Achieving Successful In-Line Inspection Tool Runs in Nitrogen-Filled Pipelines

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Abstract

This paper presents the lessons learned by the team that planned, designed, and managed a project to run gauge pigs and in-line inspection (ILI) tools through an idled pipeline. The runs covered the multiple piggable segments of a nitrogen-filled 450-mile liquid hydrocarbon product line in preparation for its return to service. Running ILI tools in lines previously in liquid service and subsequently filled with nitrogen presents challenges. This study provides insight into the pipeline system characteristics, including human factors, that must be addressed to achieve successful tool runs in nitrogen.

For this project, the team synthesized requirements from management, technical, and operations stakeholders, and developed an execution plan. During planning, the team built a numerical hydraulic model to calculate the nitrogen flow rates and pressures required to successfully run the pigs. The team worked with local operations personnel and the ILI vendor to develop detailed work procedures. During operations engineers worked on site tracking procedure completion and monitoring operating conditions. Two ILI runs failed to meet acceptance criteria, one due to abnormal ILI tool drive cup wear and one due to inadequate nitrogen control procedures. The team identified the problems and designed solutions. After each operation, the team captured lessons learned and updated subsequent procedures accordingly.

The execution plan provided the company's management with confidence that the project could be completed safely. The numerical hydraulic model allowed the team to optimize nitrogen injection and release locations, plan injection and release operations, and verify that pressures and pig speeds could be kept within acceptable operating ranges. The solutions for the failed runs (a revised ILI tool drive cup design and a new procedure for nitrogen control) prevented recurrence of the problems and resulted in successful reruns. The lessons learned process allowed the team to improve its numerical model and human performance as the project progressed. By monitoring and analyzing the operating conditions in real time, the engineers were able to provide the project manager with the information and recommendations needed to run the operations safely and recognize emerging problems quickly.

Pipeline operators are frequently faced with the need to respond to changing market conditions and must be able to safely inspect idled lines in a timely manner. The results of this study provide operators with insight into the factors that must be addressed to achieve successful tool runs in nitrogen. These results complement the findings of previous case studies (Bonner, et al. 2018).

Introduction

In preparation for the reactivation of an idled pipeline, a liquid pipeline operator conducted an integrity assessment via in-line inspection (ILI). The ILI included gauge pig and high-resolution caliper, mapping, and magnetic flux leakage (MFL) combination tool runs. The major objectives for the project were to complete the runs safely, to successfully identify any pipeline deficiencies that needed to be addressed prior to reactivation, and to complete the work within time and budget constraints. The operator contracted HT Engineering to support the planning and engineering of the in-line inspections and associated nitrogen operations.

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The pipeline section inspected was a 450-mile portion of the idled 500-mile, 8-inch carbon steel pipeline. The original pipeline included 10 piggable segments and was driven by an origin pump station and three mid-line pump stations. Before idling, the pipeline transported xylene, a refined product often used as a solvent. After reactivation, the southernmost pump station would not be needed, nor would the southernmost two piggable segments.

The pipeline comprises 8.625” outside diameter pipe with steel grades ranging from API 5L grade B to API 5L grade X52 and wall thicknesses ranging from 0.188 to 0.500 inches. The pipeline’s Maximum Operating Pressure (MOP) prior to idling was 1,440 psig. The operator’s internal standards limited nitrogen pressure in the pipeline to 500 psig or less. Prior to the start of the inspection efforts, the entire line had been purged of xylene and packed with nitrogen to between 200 and 350 psig.

The project team’s challenge was to achieve successful ILI tool runs in a nitrogen-filled pipeline that was designed for liquid service and with human resources that were accustomed to operating a liquid system. Several issues are frequently encountered in this context:

Tool Speed Control: Liquids are relatively incompressible; gas is very compressible. Liquids provide “strong springs” upstream and downstream of the tool that hold it in place within the product column even when the tool encounters resistance. However, gases like nitrogen are a “weaker spring” that may not immediately provide enough pressure to move the tool through constrictions. If the tool slows or stops, gas will build up behind it, increasing the upstream pressure, while gas continues to flow out of the line downstream of the tool, decreasing the downstream pressure. When the differential pressure builds to the point that it overcomes the resistance and the ILI tool moves past the constriction, it can surge forward against the weak “spring” in front of it at too high a speed to gather data of acceptable quality until the differential pressure rebalances.

Stored Energy: The disparity between liquid and gas compressibility can also manifest in the consequences of a pipeline failure. In a pipeline failure in liquid service, the energy stored in the pressurized product is released relatively quickly. But a release of the same volume of gas at the same pressure lasts much longer, and the destructive force of the release has much more time to affect the pipe and the surrounding environment. This results in a greater direct safety hazard to workers and the public for a gas release than for a liquid release.

Cup Wear: ILI tool cup abrasion may be greater in gas. In a liquid line the cargo usually provides some lubrication value, so the tool slides past restrictions. Liquid also provides lubrication against grit in the line that can otherwise abrade the tool’s drive cups. Nitrogen and historical pipe scale can result in significant degradation of the tool cups.

Polymer Degradation: Some polymers used as sealing elements or other soft goods in valves and other pipeline equipment are dependent on constituents of the product to maintain their properties. These materials can “dry out” and become brittle when immersed in nitrogen or other gases. Additionally, in this case, Xylene is a solvent that causes additional degradation of soft goods.

While the challenges of running ILI tools in nitrogen or another inert gas are substantial, the alternatives, like running tools in water or liquid product, can be cost-prohibitive or make operations prohibitively complex. As the most economical inert gas available, nitrogen is often the only feasible option for ILI tool runs in idled assets. It is worth noting that while air is sometimes considered and even used for pig runs, it can introduce corrosive, flammable, and/or explosive atmospheres into the

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pipeline, especially those that have historically transported hazardous materials. Even with a purged system, there is a small amount of material left as a film on the pipe wall and trapped in drains, valves, and other dead legs. Combined with air, these residual hydrocarbons can potentially produce an explosive atmosphere within the pipeline.

The solutions developed by the project team to the problems posed by using nitrogen for this project included:

- Development of a detailed execution plan that accounted for human performance
- Preparation and tuning of a numerical hydraulic model
- Evaluation of ILI tool drive cup design
- Development of a procedure for nitrogen control
- Monitoring and analyzing the operating conditions in real time
- Providing the project manager with the information and recommendations needed to run the operations safely and recognize emerging problems quickly
- Capturing lessons learned and updating subsequent plans accordingly

The methods used for this project, coupled with the lessons learned from the results, should prove useful to others attempting ILIs in nitrogen and, to a limited extent, other gases. As a case study, this project yields insight into the pipeline system characteristics, including human factors, that must be addressed to achieve successful ILI tool runs in nitrogen for pipeline reactivation.

Methods

Prior to the ILIs tool runs, the consulting engineer worked closely with the company's project team to understand requirements from management, technical, environmental, and operations stakeholders and prepare an execution plan that provided the company's management with confidence that the project could be completed safely. The key decisions and outputs of the planning phase were:

- Selection of a run medium
- Consideration of a duration reduction option
- Hydraulic modeling and run sequencing
- Plan for nitrogen control
- Plan for monitoring and analyzing operating conditions
- Plan for project management and communications
- Work procedures, including contingency plans

Selection of Run Medium

The first step in the planning process was the selection of a method to propel the ILI tools through the pipeline. Three options were considered: compressed air, water or water slugs, and compressed nitrogen. Each medium carried distinct advantages and drawbacks, prompting a comprehensive evaluation to determine the most suitable choice.

