Inspect the Unexpected: An Iterative Approach to Developing the Only NPS 4 1.5D Triaxial MFL Combo Tool

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Abstract

The gathering market primarily involves small-diameter pipelines, typically ranging from Nominal Pipe Size (NPS) 3 to NPS 6, with NPS 3 and NPS 4 being the most common sizes. Construction practices for these pipelines emphasize rapid installation to align with the operational timelines of wellheads or production pads, making inspection and maintenance secondary considerations. These pipelines often feature tight bends, heavy wall thicknesses, variable product flows and pressure conditions that are not ideal for In Line Inspection (ILI), especially for smaller diameters like NPS 4.

Historically, inspecting these pipelines required taking them offline and accessing them through bell holes or mid-bend risers, using tethered wireline or crawler systems. However, recent economic shifts have led to higher operating pressures and increased throughput, necessitating a more efficient inspection approach with minimal operational disruption.

This paper highlights the challenges of designing small diameter ILI tools and the iterative design and development process undertaken by Onstream to advance a NPS 4 1.5D TriStream MFL™ technology. This combination Magnetic Flux Leakage (MFL), caliper and inertial mapping tool is designed to inspect gathering lines that were previously deemed uninspectable due to their tight bends and heavy wall thicknesses (HWT). This paper will also present a case study of a recent 1.5D inspection conducted for a pipeline gathering operator. This inspection, which had previously been performed using a tethered wireline tool seven years ago, was recently achieved with a free-swim ILI tool, demonstrating the technological advancements and improved inspection capabilities.

Background

Western Canada, particularly Alberta, is a large oil and gas producer and substantial pipeline gathering market (Alberta Energy Regulator, 2024). Over 80% of pipelines in Alberta are from NPS 2 to NPS 6 (Alberta Energy Regulator, 2024). The map below in Figure 1 shows gathering pipelines in Western Canada (AbaData, 2024).

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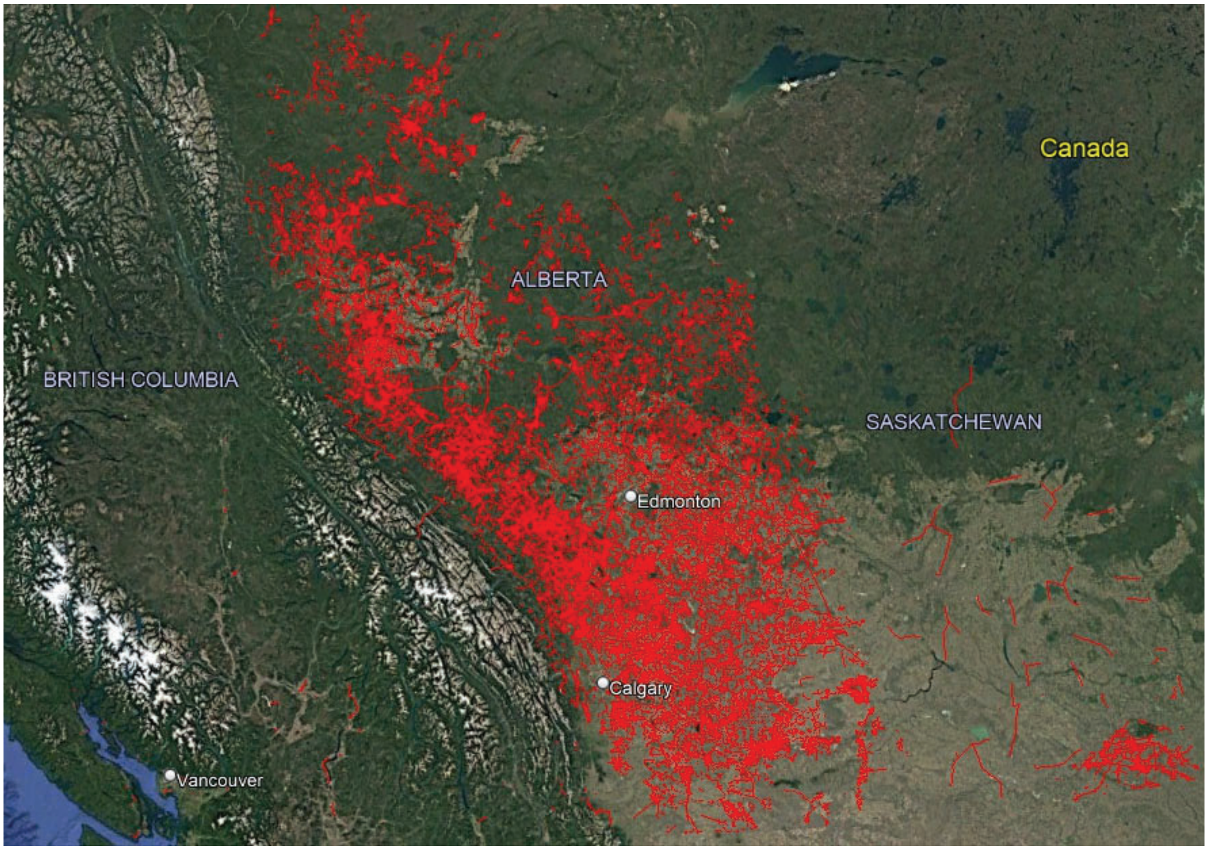


