented by ROSEN at IPC 2024 [7] provides an insight into recent ILI improvements through understanding how thermal cycles influence hard spot ILI signal characteristics.

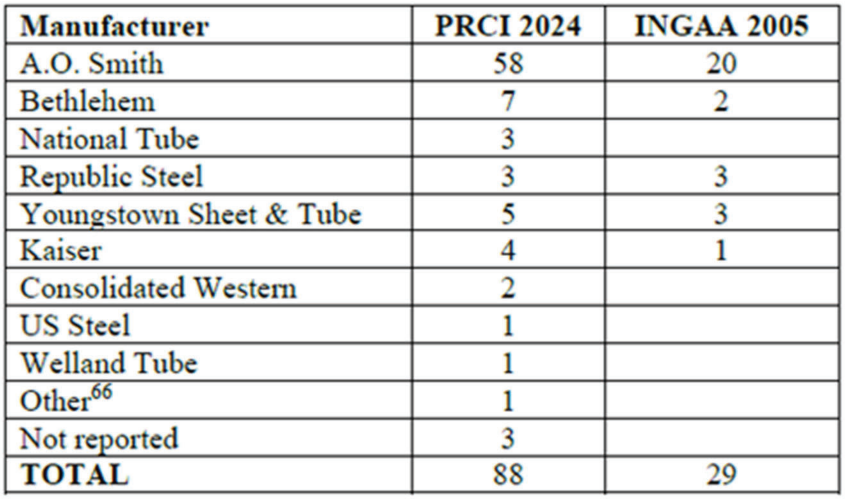
Without all three major components, effective management of hard spot threats is not possible. This paper will discuss all three major components focusing on ILI technological developments as this is key in effectively managing the threat of hard spots.

2. Hard Spot Susceptibility

Pipeline and Hazardous Materials Safety Administration (PHMSA) recently issued an Advisory Bulletin (2024-26725) [8] advising operators to review records to determine whether the types of pipe in their systems are susceptible to hard spots and develop an assessment program to validate hardness anomalies. In 2023, PRCI commissioned two projects; MAT-7-2 [6] and MAT-7-2A [9]. MAT 7-2A discusses the performance of ILI technologies within hard spot detection, identification and sizing. The report for MAT 7-2A is still in progress at the time of writing this report. MAT 7-2 is a research paper that summarizes the results of a study to identify susceptibility criteria for the integrity threat to pipelines posed by “hard spots”. The project compiled 88 pipeline ruptures, leaks, or near-miss incidents associated with pipe body hard spots, reviewed the causes of such hard spots, identified the susceptibility factors, and discussed appropriate integrity management responses.

The majority of the pipes listed above in Table 1 have been manufactured from discrete plate, namely SAW, FW, and ERW pipe manufactured by Youngstown and are all considered susceptible. Very few incidents have been associated with hard spots in SMLS pipe or continuous-skelp ERW pipe, and none in BW/FBW pipe. SMLS pipe, continuous-skelp ERW pipe, and BW/FBW pipe are therefore considered to represent an inherently low threat level unless there is information available that the specific pipe of interest is susceptible [9].

Table 1: manufacturers of pipe with hard spot failures, extract from [6].



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[66]	1	
Not reported	3	
TOTAL	88	29

Pre 1970's pipe has typically been referenced in relation to hard spots [8], however the years of 1944-1959 shown in Figure 1 make up majority of the historic failures of hard spots. This shows a high hard spot susceptibility to the years of 1944-1959 with a particularly high rate in the years of 1951-1955. Whilst there have only been a handful of failures involving 1960's pipe it is interesting to note that this does not mean that 1960's pipe is not susceptible to hardness anomalies. It may simply mean the level of hardness of these hardness anomalies may not be as severe and as such have not resulted in any failures. As we inspect and validate more hardness anomalies over time we will increase our knowledge of hard spot susceptible pipe.

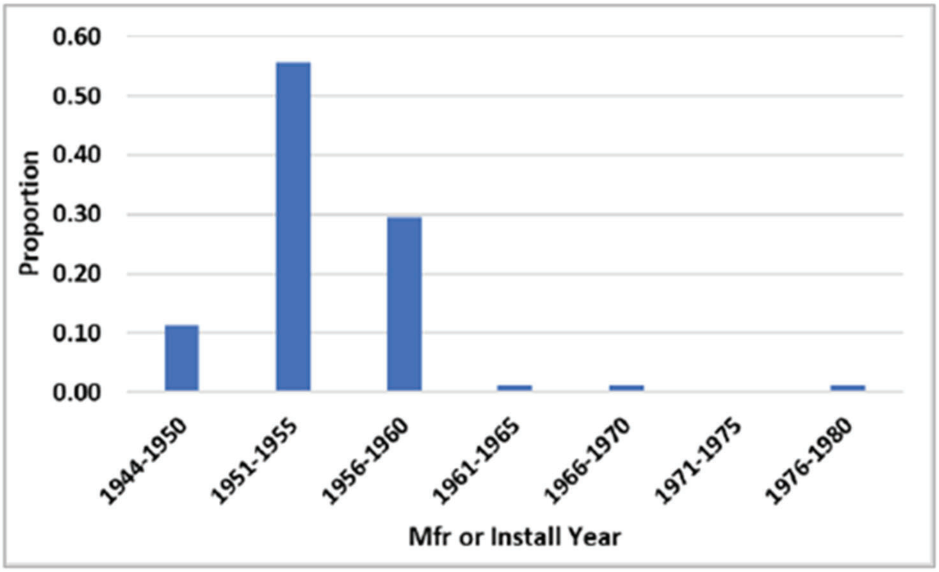


Figure 1: Distribution of affected pipe vintages, extract from [6]

3. Hard spot vs hardness anomaly

A hardness anomaly is a localized area in the pipe body 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. US gas regulation defines a hard spot as 'an area on steel pipe material with a minimum dimension greater than two inches in any direction and hardness greater than or equal to Brinell 327 BHN'. As such, not all hardness anomalies are considered hard spots until the dimensions and hardness are verified in the field.