Compressed air's cost-effectiveness is a compelling advantage. However, oxygen's reactivity combined with the presence of residual hydrocarbons results in the risk of flammable or explosive atmospheres and oxygen's reactivity combined with the presence of some common particulates presents the risk of an exothermic chemical reaction within the pipeline. At least one explosion has occurred while compressed air was being used to pig a hydrocarbon pipeline. On April 10, 1989, a Dow Chemical

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Company NGL pipeline in Amber Township, Michigan was being cleaned with a pig propelled by compressed air. Iron sulfide residue inside the pipeline reacted with the oxygen in the air, resulting in a temperature high enough to ignite the combustible mixture of air and residual hydrocarbons in the line and causing an explosion that ruptured the pipe in 20 places over the course of a mile (Dow still hunting for cause of blast 1989) (Residue blamed for explosion in Dow pipeline 1989). The presence of oxygen and moisture in air presents the risk of corrosion of the carbon steel pipeline material (Cai, et al. 2020).

Utilizing water or water slugs in combination with nitrogen offered benefits such as lower stored energy, increased lubrication, reduced cup wear, and improved speed control. Nevertheless, the volume of water required for all-water runs was not economical, and the complexity of the slugging process, involving launching and receiving at least two displacement pigs plus an ILI tool and water between each would make the runs logistically risky. Furthermore, the internal corrosion risk to the pipeline from residual water added another layer of consideration, especially with the possibility of the pipeline remaining idle for an extended period after the inspections.

Compressed nitrogen stood out for being inert, circumventing the risk of fires or explosions and corrosion, and for its history of safe use for displacements and pig runs on this and other pipelines.

In evaluating these options, the team considered critical constraints: safety, time, and cost. Given the pipeline's length and the number of expected tool runs, any added time for each run operation would have significantly impacted the overall project duration and resulted in potential ILI tool battery failure. Cost considerations were pertinent, as the company was responsible for all expenses incurred. However, the paramount factor in the decision-making process was safety – prioritizing the integrity of the pipeline and the well-being of the public and the environment that could be impacted by any potential failure.

After a thorough analysis, the team decided on the use of compressed nitrogen. This decision allowed the team to safely meet the constraints imposed for time and cost. The safety and/or schedule risks associated with the compressed air and water slug methods were deemed too high to accept, leading to the selection of compressed nitrogen as the most suitable method for propelling the ILI tools through the pipeline.

Consideration of a Duration Reduction Option

In the subsequent phase of the planning process, the focus shifted to determining the most effective method completing the gauge pig and ILI tool runs of all eight segments. The team initially considered a plan to run multiple pigs simultaneously that was driven by a desire to minimize nitrogen costs and project duration. In questions was whether to run pigs in multiple segments simultaneously or to run each segment one at a time. With sixteen runs initially planned, this decision would have a crucial impact on the project duration and cost.

For the first method, running pigs in multiple segments simultaneously, the potential cost savings were a notable advantage, as injecting nitrogen once for all the gauge pigs and once for all the ILI tools would be economically efficient. However, this approach would require labor support and heighten the consequences of any operational issue. If one pig got stuck, it could potentially stall all the other pigs running at the same time. Other variations of this concept, such as running pigs in two or three segments simultaneously were also considered.

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The second method under consideration was to run each gauge pig and ILI tool independently. This approach aimed to streamline resource requirements and minimize risk by eliminating the complexity associated with running multiple pigs simultaneously and reducing the labor and equipment requirements. Additionally, this method eliminated the risk of multiple pigs getting stuck during the same operation. However, the trade-off was an increased project duration.

In evaluating these options, the team weighed the significant factors of risk, time, cost. The decisive factors that emerged during the comparison of the two methods were the multiplied consequences of a stuck pig in the simultaneous run option and the availability of qualified operational personnel. As a result, the decision was made to run each tool independently, prioritizing reduced complexity and mitigated consequences, despite the longer duration and higher cost. This strategic decision underscored the team's commitment to ensuring the overall success and safety of the inspection project.

Hydraulic Modeling

During the planning process, HT Engineering built a numerical hydraulic model to calculate the nitrogen flow rates and pressures required to successfully run the gauge pigs and ILI tools. Multiple iterations of planning, modeling, and validating were completed to satisfy the operator and ILI vendor stakeholders. The model allowed the team to optimize nitrogen injection and release locations, plan injection and release operations, and verify that pressures and pig speeds could be kept within acceptable ranges for the inspection of each segment.

While some pipeline segments contained large elevation differentials and frequent elevation changes, analysis revealed that they would not significantly impact the nitrogen density or the tool speed. See Figure 1 for the elevation profiles of pipeline segments one through eight.

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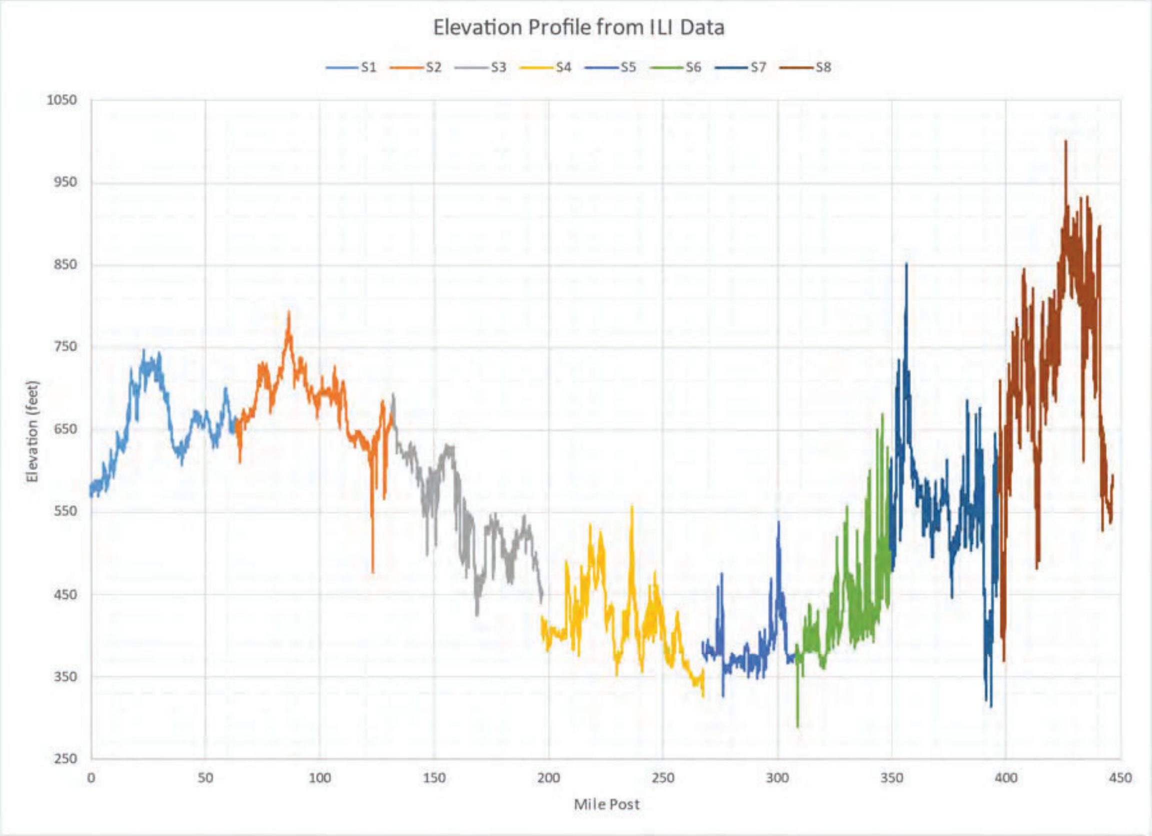