Figure 1. Gathering pipelines in Western Canada

Gathering assets transport liquid and gas products from the wellhead or production pad to a collection station. These gathering systems are typically difficult to inspect assets, where inspection and maintenance are an afterthought during the construction phase of these lines. Many consist of tight bends (Figure 2), short launch and receive barrels for single body cleaning tools, variable product flows, etc, as a result, many of the lines are inspected with wireline tether application (Schartner, et al., 2022). In the cases where conventional free swim is possible, nearly 50% of the lines still have tight radius bends. Many of the operators NPS 4 assets include 1.5 D bends, that are predominately 4.77 mm wall thickness (WT). 20% of the NPS 4 assets have a WT above 6.02 mm (AbaData, 2024). The ability to inspect these lines from end to end, navigating tight bends, handling the winter climates and fully saturating the lines that have WT above 6.02mm (20% of lines), requires a new ILI technology development.

Figure 2. Piping example (Cenovus, 2024)

MFL ILI Tool Technology Review

An MFL ILI tool is a multi-faceted system consisting of magnetics, electronics, high energy density batteries, mechanical systems (materials, computer aided design (CAD) and manufacturing methods) and artificial intelligence (AI). In 1994 Laursen and Atherton published the technical challenges of designing small diameter ILI tools and requirements of technology innovation in order to ease challenges (Laursen & Atherton, 1994), given that it has been 30 years, developing an NPS 4 ILI tool in 2023 should be easier, however, upon a detailed review of the state of all the systems that make up an ILI tool, it becomes apparent that innovation for the majority of these systems have remained unchanged since that time.

For example, magnetic materials, a key component of an MFL tool, utilizes permanent magnets. Nd-Fe-B a now common magnetic material used on MFL ILI tools was introduced in the 1980s and has plateaued with high grade N50+ materials becoming readily available since the 1990s (Ormerod, 2018). Figure 3 shows the trend of magnetic material strength increasing in the mid 1950s and levelling over time.

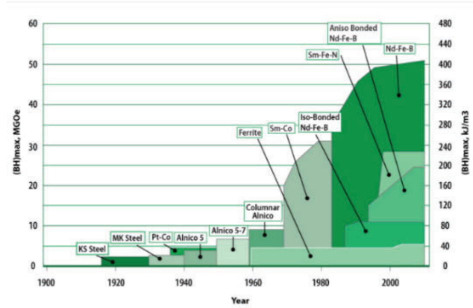
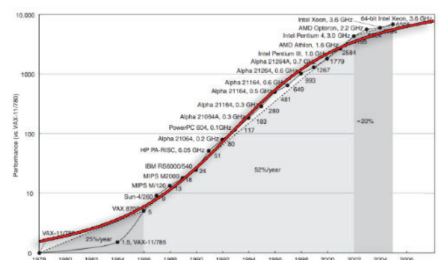


Figure 3. Magnetic material timeline

In the case of electronics and components on printed circuit boards, Moore's Law, the prediction that the number of transistors on an integrated circuit doubles every 2 years was a steady rate of innovation until the 2000's when the rate began to slow (Simonite, 2016). The integrated circuit sizes are reaching the limitation of what is physically possible, Figure 4 shows the plateauing trend of this limitation (Mancusi, 2018).