Figure 3 shows some examples of verified hardness anomalies. The level of hardness is an indication of how much martensite is present. Typically, higher levels of martensite result in higher localized

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hardness. More detail about the formation of hard spots is given in reference [10]. Hardness anomalies exhibit a variety of morphologies and microstructures. Patterns include sawtooth, splash, single or multiple spots, elongated or oval spots, or nearly round spots as seen in Figure 3. These can also be orientated internally or externally or a combination of both (through-wall) [10].

Figure 2: Hardness anomalies verified in ditch <327 BHN

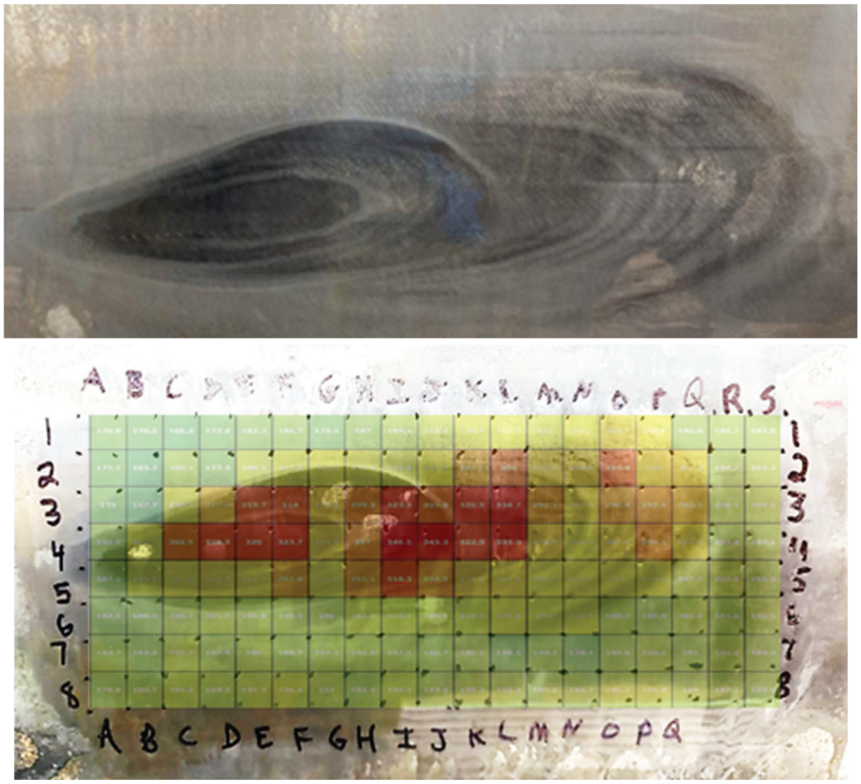

Figure 3. Verified hard spot ≥327 BHN, with hardened areas >300 BHN indicated by red

4. New learnings on hard spot formation

The ILI signal characteristics for different hardness anomalies vary considerably based on the thermal cycle and/or heat treatment applied to the steel to form the hardened microstructure. It is well understood that vast majority of hard spots are caused by an upset in the thermal cycle, when an area of the plate is quenched during rolling.

After the inadvertent quenching action has finished, the affected area is at a lower temperature and a specific microstructural transformation will have occurred, whether that be a transformation to martensite of some other microstructure. The remaining portion of plate (that has not been quenched) will be at a much higher temperature. The effect of the surrounding hot plate raises the temperature of the quenched region. The combination of both the unintentional quenching and potential subsequent heating means that a wide range of thermal cycles are possible, and hence a wide range of resulting microstructures are possible.

ROSEN investigated this issue in detail when developing improvements to the hard spot ILI assessment method [7]. Artificial hardness anomalies were created using a range of thermal cycles, including a simple quenching process and variations of that combined with subsequent heating. Hardness measurements and microstructural investigations were combined with a review of the B-H and μ -H curves to determine the signal characteristics from a specific thermal cycle. An example of the resulting effect on the μ -H curves is shown in Figure 4, and the range of signal responses are shown in Figure 5. It must be noted that the ILI technology referred to in this paper is based on magnetic flux and eddy current principles using a dual field approach, which is described in detail in reference [13].

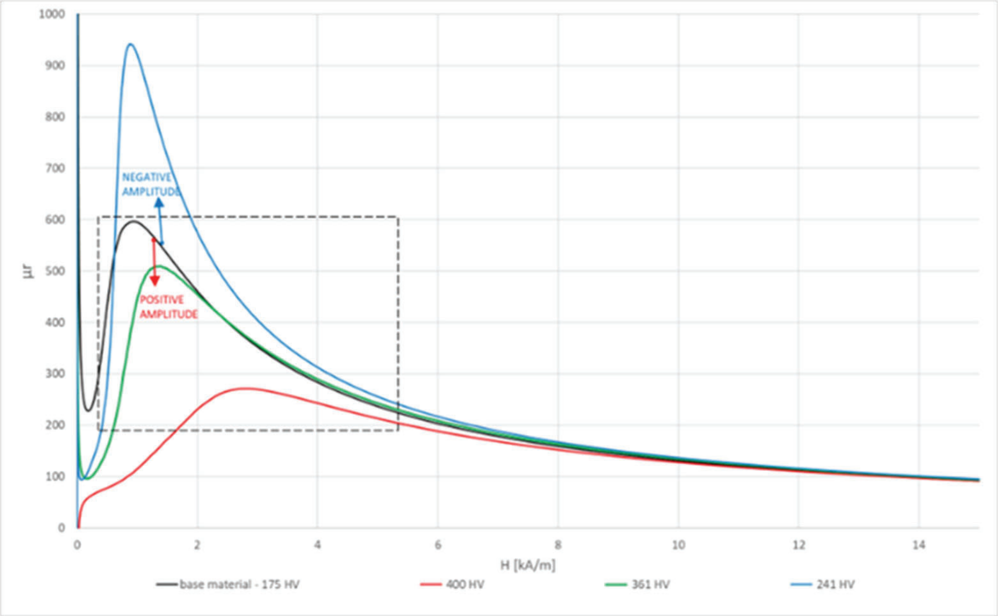

Figure 4: μ-h curves of artificial hardness anomalies with different thermal cycles