Figure 1. Elevation Profile

The piping configuration at the three mid-line pump stations provided an easy opportunity to install bypass piping at these locations and combine segments 2 and 3, 4 and 5, and 7 and 8. The hydraulic model allowed the team to evaluate whether the ILIs in these longer combined segments would be feasible for the proposed tools. While the longer runs did add some risk with respect to battery life and data quality, the increased operational and safety efficiencies gained by reducing 16 runs down to 10 resulted in the team making the decision to install the bypasses.

The hydraulic model was also used to evaluate various run sequences to see if nitrogen volumes and costs could be reduced. Though alternatives such as releasing nitrogen at a single location and moving the pumper truck to the start of each segment, and running the segments in reverse sequence were evaluated, none were found that offered better efficiency than simply running the segments in order from upstream to downstream. See

Table 1 for a summary of the hydraulic model outputs for the ILI runs. Outputs for the gauge pig runs were similar.

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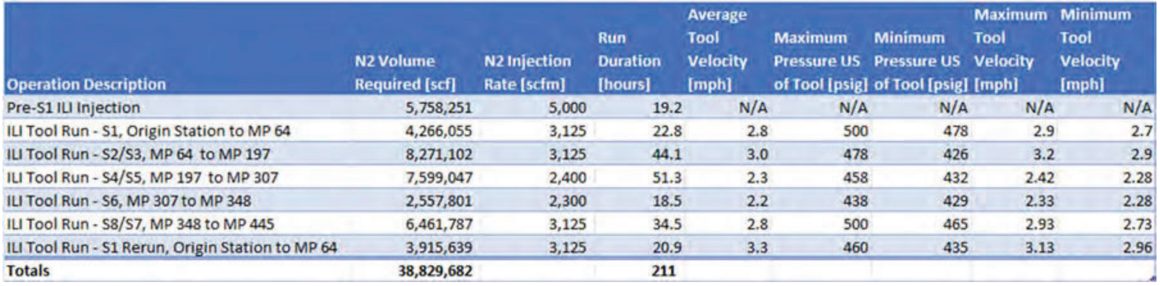
Table 1. Hydraulic Model Outputs



Operation Description	N2 Volume Required [scf]	N2 Injection Rate [scfm]	Run Duration [hours]	Average Tool Velocity [mph]	Maximum Pressure US of Tool [psig]	Minimum Pressure US of Tool [psig]	Maximum Tool Velocity [mph]	Minimum Tool Velocity [mph]
Pre-S1 ILI Injection	5,758,251	5,000	19.2	N/A	N/A	N/A	N/A	N/A
ILI Tool Run - S1, Origin Station to MP 64	4,266,055	3,125	22.8	2.8	500	478	2.9	2.7
ILI Tool Run - S2/S3, MP 64 to MP 197	8,271,102	3,125	44.1	3.0	478	426	3.2	2.9
ILI Tool Run - S4/S5, MP 197 to MP 307	7,599,047	2,400	51.3	2.3	458	432	2.42	2.28
ILI Tool Run - S6, MP 307 to MP 348	2,557,801	2,300	18.5	2.2	438	429	2.33	2.28
ILI Tool Run - S8/S7, MP 348 to MP 445	6,461,787	3,125	34.5	2.8	500	465	2.93	2.73
ILI Tool Run - S1 Rerun, Origin Station to MP 64	3,915,639	3,125	20.9	3.3	460	435	3.13	2.96
Totals	**38,829,682**		**211**					

Nitrogen Pressure and Flow Control

Controlling tool speed in relatively incompressible liquids is much different than in a compressible gas. In liquid, an increase in tool travel resistance caused by pipe wall thickness changes, bends, or other factors results in an almost immediate pressure differential increase across the tool, which overcomes the resistance and keeps the tool speed close to the average liquid velocity. In gas, the pressure differential takes time to build up when the tool encounters an obstruction, and after it builds up enough to push the tool through, it takes time for the pressure differential and tool speed to return to a steady state. The gas acts more like a spring than a hammer.

Low pressures mean the spring is weak, and high pressures result in strong springs. For this project, the nitrogen pressure in the pipeline was limited to 500 psig, which is relatively low when compared to the operating pressure of most gas transmission pipelines. Long distances between pressure sources and control points also mean weak springs, and shorter distances result in stronger springs. At the speed of sound, changes in pressure at one end of the 450-mile line in this project took about 33 minutes to travel to the opposite end, and significant pressure changes involving nitrogen volume transfer took even longer. The velocity of the nitrogen also increased from the upstream end of the line to the downstream end as it lost pressure to friction and expanded. These factors had to be considered while planning for nitrogen injection and release.

Because tool speed responsiveness to the nitrogen flow is affected by the distance of the tool to the injection and control or release points, injection and release points should be located at or close to the ends of the segment in which the ILI tool is being run. However, each injection and release location comes with a cost, which must be balanced with tool speed responsiveness.

For this project, an existing nitrogen production plant was located near the origin station, and the cost of operating injection points downstream of the origin rose sharply with distance. Even though less nitrogen overall could have been injected if the injection location for each run was at the launch location, it was most cost effective to inject more nitrogen at the origin at a lower delivery fee. The

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origin was selected as the injection location for the inspections of segments 1, 2/3, 4/5, and 6. While this placed the injection point close to the ILI tool for the upstream-most segments, it was hundreds of miles away for the segments farther downstream, which meant that the pressure upstream of the tool would be slow to respond. To expedite nitrogen release permitting, segments 7/8 were run in reverse, with the nitrogen injection point located at the pig trap at MP 446. This placed the injection point close to the ILI tool for these segments. A contingency plan for injection at MP 267 was put in place in case nitrogen injection further downstream was necessary or preferred.

For nitrogen release points, the cost was influenced more heavily by the number of release locations than their proximity to any fixed location. Each release location required a frac tank and the associated hard piping and valves shown in Figure 1. Nitrogen release points were installed at MP 197 (the end of segment 3 and beginning of segment 4) and MP 348 (the end of segment 6 and beginning of segment 7) to ensure an adequate level of ILI tool speed control and to distribute nitrogen release geographically.

