SPE-229377-MS

Next-Gen Coiled Tubing: Automation Meets Expertise

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Abstract

Modern Coiled Tubing (CT) operations remain heavily manual, relying on the tacit knowledge of experienced operators. However, since the 2014 industry downturn, the experience level of CT operators has stagnated or declined, with no comprehensive data available. High workforce turnover, driven by factors such as cyclical business trends, economic downturns, and an aging workforce, limits operators' training opportunities, resulting in repeated mistakes. This paper addresses the urgent need to bridge the experience gap through automation.

An advanced control system has been developed to automate key CT processes and replicate the decision-making capabilities of a seasoned operator. This system enables operators with limited experience to perform at expert levels by automating running in hole (RIH) and pull out of hole (POOH). It also includes pre-programmed pull tests and completion restriction speed control, with automated motor pressure (torque) regulation to reduce the risk of over-pull and over-snubbing incidents. Additionally, the system optimizes tubing speed through automatic control of variable speed and motor displacement while managing injector head traction, tubing tension, and reel tension.

The advanced control system is built as an add-on to the existing proven safety system (Fig. 1). This safety system continuously monitors real-time operational parameters and acts as a fail-safe mechanism. If an operator performs an action that could lead to unsafe conditions, the safety system immediately intervenes by reducing the injector motor pressure to prevent accidents or equipment damage. This ensures that even in manual or semi-automated modes, operational integrity and safety are always maintained. The advanced controls system leverages fuzzy logic and cascade control algorithms to simplify complex manual tasks. It operates the CT unit to a target depth at a defined rate (ft/min) with minimal operator intervention, while continuously monitoring safety parameters. If anomalies are detected, the existing proven safety system overrides automation to ensure operational integrity.

This paper presents the testing methodologies and integration techniques used to connect office-engineering design software with field execution systems. The result is an auto-pilot automation approach that enhances safety, consistency, and efficiency—empowering the next generation of CT operators while bridging the experience gap. By enabling less experienced operators to perform at advanced levels, the system delivers significant client value through improved operational reliability, reduced downtime, and optimized performance.

Introduction

The Oil & Gas industry is undergoing a significant transformation driven by increasing operational complexity, heightened safety expectations, and a growing demand for sustainable practices. CT interventions, essential for well maintenance and production optimization, are facing unprecedented challenges due to deeper, high-pressure wells and the need for flawless execution.

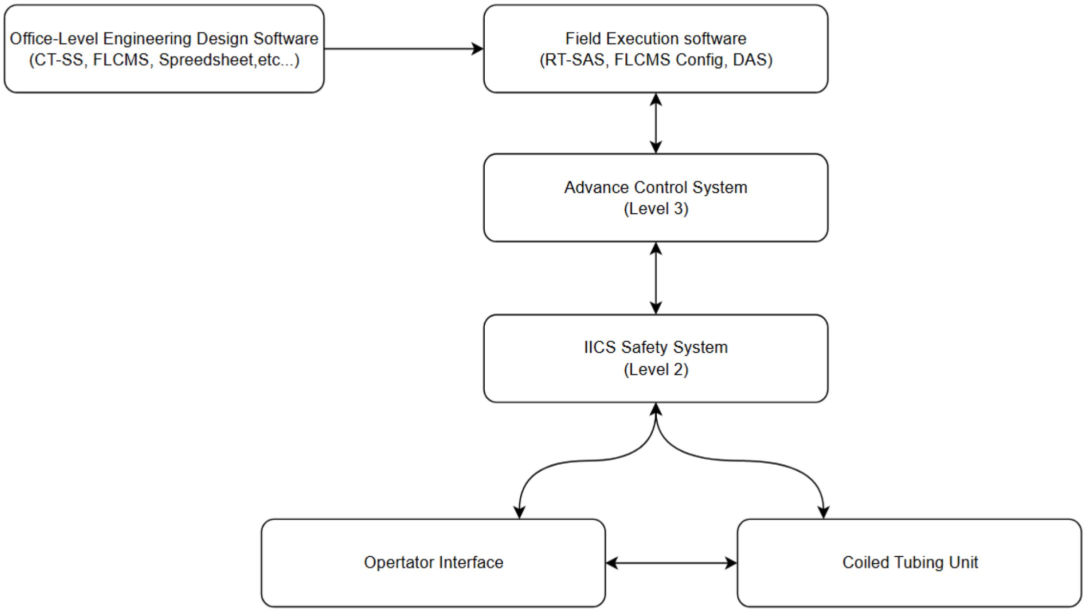

Figure 1—Higher overview of coiled tubing operation.