In summary, the ILI signal variations observed for hardness anomalies are now understood to be a result of the thermal cycle. We are now able to link ILI signal characteristics to different thermal cycles and now understand the influence of the microstructure on the magnetic characteristics of hardness anomalies. This provides the ability to recreate different types of hardness anomalies which is a step change into the development of ILI approaches to reliably detect, classify, and size hardness anomalies.

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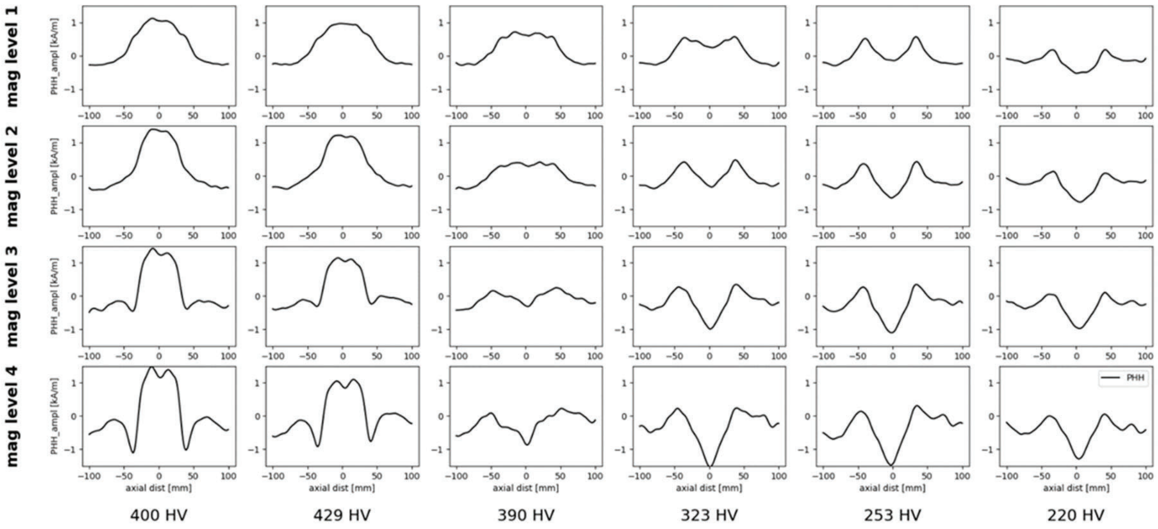

Figure 5: Magnetic signal responses of artificial hardness anomalies with different thermal cycles

5. ILI developments

Up to this point in time the qualification of ILI tools for hardness anomaly detection, identification, and sizing has relied on historical data from validated inline inspections, small number of real pipeline samples and artificial hardness anomalies manufactured in large scale tests. The latter has not represented all the real world types of hardness anomalies that have been validated or that could exist in pipelines around the world.

In addition to this, the challenge has always been around the number of field validation as well as the number of in service samples that existed within the industry to provide a large enough sample base to have statistical confidence in POD, POI, and sizing for all hardness anomaly types.
Another challenge within the industry is that any historic leaks or ruptures due to hard spots typically result in the sample being destroyed either through the rupture and/or destructive testing. This means ILI has typically relied heavily on in ditch validation which comes with its own challenges (refer to section 6) and until recently (since 2020) there has not been a significant amount of work done in this space. This is due to the low number of inspections performed in the past, relatively low emphasis on hard spot validation compared to other anomaly types and the fact that methods and processes were not developed or properly understood.

Given the complexity around hardness anomaly ILI signals and differing approaches (remanent vs dual field) the question has always been - How does an operator qualify (and gain confidence) in an ILI technology in regard to POD, POI, and sizing of hardness anomalies when there is a limited amount of samples and validation that exist compared to other technologies (metal loss, cracks)? As mentioned earlier, the work presented by one operator at IPC 2024 [4] discusses a very through

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approach to qualifying a hard spot vendor. MAT 7-2A study is also assessing the capability of ILI technologies using pull tests containing a statistically significantly number of in-service features from different manufacturers and varying levels of hardness. Recent improvements in POD, POI, and sizing discussed in this paper have been based on a combination of statistically significant validation data and in service samples, whilst leveraging the knowledge of the different thermal cycles.

5.1 Reanalysis or reinspection

Continued improvements in POI have resulted in operators considering a reinspection or reanalysis of prior run data to capture the latest knowledge and experience, if the data is deemed adequate. This is important for operators to increase the confidence that all ILI signals indicative of hard spots have been characterized [2] [3].

POI has been a challenging aspect for hard spot ILI technologies as there are many signals observed within the ILI dataset which exhibit similar characteristics to a hardness anomaly i.e. dents, gouges, etc. [11]. Welding related features (CAD welds, puddle welds and weld repairs) exhibit similar characteristics in the ILI data, and validation has shown these types of features can exhibit highly localized (<0.25”) areas of high hardness up to 400 BHN [12], however, the extent of these have not been found to be through-wall or have the same consistent microstructure as a hard spot created in the plate mill due to the different thermal cycle.