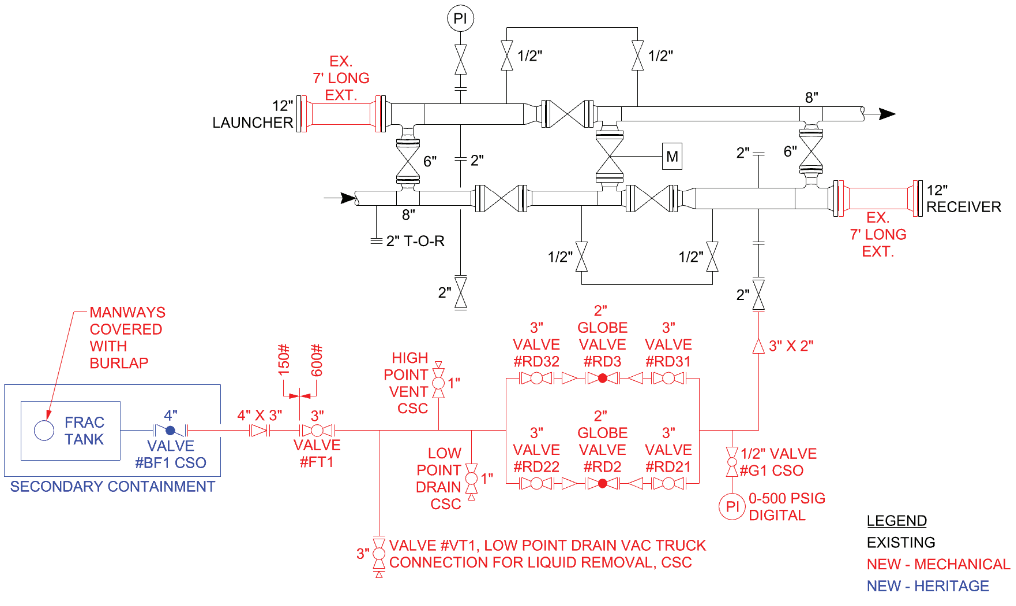

Figure 2. Typical Nitrogen Release Location Schematic

The combination of injection and release points selected by the project team resulted in a maximum span between control locations of less than 200 miles.

Two measurements can be used to control nitrogen flow in pipeline: flow rate and pressure. At both the injection and release locations, pressure measurement and control were more accurate and cost-effective than flow rate. While temporary gas flow rate meters could have been utilized, they would depend on the availability of power, and pressure gauges were a simpler solution.

With pressure control selected for this project, two basic approaches were available for controlling the differential pressure across an ILI tool. The first was to have the release location operator manually maintain a fixed downstream pressure using a throttling valve while injecting nitrogen at a constant rate and allowing the upstream pressure to vary. The second was to have the nitrogen

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injection operator manually maintain a fixed upstream pressure by varying the injection rate while holding the release rate constant and allowing the downstream pressure to vary. Initially, the team selected the second option to prioritize the maximization of the pressure behind the tool.

The project team developed the following logic to direct field personnel to control the pipeline.

- To start, inject nitrogen at MP 0 and release it at the nearest downstream release point to maintain planned pressures.
- If tool speed is higher than planned,
    - reduce the nitrogen release rate until tool speeds are acceptable, then adjust the nitrogen release rate to maintain the current pressure.
- If tool speed is lower than planned,
    - increase the nitrogen release rate until tool speeds are acceptable, then adjust the nitrogen release rate to maintain the current pressure.
- If nitrogen pressure at MP 0 is higher than allowed (500 psig),
    - reduce the nitrogen injection rate at MP 0 until pressure is acceptable, then adjust the nitrogen injection rate to maintain the current pressure.
    - Increase the nitrogen release rate until the differential pressure across the tool is acceptable, then adjust the nitrogen release rate to maintain the current pressure.
- If nitrogen pressure at MP 0 is less than planned,
    - increase the nitrogen injection rate at MP 0 until pressure is acceptable, then adjust the nitrogen injection rate to maintain the current pressure.
- If a tool tracking crew does not detect tool passage within 10 minutes of the ETA,
    - verify that another crew is in place at the next planned tracking location downstream.
- If a tool tracking crew does not detect tool passage within 15 minutes of the ETA,
    - have the crew leave the location and leapfrog the downstream crew(s) to the next planned tracking location downstream.
- If ILI tool run duration may exceed battery life,
    - attempt to increase the tool speed by increasing the nitrogen injection and release rates and decreasing the release pressure as necessary.
- If the nitrogen supply is delayed,
    - decrease the nitrogen injection and release rates and increase the release pressure (but maintain acceptable tool speed) to allow current nitrogen supply to last until the next transport arrives.
- If tool speed is unacceptably erratic:
    - If approved, utilize maximum nitrogen pressure variance to increase the nitrogen pressure across all segments to provide a “stiffer spring”:
        - Shut down nitrogen release.
        - Inject nitrogen at MP 0.00 and isolate segments as needed to increase the pressure in each segment to the pressure determined by the engineer based on the variance and the expected pressure profile.
    - If run segment is downstream of MP 267,
        - isolate S4 from S5, and
        - relocate nitrogen injection and ILI control center to MP 267.

Monitoring and Analyzing Operating Conditions

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While the team conducted the ILI operations, HT Engineering worked on site, supporting the company's project manager in an "ILI control center" by tracking procedure completion and monitoring operating conditions using a spreadsheet tool built for the project. During all nitrogen injection and gauge pig or ILI tool run activities, the ILI Control Center collected and recorded information per Table 2. The ILI Control Center engineer used the tracking spreadsheet for the active operation to calculate or estimate tool speed and estimated passage time for the next tracking location, and to compare actual speed and pipeline pressures with planned values. By monitoring and analyzing the nitrogen injection and release rates, line pressures, and pig location and speed, the engineer was able to provide the project manager with the information and recommendations needed to manage the operations safely and recognize emerging problems quickly. The entire project team effectively used a push-to-talk phone app named "Zello" to keep up to date on the status of the operations.

Table 2. Communications Requirements

Party Responsible for Initiating Comm.	Parties to be Contacted	Comm. Method(s)	Required Information	Frequency or Trigger
ILI Control Center	Nitrogen Injection Truck Operator	Text or in person	Nitrogen injection rate (SCFM), Volume of nitrogen injected (SCF), Nitrogen injection temperature (deg F)	Every 30 minutes and/or as the pig/tool passes each tracking location
ILI Control Center	Calumet Launcher Pressure Gauge	In person	Nitrogen injection pressure in the pipeline (psig)	Every 30 minutes and/or as the pig/tool passes each tracking location
ILI Control Center	OCC	Phone or Zello app	Pressure at intermediate locations and nitrogen discharge location (psig)	Every 30 minutes and/or as the pig/tool passes each tracking location
ILI Control Center	Operator at Nitrogen Release Location	Text or Phone or Zello app	Control pressure upstream of globe valve	Every 30 minutes and/or as the pig/tool passes each tracking location
Pig Tracking Crews	ILI Control Center	Text and Zello app	Pig passage times at predetermined tracking locations	ASAP after each passage
Nitrogen Injection Truck Operator, ILI Control Center, or OCC	ILI Control Center, PM	Zello app or Phone Call and Text	Location of exceedance, maximum pressure experienced, and current pressure	Pipeline pressure exceeding 500 psig
Nitrogen Injection Truck Operator	ILI Control Center	Text or in person	Time of change, rate before change, rate after change, reason for change	Change in nitrogen injection rate
Nitrogen Injection Truck Operator	ILI Control Center, PM	Text or in person	Time of failure, cause of failure, and, when known, plan to get running again	Nitrogen injection truck failure