Simultaneously, the industry is experiencing a generational workforce shift, resulting in a reduced pool of experienced personnel and difficulty attracting new talent. Customers are also demanding more automated solutions that minimize on-site personnel and reduce environmental impact.

To address these challenges, designed a digital software suite designed to revolutionize CT operations. This solution integrates:

- Pre-job modeling to optimize planning and mitigate risks.
- Real-time operational feedback for dynamic decision-making.
- Active control of surface equipment to enhance safety, efficiency, and execution certainty.

This less human-centric approach not only reduces non-productive time (NPT) and equipment failure risks. By digitizing and automating CT workflows, it enables a more resilient, efficient, and attractive operational model for both current and future talent. This strategic shift positions our organization at the forefront of innovation in well intervention services, delivering superior value to customers while ensuring operational excellence in a rapidly evolving energy landscape.

Foundation of this work builds upon the challenges outlined in (B. Aiken SPE-188685-MS), where the human element in CT operations was identified as a critical factor affecting service delivery and operational safety. That paper highlighted a significant drop in average field supervisor experience—from 8.5 years to just 3.5 years—during the North American shale boom, which coincided with a rise in human-error-related high-impact failures (HIFs). It also emphasized the industry's sluggish adoption of automation, despite the clear need to reduce non-productive time (NPT), improve consistency, and enhance safety.

From the client's perspective, service delivery and Health, Safety, and Environment (HSE) remain the two most critical performance indicators. In manual CT operations, it is well understood that the tacit knowledge of the operator plays a defining role in how a job is executed. Field teams often know which operators to assign to high-risk or critical wells and which ones to hold back. This informal knowledge-sharing system, while effective in the short term, is not scalable or sustainable—especially in a workforce increasingly composed of less experienced personnel.

If the industry continues to rely solely on traditional methods without evolving how operations are executed, then risks repeating the same mistakes. This recognition was the catalyst for initiating this project: to explore how to bridge the gap between a 20-year veteran's expertise with a 3-year operator's capability. The answer lies in automating the task, not the role—capturing expert decision-making logic and embedding it into a system that can assist any operator, regardless of experience.

In response to these challenges, the first controls system introduced was a Level 2 automation solution (S. Craig SPE-218349-MS)—primarily acting as a fail-safe mechanism. That system continuously monitored real-time operational parameters and intervened only when unsafe conditions were detected, such as excessive weight or speed. While this approach provided a critical safety net, it remained passive in nature —reactive rather than proactive—and did not assist in executing job sequences or optimizing performance in real time.

A level 3+ intelligent injector control system that transitions from passive safety monitoring to proactive is an add-on automation. This system is designed to augment operator capability by automating key operational sequences such as:

- RIH at target speed
- POOH at target speed
- Automated weight checks and pull tests
- Maintaining minimum reel tension

Unlike the previous Level 2 system, which only intervened in emergencies, the new system actively manages injector control and hydraulic parameters to execute these tasks with minimal operator input. It uses fuzzy logic and cascade proportional–integral–derivative (PID) control to replicate expert decision-making, ensuring smooth transitions, optimized speeds, and consistent force application throughout the job.

Included here are the detail design, simulation-driven development, and prototype validation of the intelligent injector control system. By bridging the gap between engineering design and field execution, this system represents a significant step forward in CT automation—delivering improved reliability, reduced downtime, and consistent service quality in today's increasingly complex and dynamic oilfield environments.