Batteries, the system used to power the ILI tool remotely, its innovation timeline is like magnetic materials. High energy density batteries became available in the 1980s. From the 1980s to the 2010s the energy density only increased by 10% in this period, see Figure 5 (Chen-Xi & Hong, 2011). Primary lithium batteries are commonly used in ILI tools and in some applications, particularly large diameter ILI tools a case can be made for rechargeable batteries. The recent developments in the electric vehicle sector may spur rechargeable battery innovation, seeing an increase in battery energy density, however, at this time, battery energy densities remain quite similar, where lithium cells or rechargeable battery configurations are being utilized.

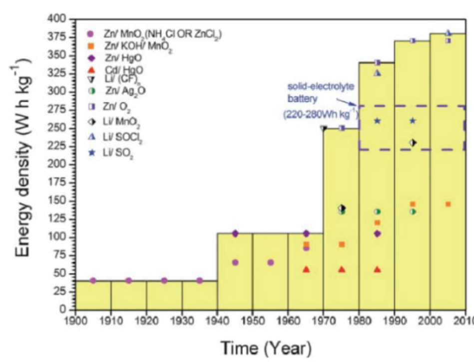


Figure 5. Battery energy density timeline

Mechanical systems such as fasteners have remained unchanged, however, aerospace has driven innovation with super alloy materials, albeit the majority still beginning in the 1950s, see Figure 6 (Akrami, Edalati, Fuji, & Edalati, 2021). Computer aided design (CAD) was a significant innovation in the design and drafting of mechanical systems first introduced in the 1960's for aerospace design, with much of the 3D CAD innovation in the mid to late 1990's (Beck, 2017). The most recent mechanical developments surround Additive

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Manufacturing or 3D printing (AM) both with polymer, metal, ceramic and composite materials. The AM innovation shows no trend of slowing down, refer to Figure 7 (AMFG, 2019), hobby level polymer printers are now readily available, highly accurate and very economical. Additionally, AM metal printers are at the tipping point of access, economics, material availability, etc (Fidan, 2023).

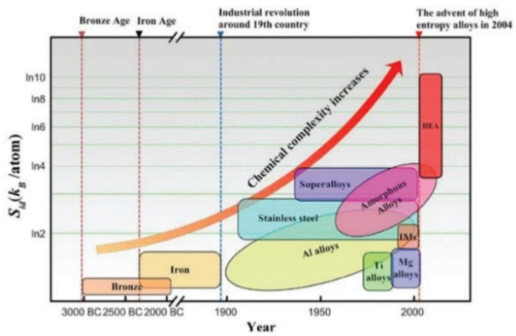

Figure 6. Materials developments

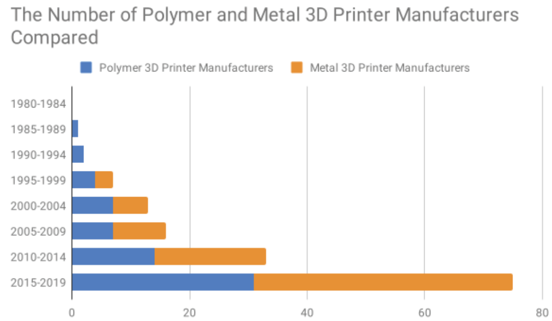

Figure 7. Polymer and metal 3D printing

AM provides the designer the ability to put a physical prototype in their hand the next day. In addition, metal AM material advancements have grown 4-fold, 5 years ago a designer may be able to choose from a handful of materials, with only one or two being truly economical to print with the right design or part geometry. Today, a designer can select from well over four times the materials, magnetic, nonmagnetic, lightweight, hyper strong, etc. with print costs not only challenging traditional subtraction machining methods but becoming economical. Lastly, AM also provides the ability to combine parts or components, reducing part count, saving space and simplifying systems (Sheng Yang, 2018).