Only through extensive validation experience, and an understanding of how different thermal cycles affect ILI signal characteristics is it now possible to refine search algorithms to not only remove false positives (dents, gouges) and identify welding related hardness anomalies, but to have confidence that all hardness anomalies are characterized accurately.

5.2 Internal vs external discrimination

Hardness anomalies may occur on the OD or the ID, and can be subsurface as shown in Figure 6, embedded, or extend through the wall as shown in Figure 7. This highlights the importance of understanding whether the feature is likely to be found on the external surface prior to going into the ditch to validate, as cut outs are often not a viable option

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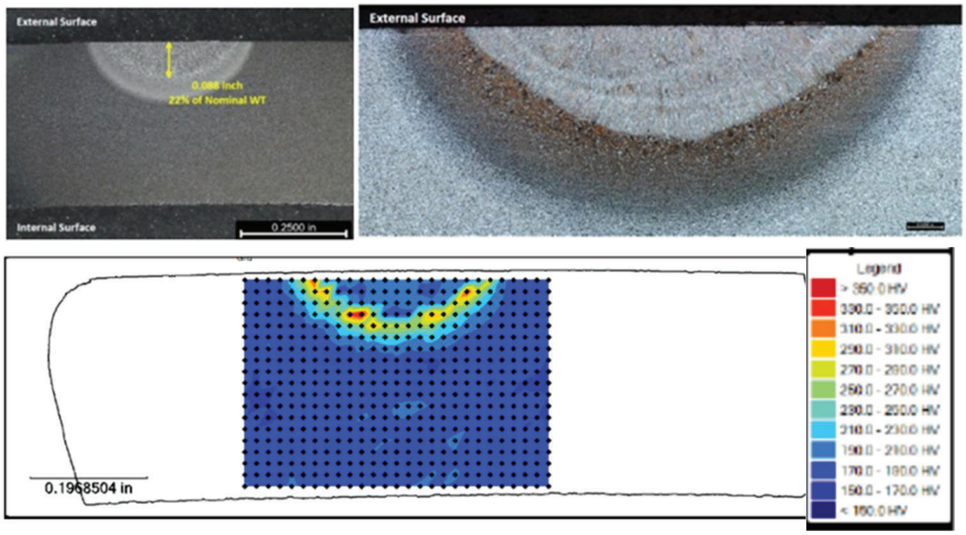

Figure 6: Hardness anomaly (welded repair) with hardness increase on external surface and subsurface

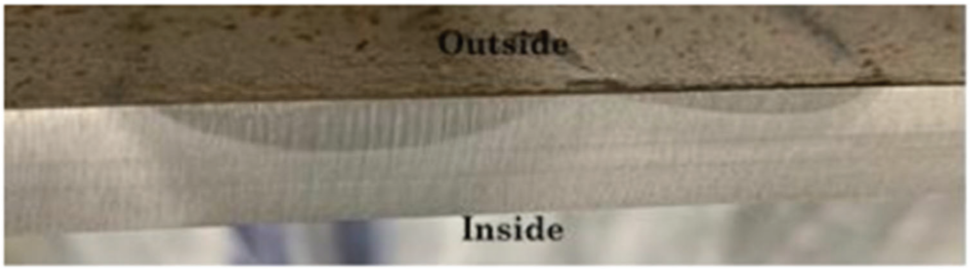

Figure 7: Cross section of hardness anomaly where the hardness increase extends through wall

One of the papers at IPC 2024 [2] highlighted that 37% (56 out of total 152) of validated features had no external hardness increase, stating that an internal hardness increase could not be excluded. Leveraging the use of Eddy Current (EC) technology in combination with a thorough understanding of the type of hardness anomaly (e.g. welded repair will only be apparent on one surface) can help with determining whether the operator can expect a through wall feature or externally orientated feature. This can help significantly reduce the number of unnecessary digs. Figure 8 shows a particular hardness anomaly that has been verified as only been internal. This feature type and its surface orientation (internal) can be identified through the EC ILI signal characteristics and when reported, operators know that this feature type can only be validated by means of a cutout.

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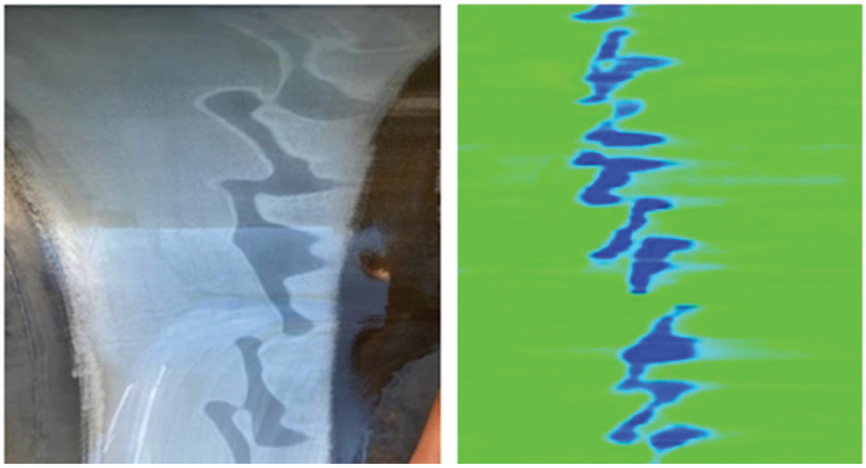

Figure 8: Hardness anomaly on ID (left) and eddy current ILI data (right)

5.3 Qualification of Hardness Sizing

Figure 9 and Table 2 show all field validation data to date, which has allowed improvements in not only POD & POI but in hardness sizing algorithms across different feature types. It is important to note that there is a heavy bias towards two (2) manufactures; AO smith and Bethlehem as these two manufacturers comprise the highest percentage of documented failures (Table 1) and a high field verified hard spot per mileage rate [5].