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Table 2 cont'd

Party Responsible for Initiating Comm.	**Parties to be Contacted**	**Comm. Method(s)**	**Required Information**	**Frequency or Trigger**
Nitrogen Injection Truck Operator	ILI Control Center	Text or in person	When supply will run out at current injection rate, when next truck should arrive, whether vendor can get back on track or delay will domino	Nitrogen supply delay
ILI Control	PM	Zello app or Phone Call and Text	Current pig speed, what has been attempted so far to rectify it	Pig speed between 4 and 6 mph for over 1 hour
ILI Control Center	PM, Engineers	Zello app or Phone Call and Text	Current pig speed, what has been attempted so far to rectify it	Pig speed over 7 mph for over 1 hour
ILI Control Center	PM, Engineers	Zello app or Phone Call and Text	Current pig speed, what has been attempted so far to rectify it	Pig speed under 2 mph for over 1 hour
Operator at Nitrogen Release Location	ILI Control Center	Text or Phone or Zello app	Time of change, position before change, position after change, reason for change	Change in throttling valve position
Operator at Nitrogen Release Location	ILI Control Center	Text and Phone or Zello app	Whether pressure is increasing or decreasing, rate of change	Uncontrollable change in pressure
Operator at Nitrogen Release Location	ILI Control Center	Text and Phone or Zello app	Time of appearance, approximate volume, whether more is coming in	Presence of liquid in frac tank
OCC	ILI Control Center	Text and Phone or Zello app	Time(s) and location(s) of surge(s)	Pressure surge or significant fluctuation
OCC	ILI Control Center	Email	Pressure data recorded from transmitters during the run	After completion of each run
All team members	ILI Control Center	Phone or Zello app and Text	Description of condition	Contingency or other abnormal condition

Work Procedures

In addition to the execution plan, HT Engineering worked with the local operations personnel and the ILI vendor to develop detailed work procedures and facility schematics that guided the team step by step through each of the gauge pig and ILI tool runs.

During a prior nitrogen displacement operation, personnel had defaulted to the standard lock out, tag out procedure for pigging and opened a valve that allowed a significant volume of nitrogen to migrate into the liquid product downstream of the trap. To reduce the opportunity for similar human errors on this project, the engineer tracked completion after vocal verification for each procedure step, and all direction to field personnel came from the project manager.

After each operation, the team planned to capture lessons learned and update the subsequent procedures accordingly, allowing the team to improve its performance as the project progressed.

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Results

Summary

Table 3 contains a list of the operations that the team executed during the project, along with a summary of the results. While most operations were uneventful, several unforeseen issues resulted in lessons learned that are elaborated in the following sections.

Table 3. Results of Inspection Project Operations

Operation	**Results**
Install Temporary Piping	Success
Prefill/Prelease Nitrogen before Gauge Pig Runs	Had to adjust plans during operation for check valve that had not been considered. Lesson learned: See Check Valves section below.
Run Gauge Pig – Segment 1	Success
Run Gauge Pig – Segments 2/3	Success
Run Gauge Pig – Segments 4/5	Success
Run Gauge Pig – Segment 6	Success
Run Gauge Pig – Segments 7/8	Success
Run ILI Tool – Segment 1 – Attempt 1	Failed run, tool stalled, line blown down and tool cut out. Lesson learned: See Tool Design section below.
Inject Nitrogen before S1 ILI Tool Run	Success
Run ILI Tool – Segment 1 – Attempt 2	Failed run, speed excursions. Lesson learned: speed control.
Run ILI Tool – Segments 2/3	Intended a single run through combined segments, but tool stuck in station piping. Tool removed and relaunched. Lesson learned: See Heavy-Wall Bends section below.
Run ILI Tool – Segments 4/5	Success
Run ILI Tool – Segment 6, then equalize pressure in S1 through S8	Success
Run ILI Tool – Segments 8/7 (Note ILI direction is reverse of normal flow)	Success
Rerun ILI Tool – Segment 1	Success
Remove Temporary Piping	Success

Lessons Learned

Check Valves

During the first project operation, a check valve that had not been accounted for in the plan and procedures prevented the nitrogen from equalizing across the entire pipeline length as intended. The project team was able to determine a workaround and get the nitrogen pressure equalized and the operations team conducted a full review of the pipeline to ensure all valves were accounted for and orientations verified.

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Tool Design

The first ILI tool run on segment one failed due to abnormal ILI tool drive cup wear. Approximately 40 miles into the 64-mile segment, the tool stalled. The team used stop work authority and halted the operation, located the tool, excavated the site, verified the tool location with X-ray, blew the line down, and cut out and replaced the pipe containing the tool. See Figure 3 for the run data showing where the tool velocity slowed significantly due to cup wear. See Figure 5, Figure 6, and Figure 7 for X-rays showing the cup wear.

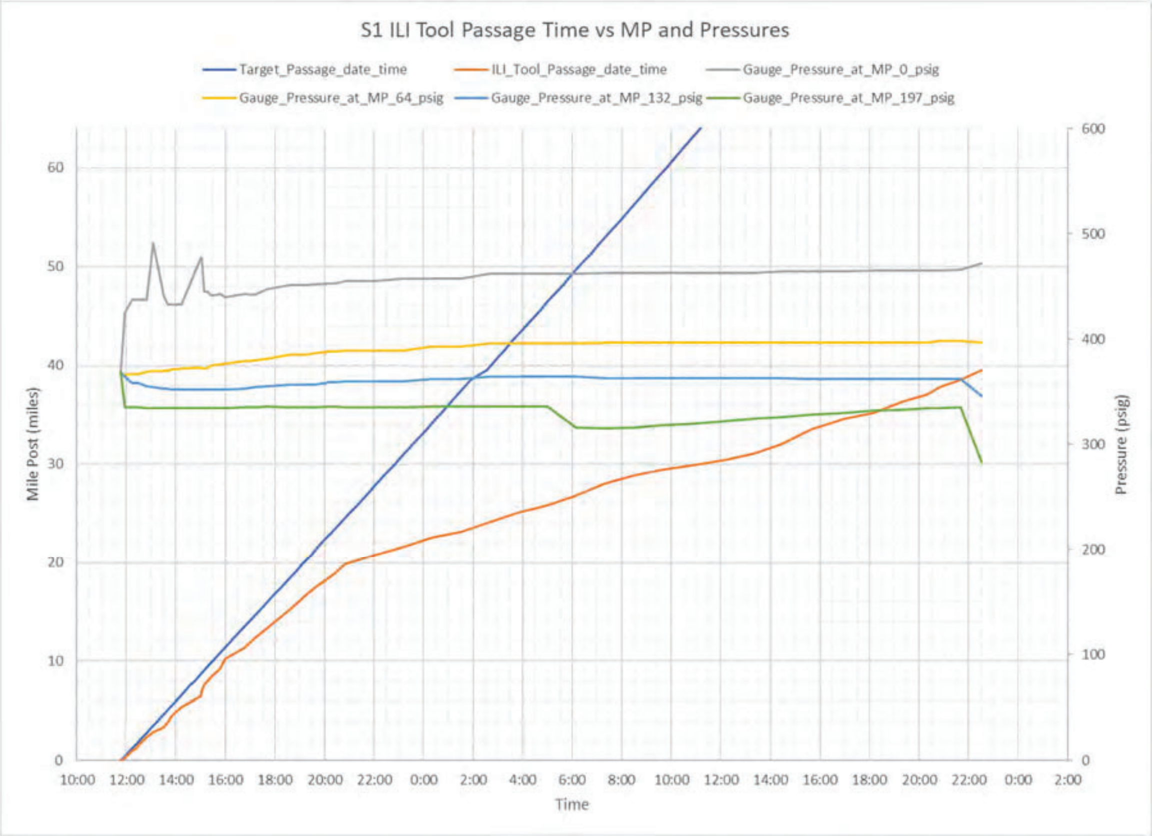

Figure 3. Tool location and pressure data from the first failed ILI tool run on segment 1