The last main system utilized in ILI is AI for the analysis and sizing and specification deliverable. There has been significant innovation with AI in recent years that it is now commonplace, websites like chat gpt provide users with the ability to "write" whole papers like this one with only a few prompts. However, AI is not new in the ILI sector, particularly MFL sizing, where it has been used to predict corrosion depths, lengths and widths from MFL signals since the 1990's (Sutherland & Siebert, 1999). Advances in AI have allowed ILI vendors to push the boundaries of what is possible, now ILI vendors are taking whole images of a MFL defects captured by an ILI tool and reverse processing the image to predict the corrosion profile, rather than basic length, width and depth parameters (Peng, Siggers, Wright, & Palmer, 2024). In the case of developing a small diameter MFL tool, AI does help on the back-end deliverable, providing high confidence sizing specification, however, it does not help with the development from a compliance and design point of view.

Design Challenge and Methodology

Design Challenge

The challenge remains for developing a small diameter NPS 4 MFL, Caliper and IMU tool able to navigate tight bends and saturate most WT's. The primary issue is the volume of space available in an NPS 4 pipe. Due to the size limitation of the NPS 4 pipe diameter and the short length of 1.5D bends, the tool ends up consisting of multiple bodies tied together with articulating u-joint connections. With the industry expectation of requiring multiple data sets in one inspection, MFL, caliper geometry and Inertial Measurement Units (IMU), the tool becomes long.

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The fundamental principles for MFL technology require a certain amount of metal in a return path to saturate a given WT (Jansen, van de Camp, & Geerdink, 1994). The trade-off between tool magnetization and module compliance is significant and, in some scenarios, physically impossible. For example, the required return path to saturate 0.5" WT and have a collapsibility of 75% is physically not possible. Now consider the scenario where the magnetizer must saturate 0.337" WT (schedule (SCH) 80) and collapse 75%, next adding a heavy girth weld of 0.125" tall, this weld would put the internal diameter of the pipe beyond the compliance of the tool. The heat diagram in Figure 8 shows the compliance of the tool against the WT, green indicates possible, and red indicates physically not possible. To be able to transverse 1.5D bends, the tool compliance must be very high, upwards of 75-80%, but WT beyond SCH 80 becomes not possible.