One observation is that approx. 8% of validated hardness anomalies are registered as a hard spot (≥327 BHN) with ~18% >300 BHN. Reference[6] shows that the majority of failures (rupture or leak) are on hard spots ≥327 BHN, with one failure occurring on 313 BHN. Figure 10 shows the allowable hardness vs probability of failure, based on data from historic failures and certain assumptions (hardness ratio of 0.7). Taking the conservative approach would mean that a hardness of 300 BHN would have < 0.5% probability of failure. From an ILI perspective this means that it is critical that the sizing models have a high level of confidence on features >300 BHN and that there is a large enough sample size that represents that hardness range.

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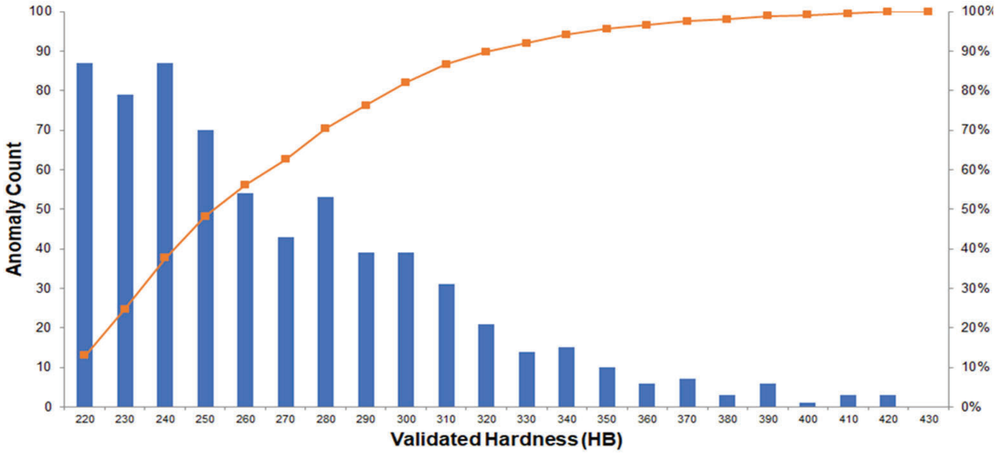
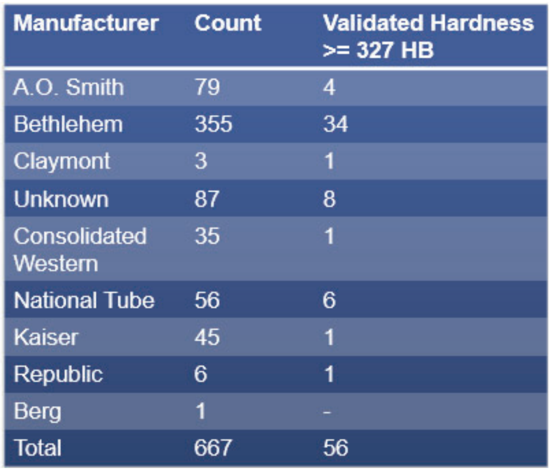


Figure 9 Hardness anomaly validation data including destructive and NDE

Table 2 Number of validated hardness anomalies by manufacturer



Manufacturer	Count	Validated Hardness >= 327 HB
A.O. Smith	79	4
Bethlehem	355	34
Claymont	3	1
Unknown	87	8
Consolidated Western	35	1
National Tube	56	6
Kaiser	45	1
Republic	6	1
Berg	1	-
Total	667	56

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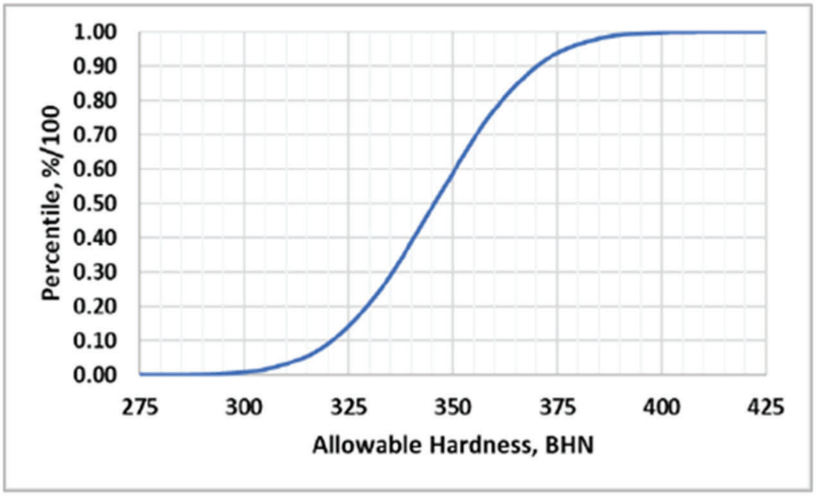

Figure 10 Probabilistic allowable hardness, extract from [6]

Reference [7] showed recent developments in hardness sizing approaches for a certain type of hardness anomaly. As discussed previously, each thermal cycle (Figure 5) will produce distinct signal characteristics in the ILI data, which will allow for both the detection and identification of the hardness anomalies and the corresponding thermal cycle. Once a particular thermal cycle is identified the relevant sizing approach can be applied. Figure 11 shows a hardness accuracy of +/-50 BHN at a certainty level of 87%. Utilizing the Clopper-Pearson method with a 95% lower confidence limit yields a lower limit of 84%.