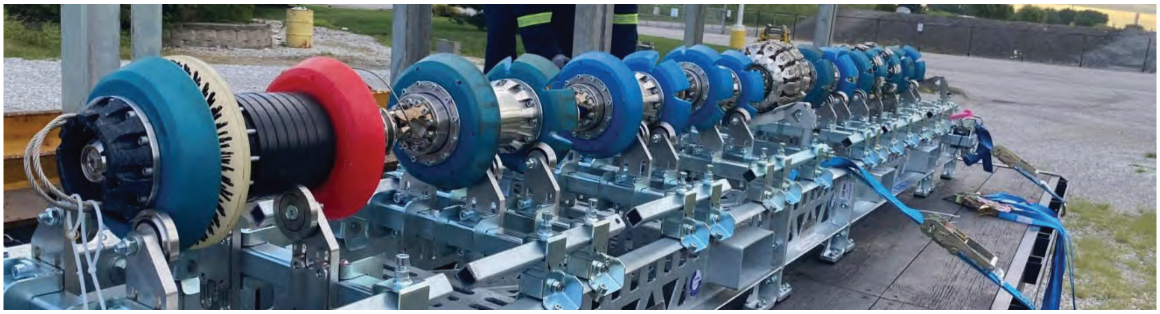

Figure 4. ILI tool configuration that resulted in failed run

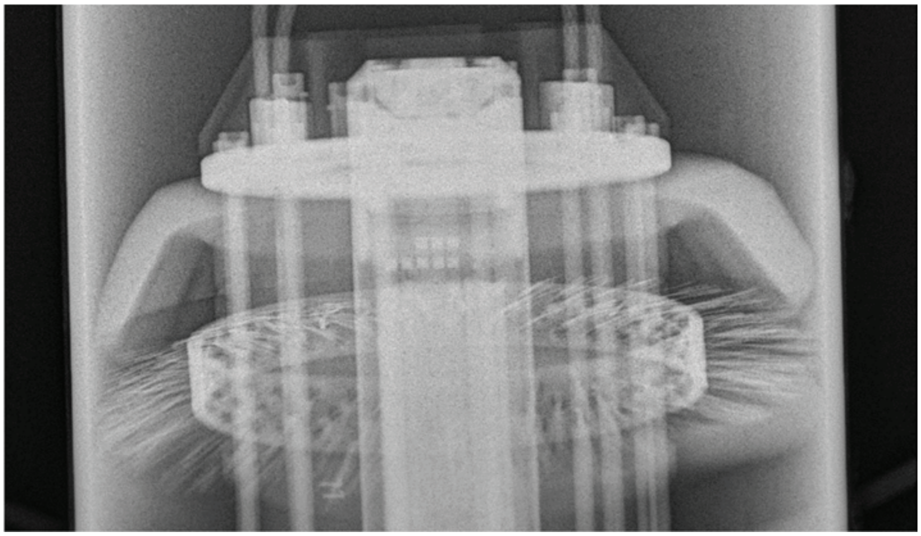

Figure 5. Stiff front drive cup showing abnormally hight and uneven wear

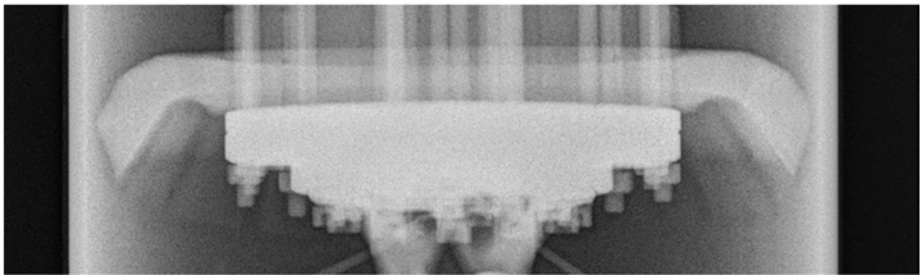

Figure 6. Flexible second drive cup showing abnormally high wear

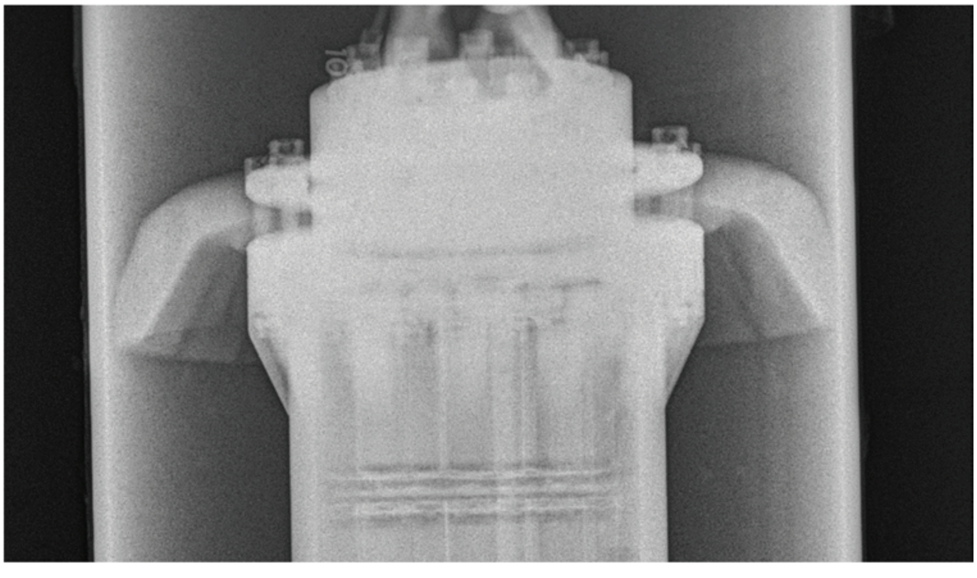

Figure 7: Stiff rear cup showing normal wear

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The tool vendor determined that the premature wear of the polyurethane cup material was caused by the dry propellant (nitrogen), the lack of tool rotation, the unsteady velocity profile, and the use of harder cup material for the front cup. The solution was to use softer material drive cups with sliding metal inserts specially designed for heavy wear environments that protected the polymer from abrasion and allowed it to maintain a seal and to include static bypass holes on the cup located on the front of the pull unit. See Figure 8 for a photo of the revised tool configuration after a successful run.