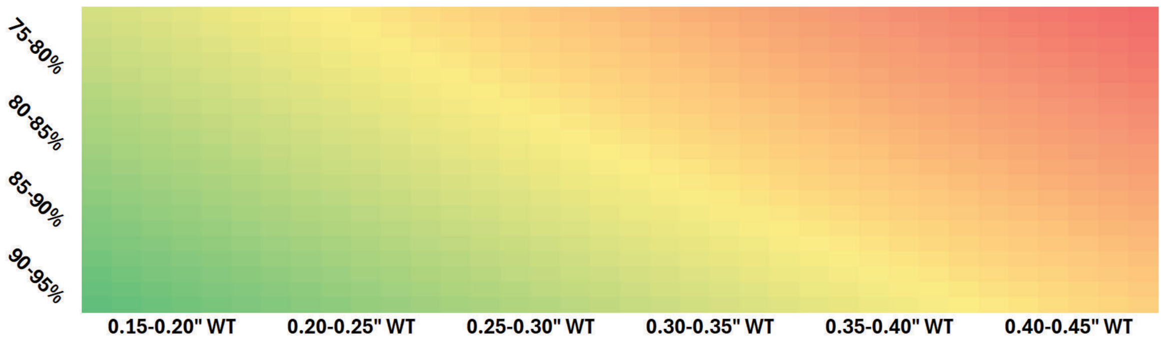

Figure 8. Tool compliance heat map compared to WT

Battery capacity and suitable form factors that work with the small NPS 4 size is a substantial challenge. The common place cells used in larger diameter ILI tools are generally much larger and longer than what would fit in the NPS 4 pipe. Adding in a pressure vessel and wire routing only further exacerbates the issue, where the remaining volume for the battery becomes quite limited. The limited volume results in a small battery, with limited capacity, impacting the run time of the tool. A solution to this issue is to add more battery modules at the expense of increasing the tool length. Another challenge with the small battery volume is the batteries susceptibility to cold weather. Even mildly cold weather, 23°F (-5 °C) can be detrimental to the battery capacity, significantly dropping the voltage or even passivating the cells so they become inoperable.

Design Methodology

There are several different design methodologies can be applied when developing a new product, whether it is software, electronic printed circuit board, or a multifaceted product such as an ILI tool. Two common methodologies that are used include a traditional waterfall approach or concurrent engineering. The well know waterfall process consists of each development step in series. Figure 9 shows the waterfall process where the project begins with requirements, followed by design, implementation, verification and deployment. Concurrent engineering is slightly different from waterfall, it involves a planning phase, establishing requirements and follows an iterative cycle back to the requirements, eventually with a deployment of the product. The common development steps for concurrent engineering are highlighted in Figure 10.

For any design methodology, the project requirements must be established at the beginning – in the case of the NPS 4 1.5D design, this information came from industry research, past run history, client discussion and missed opportunities. The ILI vendor already had a NPS 4 tool, however, the design

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was bend limited to 5D, therefore, the ILI vendor primarily used past run history and missed opportunities to develop requirements.

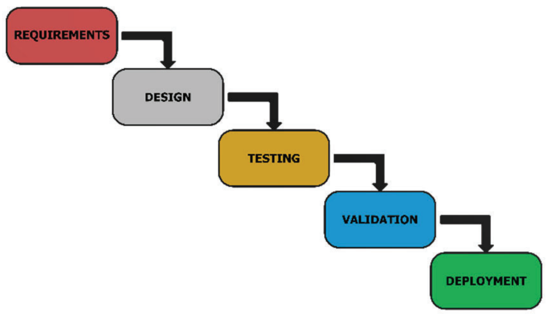

Figure 9. Traditional waterfall

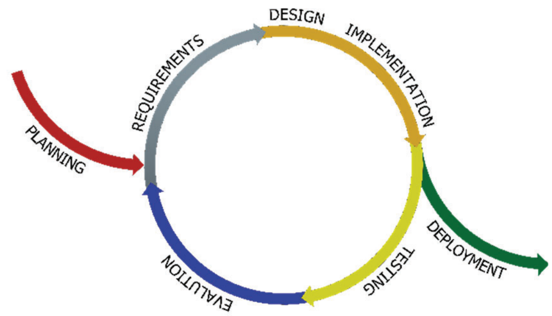

Figure 10. Concurrent engineering

The methodology followed for this project was based on the concurrent engineering model. The three main reasons included:

1. Multiple designers can work simultaneously on individual modules on the tool. For example, a designer specific for each unit, magnetizer, caliper, and recorder system, respectively.
2. The nature of the limited design envelope in such small pipe drives the need to design, prototype and test in real pipe, iteratively, to understand if the requirements can be met. The white space available in a CAD model can be very deceiving when it comes to the reality of fitting around a tight bend, how a designer predicts a suspension system will collapse and how it does in reality can be different.
3. The ability to prototype and test in a flow loop system, that mimics pipeline operating conditions, in-house is not an unreasonable cost with small diameter ILI tools such as NPS 4 as compared to a larger diameter tool such as NPS 24.