One important point to note is the number of data points used to develop and qualify the sizing model (>350 data points), as well as the spread of hardness ranges (180 BHN – 425 BHN). It is important to note that not all data points from FIGURE 9 were used to develop the sizing model shown in Figure 11 as this is based on a particular thermal cycle. The sizing model is also not restricted to only one steel/pipe manufacturer as we have used data points from several different manufacturers within the model.

As mentioned earlier the challenge with hard spot ILI technologies has always been the historically limited amount of data points to validate and subsequently improve the detection, identification and hardness sizing performance of ILI tools. With a large sample size of field validation, destructive testing and pull test data, there is now a statistically valid number of data points to develop accurate hardness sizing models.

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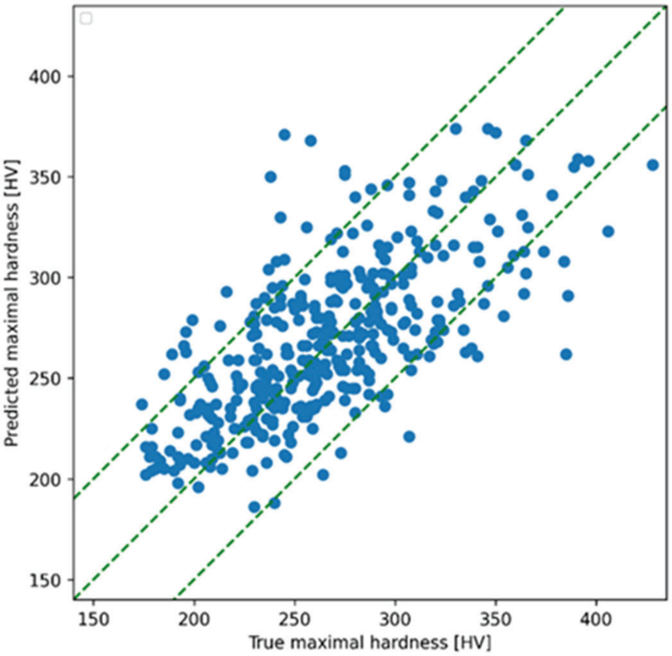

Figure 11 Unity chart for hardness anomalies based on specific thermal cycle

6. NDE vs destructive testing - what is ground truth?

There are various in ditch hardness measurement devices used within the industry (Leeb based, UCI based), each with their own advantages and disadvantages. Reference [13] provides a good description of the process for NDE, as well as the advantages and disadvantages of the hardness measurement devices. Both the Leeb-based and the UCI-based technology are a direct measure of the hardness and rely on an indenter contacting the hardness anomaly. A typical uncertainty for these hand-held measurement devices is +-25 BHN according to [14].

NDE typically serves two purposes:

1. to measure the maximum hardness so that the operator can determine what repair actions are necessary, and
2. to validate the performance of the ILI technology

There are robust processes for measuring hardness on the external surface, so in general the current processes and measurement devices allow us to carry out point 1. However, the following issues arise when we look to validate the performance of an ILI technology using NDE.

- There are limited devices available to identify a hardness anomaly on the internal surface. Eddy current array devices can only detect and locate externally orientated features.

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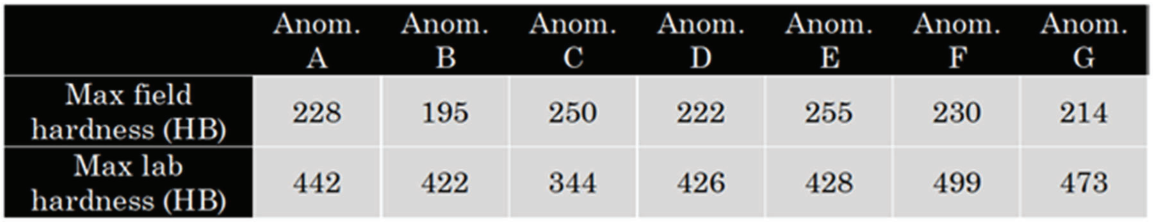
- The NDE hardness measurement device measures only external hardness. The ILI technology is reporting max hardness which could be internal and/or subsurface.
- Most ILI technologies have a tolerance of +-50BHN. If the hardness measurement device has an uncertainty of +-25BHN then we need to consider the tolerance of both devices.
- NDE hardness measurement procedure may not be the same for every operator. An ideal procedure is where measurements are conducted in a 0.5” x 0.5” grid. 5 measurements are taken within the grid. The lowest and highest measurement in each grid is then removed to account for any erroneous measurements. The results in each 0.5” x 0.5” grid are then averaged.
- Human variability factor of NDE technician which can be influenced by the competency and experience of the technician.

Destructive testing results can differ significantly from NDE hardness measurements. Table 3 shows a large difference for welded repairs mainly because majority of the hardness increase is sub surface. [12] also showed a 30” DSAW hard spot that had max NDE measured 367 BHN vs 429 BHN in the lab. This difference can be due to the tolerance of the NDE device as well as the fact that destructive testing measures hardness to a much higher resolution or spacing (0.5mm or 0.02 in) than the resolution taken in the ditch (0.5” x 0.5” grid).

Given all this uncertainty in the NDE methods for measuring hardness how can we accurately establish the true performance of an ILI technology? If we are not able to establish a reliable ground truth for hardness measurements it becomes difficult to make accurate improvements to the ILI hardness sizing performance.