Figure 8. Cup design with metal inserts

Speed Control

Speed excursions during the rerun of the first segment made another of the early runs unacceptable. The tool would slow or stop in sections of heavy wall pipe until the differential pressure built up enough force to move the tool. When the tool reached the end of the heavy-wall pipe sections, the high differential pressure that had built up and the sudden reduction in resistance as the tool entered the thinner-wall section would cause the tool to accelerate to unacceptably high speeds until the differential pressure would return to normal.

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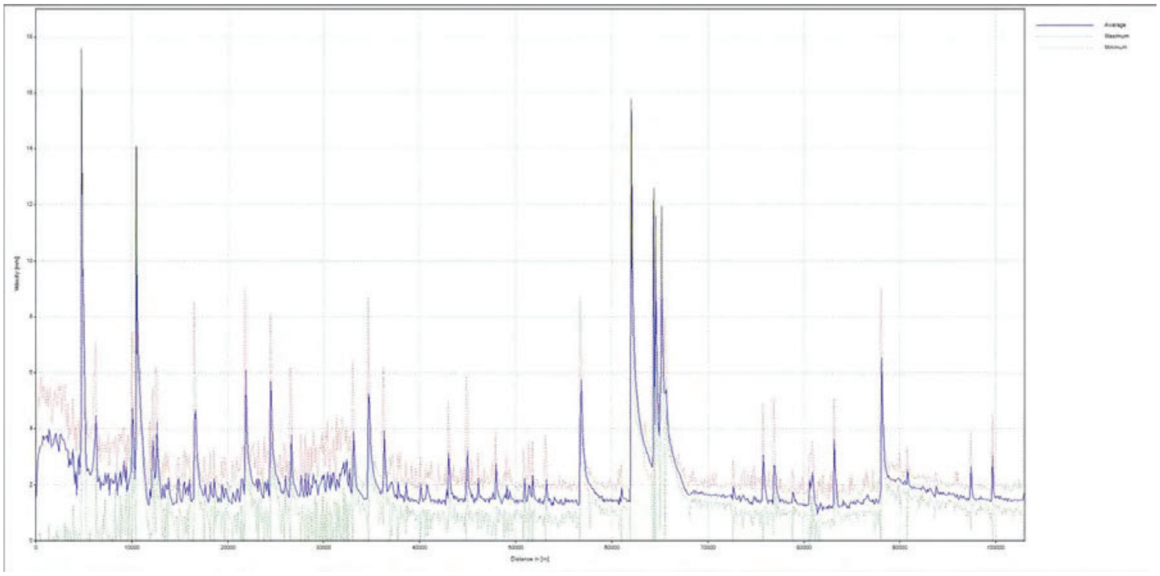

Figure 9. Velocity profile of the failed tool run

The solution in this case was straightforward. The team had been reducing nitrogen injection to maintain a constant pressure on the upstream side of the tool and increasing the release of nitrogen to lower the pressure on the downstream side to achieve the differential pressure needed to get the pig through the heavy wall pipe. This created a "weaker spring" in front of the tool when it entered the thinner-wall pipe that was unable to prevent it from accelerating to unacceptable speeds.

For future runs, the team held the pressure in front of the pigs constant and increased the pressure behind them when necessary, maintaining a "stiffer spring" in front of the pigs that prevented them from exceeding their acceptable speed range.

Heavy-Wall Bends

The pig traps used to receive the ILI tools were preceded by heavy-wall pipe bends. This resulted in one instance of a stuck tool that needed to be retrieved by unbolting and removing the pump station pipe spool that contained it and relaunching it from the same location. The heavy-wall pipe bends also resulted in multiple instances where the tool temporarily stopped just upstream of the receiver and the differential pressure had to be increased to propel it into the trap. On subsequent runs, the team increased the differential pressure, and hence the tool speed, while keeping it within the acceptable range, to get the tool to enter the receiver trap without stopping.

Heavy-Wall Pipe Tool Passage

Fortunately, most of the gauge pig and tool runs were complete without incident. The run in segments 4/5 (MP 197 to 307) was one of these, but it offers an instructive example of the pressure differential buildup necessary to move a traditional cup-driven ILI tool through sections of heavy-wall pipe. See Figure 10. The locations where the tool stopped are visible at MP 200, 210, 240, and 300. Also visible after most restarts are the pressure increases upstream of the tool location and the pressure decreases downstream of the tool location.

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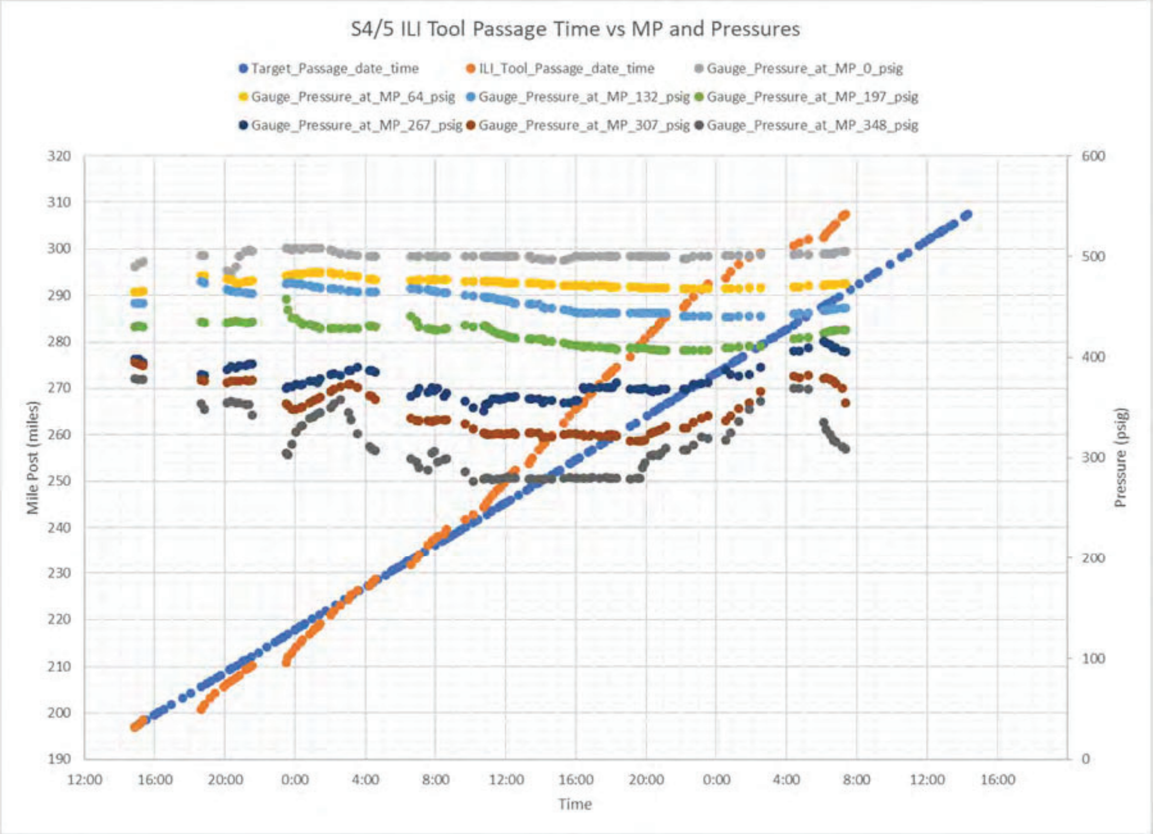

Figure 10. Tool location and pressure data from the ILI tool run on segments 4/5

Discussion

Nitrogen ILIs

This project provides a helpful case study for how to achieve successful ILI tool runs in a nitrogen-filled pipeline. The operator safely ran five gauge pigs and five combination ILI tools in nitrogen in the idled liquid pipeline and obtained the inspection data they needed to prepare it for eventual reactivation. The execution plan provided the company's management with confidence that the project could be completed safely. The numerical hydraulic model allowed the team to optimize nitrogen injection and release locations, plan injection and release operations, and verify that pressures and pig speeds could be kept within acceptable operating ranges. The solutions for the failed runs (a revised ILI tool drive cup design and a new procedure for nitrogen control) prevented recurrence of the problems and resulted in successful subsequent runs. The lessons learned process allowed the team to improve its numerical model and human performance as the project progressed. By monitoring and analyzing the operating conditions in real time, the engineers were able to provide the project manager with the information and recommendations needed to run the operations safely and recognize emerging problems quickly.