A waterfall approach can be used and is common for a large tool diameter development, where design volumes are large and more forgiving for the designer. In large diameter, breaking down a two module ILI to multiple designers can be very difficult, it can be hard to draw a line on where one system ends, and another begins. Additionally, full scale testing of an entire large diameter tool, pumping around bends, full bore tees, etc. can be very costly and time consuming, where CAD layouts with designer experience and expertise can predict with reasonable success of passage around such fittings. However, there will still be an aspect of iterative design and prototyping, but generally this applies to critical subsystems that can be tested at a lower level in a simulated pipeline condition, such as a sensor carrier or suspension system.

Ultimately, with the limited design volume available, there are substantial trade-offs during the design phase between WT saturation, bend compliance, tool robustness, serviceability, reliability, battery packaging and wire routing. Iterating and prototyping are required when space and volumes are so limited, removing 1/16” or 1/32” of material between prototypes. The small adjustments can be the difference between going around bends, fitting wiring reliably or maintaining the tool without needing special hand tools to do so.

The key for success with the concurrent model includes clear requirements, closely working design groups and consistent communication between mechanical, electronic, physics, software and AI departments. The trade off on one parameter can have a cascading impact on other parts of the design.

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Design and Development

The tool design requirements were established using past run history, the ILI vendor utilized data from the previous 3,186 4" inspections to determine common WTs, typical run time and consequently battery requirements, riser construction practices, etc. This data provided the designers target objectives for developing the tool as well as parameters to construct a test loop for flow testing modules.

With design requirements set, the next step involved assessing the current 4" design and any new improvements on NPS 3-6 tools that could be adapted for this new design. The main items that were identified to be maintained included learnings from the recent development of the TriStream MFL™ small diameter sensor head and MFL magnetizer suspension. The assessment also identified that the most challenging or highest risk items to meet the key requirements included the magnetizer module and data recorder system. The magnetizer would need to change drastically in order to fit around tight bends and yet saturate SCH 80 pipe. The design envelope required a new recorder package to fit into the space available. The remaining tool modules such as the drive unit, IMU, caliper, battery and odometer were deemed to be of less risk based on current designs and adapting to smaller available volume.

Requirements were set beginning of 2023 with design teams focused on the magnetizer and recorder systems. Simultaneously a flow loop was constructed in preparation for testing. The flow loop was developed for progression of difficulty, starting with simpler bends and more forgiving WTs (schedule 40, 80, etc.), increasing the flow loop passage difficulty as testing progressed. Figure 11 shows the different test bend configurations.

Figure 11. Test bend configurations

The design process involved several iterations in CAD, followed by AM plastic components. These plastic builds were used to determine wire routing, assembly packaging space, and real collapse compared to CAD. After several iterations at the plastic AM level, parts were prototyped for in-house testing.

While the two modules were in manufacturing, the flow loop was tested against the ILI vendors proven 1.5D NPS 4 Intelligent Gauge Tool (IGT). The purpose of this testing was to determine if the test loop mimics real world conditions. One major challenge with in-house test setups is that it can be unrealistic to real world conditions. IGT flow loop testing indicated the test loop to be on the harsh side, but acceptable with tempered designer pass expectations. For example, one ILI pass through the loop consisted of 20 welds and 6 tight bends, and multiple WT transitions, therefore 10 laps in the loop were considered adequate. Figure 12 shows the flow

Figure 12. Test bay flow loop

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loop test bay and the NPS 4 loop in the center. Initial testing of the magnetizer module proved to be very challenging, with very limited success of passage through the test loop at SCH 40 pipe and bend conditions. Iterations of the module were completed on the fly with 4 iterations occurring in a four-month span, changing u-joint (UJ) configurations, reducing the module length, optimizing the suspension systems, etc. These modifications improved the navigability of the magnetizer module from a couple of bends to several laps, however, damages were still being experienced primarily UJ's and the product flow requirements for complete navigation were quite high, likewise differential pressure requirements across the tool.

At the same time the magnetizer was being developed and tested, concurrently the recorder system was developed. After requirements for the recorder were set, board layouts and spatial requirements were determined, and several iterations were required to fit all the required components, wire routing and connectors, in such a small area. The recorder was then built and tested at a bench level. Upon successful bench testing, the recorder was subjected to pull testing followed by tether wireline ride along field trials. These field trial ride alongs provide real world data collection for comparison to current systems, as well as environmental and vibration testing. Successful tether wire line field trials provided confidence in the recorder system for use in conventional free swim applications.