Table 3 Field vs lab measurements for welded repairs extract from [12]



	Anom. A	Anom. B	Anom. C	Anom. D	Anom. E	Anom. F	Anom. G
Max field hardness (HB)	228	195	250	222	255	230	214
Max lab hardness (HB)	442	422	344	426	428	499	473

7. Integrity Management

Although there is no regulatory requirement, evaluation of hardness anomalies reported by ILI necessitates an ability to determine a dig criterion to effectively manage the hard spot threat. To create more efficient hard spot integrity programs, recent industry research with [5], [6], and [9] looked at fitness-for-service (FFS) methodologies to sentence hard spots. At a high-level, the basis for these evaluations is to consider what levels of hardness can lead to hydrogen stress cracking and what length of hard spot can result in a rupture versus a leak. This length has come to be known as the critical crack length (CCL). The hardness values recommended by [9] were at 350 BHN and greater, which considered hard spot failure data published by [6]. The CCL is a variable that is calculated from the fracture toughness arrest properties of the base pipe and this process is outlined in [9].

When evaluating the hardness value and length of hard spots, one clear relationship emerged; as the length of the hard spot increases, so does the hardness. This relationship was highlighted in [5] and this correlation does prove to be insightful for the FFS methodology.

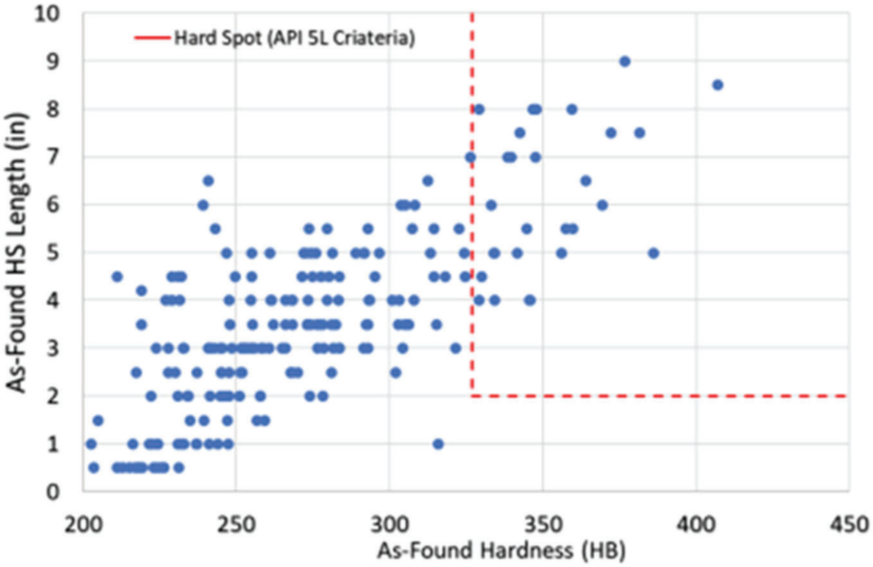


Figure 14 Features inspected with as-found length compared to as-found hardness [5]

7.1 Prioritization of Hardness anomalies and field validation

The prioritization of hardness anomalies presented in this paper was developed with the FFS methodology in mind, consideration of different hardness anomaly types, uncertainty in hardness and length prediction from ILI, and interaction with other anomalies (metal loss and/or cracks). These prioritization steps are listed below. In this evaluation, the hardness anomalies are all one specific type of feature and it is assumed these are through-wall hard spots.

1. Calculate the CCL at MAOP and 1.25 x MAOP of all hardness anomalies reported by ILI
2. Classify as Priority 1 (near term): A hardness anomaly reported at greater than 300 BHN and interacting with metal loss or crack
3. Classify as Priority 1 (near term): A hardness anomaly reported at greater than 327 BHN and greater than CCL at MAOP
4. Classify as Priority 2 (long term): A hardness anomaly reported at greater than 277 BHN (hardness sizing tolerance of +-50 BHN is considered) and CCL at 1.25 x MAOP.

A total of 30 joints (total of 220 features) across multiple segments were prioritized using the criteria above whilst leveraging the new hardness sizing model released in 2024. Majority of the joints chosen for validation contained a number of reported features (up to 30 reported anomalies in some joints) with at least one hardness anomaly reported with a hardness of >277 BHN.

Table 4 shows a POD & POI of 99% for true positives for hardness anomalies. A true positive for POD means that an anomaly was verified in the field. This anomaly may not necessarily be a hardness anomaly and could be a dent or a gouge as an example. A true positive for POI is defined as a feature that has a hardness increase of >50 BHN from base pipe and/or has a positive etching. For the majority of the pipe, the base pipe has a hardness of ~170 BHN. Based on this hardness anomalies measured >220 BHN would be considered as a true positive. POD and POI shown in Table 4 were the same as there were no features misclassified.

A total of twenty (20) features (across seven joints) are considered possible internal features as no external hardness increase was found and destructive testing was not carried out to identify any internal hardness increase. On majority of these joints however, hardness anomalies were found on the external surface which suggests that there could be internally orientated hardness anomalies with a low hardness.

Table 4 Summary of POD and POI for validated hardness anomalies

	True Positive	False Positive	True Negative	False Negative	Possibly Internal
Detection (POD)	198	2	0	0	20
Identification (POI)	198	2	0	0	20

As shown in Table 5 and 6, thirteen (13) features across six (6) joints were verified as ≥327 BHN (Figure 2) with three (3) features interacting with cracks. An example is shown in Figure 13. A further thirteen (13) joints reported ILI values that were in general agreement with the hardness values measured in-ditch.

On nine (9) joints the ILI overcalled the hardness value (outside +-50 BHN tolerance) for some of the features when comparing to the in-ditch results. One particular example had the ILI reporting a max hardness of 337 BHN vs. max 236 BHN measured in ditch. The possibility of internal hardness increases greater than the measured 236BHN cannot be ruled out, as it is well known that hardness increases can exist on both the internal and external surface.

Whilst there are still some question marks in regards to possible internal hardness increases, it is clear that the ILI system has been able to guide the operator in identifying injurious features (≥327 BHN), in a cost efficient manner.