The results of this study compare favorably with a previous contribution focused on run behavior simulation for a 24-inch diameter pipeline (Bonner, et al. 2018). This study provides a complementary look at a relatively small-diameter line with greater impacts to tool speed caused by wall thickness variations and a broader focus on the factors that affect run success.

The practical engineering and planning implications of this work for ILIs in nitrogen are as follows:

- Ensure the tool's drive and other cups are designed to accommodate the conditions in the pipeline. This may include the use of steel inserts in the polymer as well as polymers that are compatible with extended exposure to nitrogen.
- If available, use low-resistance tools or tools that have speed control; speed control can automatically allow some gas to bypass the tool and slow it down if needed. This can help avoid unacceptable excursions and reruns if significant variations in wall thickness or other restrictions are present in the pipeline.
- Especially when gas pressures must be less than ideal, maintain adequate pressure downstream of the tool to prevent unacceptable speed excursions.

Pipeline operators are facing a continued and perhaps growing need to respond to changing market conditions and must be able to safely inspect lines filled with nitrogen and other gases previously thought of as novel in a timely and cost-effective manner. The results of this study provide operators with some insight into the factors that must be addressed to achieve successful tool runs in nitrogen, with some applicability to other gases.

Additional case studies covering ILIs in carbon dioxide and hydrogen, like (Barker 2020), would be helpful to the industry. While not derived from the case study covered by this paper, the authors present the following discussion as a contribution to the ongoing conversation.

Influence of Alternate Atmospheres on Piggability

Background

The market push to green energy alternatives will not exclude the utilization of pipelines in transporting critical product mediums such as hydrogen (H_2) and carbon dioxide (CO_2) separately or blended with natural gas (up to 100%) within existing infrastructure. The unique properties of both H_2 and CO_2 (which would ship in super critical phase as a pure product) introduce elevated challenges to in-line inspections as compared to strictly natural gas and/or methane (CH_4) propellant mediums.

Fortunately, ROSEN has already gained valuable experience with inspections of pure CO_2 and H_2 feedstock pipelines. As a result, the primary ILI concerns have already been identified. It may be inferred that blends containing only 10-20% CO_2 or H_2 with CH_4 have a reduced risk factor compare to pure CO_2 or H_2. Even though blended systems present a partial paradigm shift with respect to ILI inspection efforts, previous experiences with refining feedstock pipelines provide adequate risk awareness for developing compatible ILI tool configurations.

Effect on Tool Materials

The initial consideration is related to the interaction between CO_2 and/or H_2 with the elastomer ILI tool components such as cups, discs, cable sheathings, and O-rings. CO_2 and H_2 gas molecules can easily diffuse into elastomer materials, distort their physical shape, and accelerate abrasion, resulting in compromised functionality: cups and discs will lose sealing capability and allow increased propellant bypass, and O-rings may allow product ingress, which can cause electronic component failure.

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To control this risk, specialized elastomer configurations can be relied upon to resist material deformation. The molecular diffusion is not eliminated in all materials, but rather slowed enough to allow a successful inspection. Exposure time and product pressures must be considered. ROSEN has performed internal testing to gauge the effects of prolonged exposure at high pressures to assist in gauging the feasibility of expected inspection durations. In most cases, the material deformation will be limited to the moment inspection tools are exposed to atmospheric conditions when depressurizing the receiver barrel after the run is complete. The decompression results in the expansion or even explosion of trapped gas and can severely distort the elastomer components if the pressure is dropped too quickly.

In addition to material selection, low-friction ILI tool configurations are utilized to mitigate the abrasion of discs and cups. An ILI tool that requires less differential pressure to overcome static and dynamic friction will lessen the opposing forces between cups and discs and the internal pipe surface, thereby reducing wear and prolonging functionality.

Effect on Tool Speed

The more difficult challenge is ILI tool performance. To capture quality inspection data that meets safety and regulatory needs, ILI tool speeds need to remain within a certain velocity range. The velocity limits are typically lower than transmission pipeline flow rates. Considering the anticipated higher flow rates for systems transporting hydrogen blends due to the energy per volume ratio, this concern is further exacerbated. Speed control units that allow propellant bypass are available in many diameters and may allow pipeline operators to maintain flow rates. However, a reduction of product velocity during ILIs will likely often be required to maintain current inspection standards.

In the effort to achieve stable ILI tool run behavior, H_2 presents the largest challenge by far. At equivalent pressures, hydrogen has a vapor density nearly eight times less than that of natural gas. This increased compressibility results in delayed (relative to natural gas) application of increased differential pressure (ΔP) to propel ILI tools. For example, when an ILI tool enters a restriction such as a bend or heavier wall thickness, it requires a high ΔP to maintain momentum. If this high ΔP is slow to accumulate behind the ILI tool, the probability the ILI tool will stop increases exponentially. In this scenario, the momentum is lost and frictional resistance shifts from dynamic to static. The ILI tool then requires an even higher ΔP to overcome the static friction. This type of situation typically results in a velocity excursion as the tool launches from its stationary state. The downstream pressure will have drawn down lower, providing a weaker resistance (back pressure) to slow the tool after it launches. Depending upon the severity of the velocity excursion, data quality may be reduced, or data rendered useless. Tool damage may occur as well.

To mitigate the effects of the increased compressibility of the product medium, especially in H_2, the aforementioned low-friction tool configurations can be implemented. An ILI tool with friction-reducing elements such as wheeled supports and minimized surface contact will require far less ΔP to overcome static and dynamic friction. In effect, this reduces the probability of stationary events and shortens their duration when they do occur. Although velocity excursions may still occur, their severity can be significantly mitigated with a low-friction ILI tool configuration.

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Summary

In summary, ILI technology and innovation is advancing ahead of the introduction of blended CO_2 or H_2 product streams. Challenges remain, particularly in relation to potentially high flow rates and undefined pipeline pressure limitations. It is expected that pipeline owners will need to adjust operational conditions to accommodate ILI activities but will certainly retain the inspection benefit of avoiding service interruption. Assets that are repurposed for clean energy alternatives will need to be inspected before the introduction of different hazardous materials. The lessons learned from the reactivation of the idled asset in this case study can help ensure these inspections and service conversions are completed safely and effectively.

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