These two systems were initially tested independently at the start of the project and were brought together for flow loop testing in preparation for the first conventional free swim field trial. The complete TriStream MFL™ tool including these two critical systems were tested at slow pump speeds (0.2 m/s) in various full-bore tees and bends of varying WT for final commissioning testing in preparation for field trial deployment. Figure 13 shows the final test setup. Upon successful navigation of these fittings, the tool was released to be trialed in pipelines behind the ILI vendors current NPS 4 5D tool.


Figure 13. Final flow loop test setup

The development timeline, Figure 14, for the two critical systems, MFL and recorder, as well as the complete ILI tool is included in Figure 15. Overall from inception to commercial release took 1.5 years.

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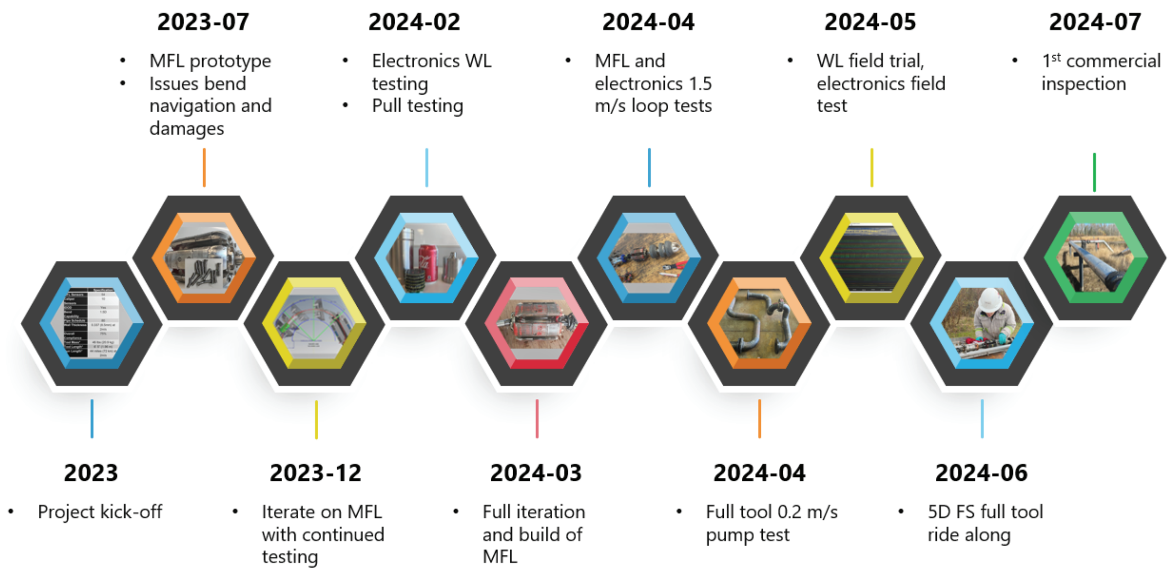

Figure 14. Development timeline

In that span of time, the tool modules were pumped through over 2750 bends, and the magnetizer alone was pumped through over 850 bends. Beyond the flow loop testing, the recorder and full tool was subjected to pull testing, wireline tether field trials and lastly, ride along conventional free swim inspection behind the previous 5D capable NPS 4 tools. These tests and field trials provided the confidence to deploy the technology for commercial release.