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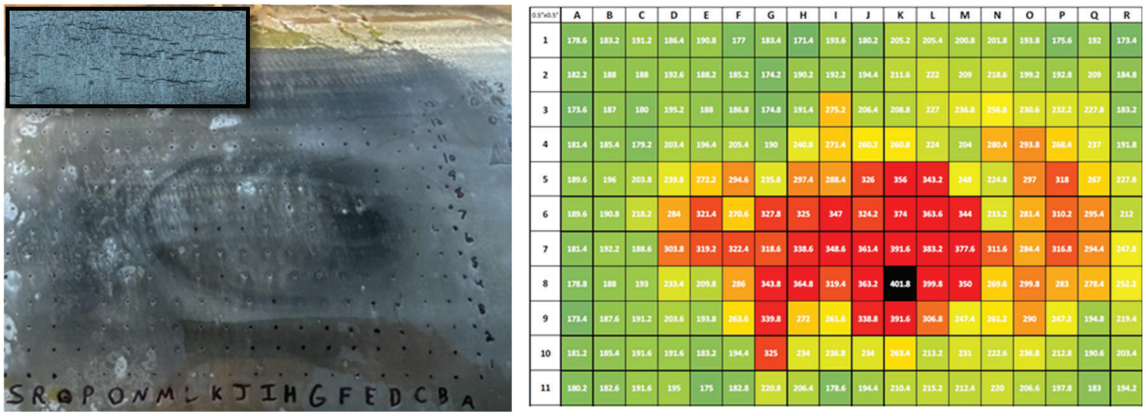
Table 5 Hardness ranges of validated hardness anomalies

	< 277 BHN	≥ 277 BHN < 327 BHN	≥ 327 BHN	Total
Hardness anomalies	55	19	10	84

Table 6 Summary of validated joints in terms of ILI performance

	Hardness as expected (+-50BHN)	Containing features ≥327BHN	Hardness over-called	Possible internal (nothing found on external)	Hardness under-called	Total
Joints / digs	13	6	9	1	1	30



0.5"x0.5"	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R
1	178.6	183.2	191.2	186.4	190.8	177	183.4	171.4	193.6	180.2	205.2	205.4	200.8	201.8	193.8	175.6	192	173.4
2	182.2	188	188	192.6	188.2	185.2	174.2	190.2	192.2	194.4	211.6	222	209	218.6	199.2	192.8	209	184.8
3	173.6	187	180	195.2	188	186.8	174.8	191.4	275.2	206.4	208.8	227	236.8	256.8	230.6	232.2	227.8	183.2
4	181.4	185.4	179.2	203.4	196.4	205.4	190	240.8	271.4	260.2	260.8	224	204	280.4	293.8	268.4	237	191.8
5	189.6	196	203.8	239.8	272.2	294.6	235.8	297.4	288.4	326	356	343.2	248	224.8	297	318	267	227.8
6	189.6	190.8	218.2	284	321.4	270.6	327.8	325	347	324.2	374	363.6	344	233.2	281.4	310.2	295.4	212
7	181.4	192.2	188.6	303.8	319.2	322.4	318.6	338.6	348.6	361.4	391.6	383.2	377.6	311.6	284.4	316.8	294.4	247.8
8	178.8	188	193	233.4	209.8	286	343.8	364.8	319.4	363.2	401.8	399.8	350	269.6	299.8	283	278.4	252.2
9	173.4	187.6	191.2	203.6	193.8	263.6	339.8	272	261.6	338.8	391.6	306.8	247.4	261.2	290	247.2	194.8	219.4
10	181.2	185.4	191.6	191.6	183.2	194.4	325	234	236.8	234	263.4	213.2	231	222.6	236.8	212.8	190.6	203.4
11	180.2	182.6	191.6	195	175	182.8	220.8	206.4	178.6	194.4	210.4	215.2	212.4	220	206.6	197.8	183	194.2

Figure 13: SCC colony (top left) found within a hard spot (left), hardness grid showing areas >300 BHN in red, max hardness 402 BHN in black (right)

7.2 Feedback loop into ILI

All validated features are fed into a validation database where the NDE data is heavily scrutinized to assess the validity of the results and remove any outliers. Next step is to identify any trends in the data that may allow the ILI vendor to identify areas of improvement in the hardness sizing models. Looking at only one singular data point in isolation may not provide the necessary information to make an informed conclusion on areas of improvements, especially when there is also an inherent level of uncertainty within the NDE methods (as discussed in Section 6). As validation data points are added to the database the sizing models are retrained and continually updated. Depending on the number of validation data received and the magnitude of the improvements, new versions of the

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sizing model will be periodically released for future use to continually improve the accuracy of hardness sizing models and reduce unnecessary digs.

7. Conclusions and the way forward

ILI technologies for hard spots have made improvements over the last 5 years, particularly around POI. This comes from an increase in validation and understanding of what ILI signals constitutes hardness anomalies. More in-service hard spot samples and in ditch validation is needed to understand all the types of hardness anomalies that exist in the US pipeline network, however this will come as we expand the number of inspections in the coming years. The ability to artificially recreate all currently known types of hard spots will help to close this gap and fulfil the requirements of large-scale testing in a pull test environment.

There is a continual need for improvements in ILI hardness sizing to reduce unnecessary digs, however we must also understand the limitations of existing NDE technology and answer the question of 'what is considered ground truth' before we can look to make significant improvements in ILI hard spot sizing.

Continue to share information within the industry on not only susceptibility and failures but on experiences and learnings on managing the threat of hard spots. The industry now has a solid understanding of hard spot susceptibility and how to manage the threat, which has come about through industry research and information share. The most important component is industry collaboration between ILI vendors, operators, regulatory and industry bodies and a willingness to understand and improve. This is the reason why the industry is now in a strong position to manage the threat of hard spots.

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