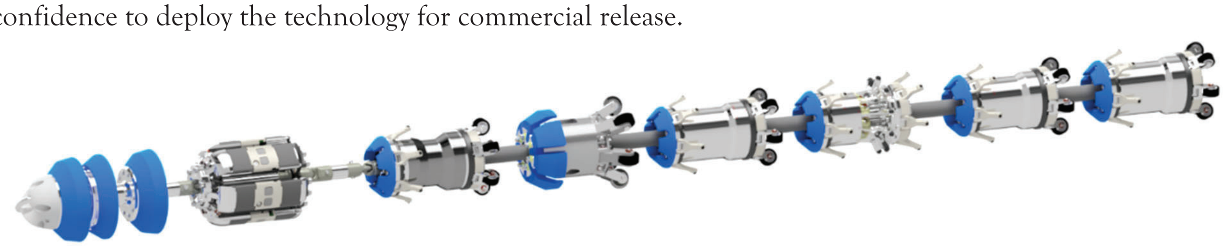

Figure 15. Overview of the complete ILI tool

Case Study

The natural gas gathering line had previously been inspected by the ILI vendor in 2017 via a bi-directional MFL combo tool tether application, where the line was accessed through a riser near the launch. In 2017 tethered application was chosen to inspect this line due to natural gas pipeline product having inadequate flows and the launch and receive risers containing 1.5D 45-degree bends. Figure 16 shows the launch site containing two tight bends before the pipeline swept into the ground. Figure 17 shows one of the two tight bends at launch.

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Figure 16. Overview of the launch site, 2 tight bends and sweep into the ground

Figure 17. 45 degree 1.5D bend at launch

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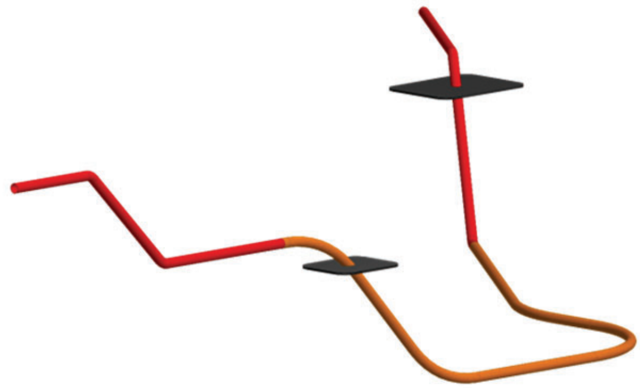

Figure 18. Pipeline layout orange indicating portion tether inspected in 2017 (not to scale)

Much of the line was inspected via access at the sweeping riser location. Figure 18 shows the orange portion inspected via the tethered system (image and pipeline not to scale), only the sections containing the 1.5D bends were not able to be inspected as the technology could not transverse the fittings. The black flat plates in the diagram indicate the ground plane. The reinspection of this pipeline was in 2024. Reviewing the previous project identified that the 1.5D bends and lack of product flows were the main reasons for the WL tether application. The ILI vendor proposed to the operator to inspect the line with the new 4" 1.5D TriStream MFL™ technology. The line still had inadequate flows and there were short cleaning pig barrels at launch and receive. To overcome these two challenges, the operator retrofitted in temporary longer barrels and prepared the system to pump the tool via a water liquid product. The ILI vendor was able to perform a successful ILI, achieving 100% coverage of the entire line with less down time and simplified project planning and preparation as compared to the previous inspection 7 years ago.

Summary

The Western Canadian gathering market consists of a substantial number of pipelines ranging from NPS 3- 6. A large portion of these lines are difficult to ILI due to construction practices and product flows. Developing a small diameter ILI MFL, caliper and IMU tool to inspect these lines is a challenging task. The small volume inside the pipe means there is a significant trade-off between tool compliance for navigating tight bends or fittings versus saturating SCH 80 pipe for the purpose of MFL metal loss inspection. An iterative concurrent design approach was used in developing the latest NPS 4 1.5D capable TriStream MFL™ utilizing the latest in AM methods and materials. Overall, the technology, in particular the MFL and recorder modules experienced several iterations and was subjected to many different in-house and in-situ tests during the development. Ultimately, the technology was deployed successfully inspecting an NPS 4 gathering line with the conventional free swim technology that previously needed to be inspected with a WL tether application. The ability to inspect the line in service saved the operator the complexity of project management and an out of service interval on the pipeline asset.

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