System Design and Features

Hydraulic design

The hydraulic system of the coiled tubing unit (CTU) is a critical subsystem responsible for the deployment and retrieval of coiled tubing during well intervention operations. The CTU described in this work incorporates a modular hydraulic power pack, which includes high-pressure pumps, return tanks, and directional control valves. This hydraulic circuit is designed to actuate the injector head, enabling precise control over the insertion and extraction of the coiled tubing string into the wellbore (Fig. 2).

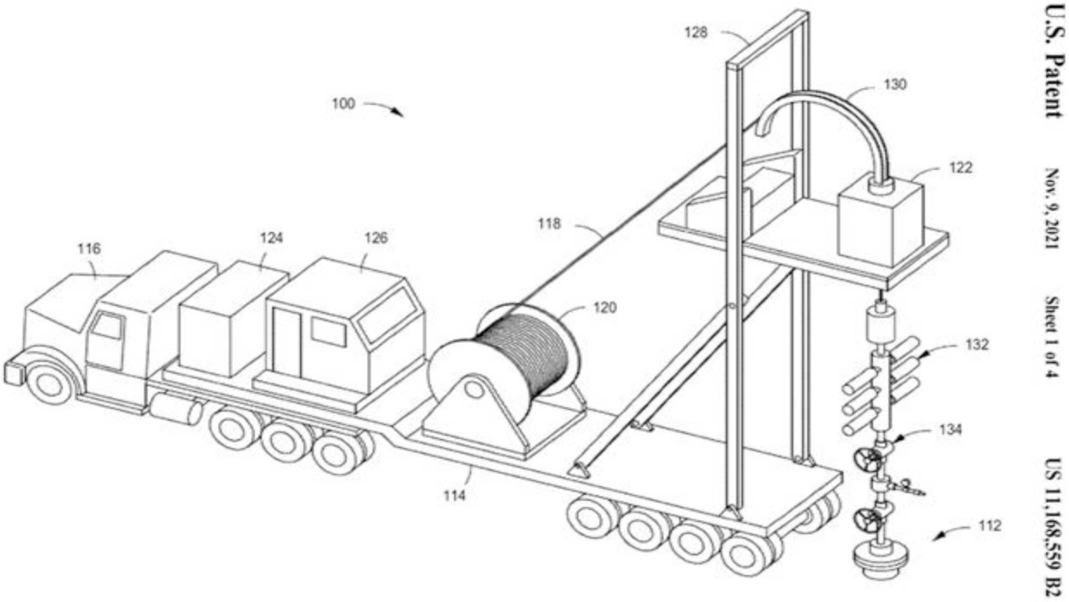

Figure 2—Typical coiled tubing unit picture from patten (US11168559 patent).

The injector head is mounted on a support frame and is hydraulically driven to maintain consistent traction forces on the tubing. The hydraulic system is integrated with a valve control module that includes a low-level valve controller. This controller regulates traction pressures and ensures that the equipment operates within predefined weight-on-bit (WOB) and rate-of-penetration (ROP) limits. These limits are dynamically adjusted based on real-time differential pressure measurements obtained from downhole sensors.

The hydraulic design supports both manual and automated control modes. In automated mode, the system receives control signals from a data integration module, which processes inputs from a coiled tubing simulator and real-time field data. The valve controller interprets these signals to modulate hydraulic pressure and flow rate, thereby adjusting the speed and direction of the injector head. This closed-loop control strategy enhances operational safety by preventing overpull, excessive snubbing forces, and tubing buckling.

To ensure system responsiveness and reliability, the hydraulic components are selected based on flow rate requirements, pressure ratings, and thermal performance under continuous operation. The design also incorporates safety interlocks and pressure relief mechanisms to mitigate the risk of hydraulic failure during high-load conditions. The automated hydraulic system is designed to be fully compatible with a range of hydraulic architectures, including high-pressure closed-loop, high-pressure open-loop, and low-pressure open-loop systems. This compatibility ensures seamless integration with both current and future CTU platforms, providing operational flexibility and scalability without requiring significant redesign or retrofitting.

Electrical Design

The electrical architecture of the CTU is engineered to support precise, real-time control and monitoring during coiled tubing operations. The control of the automated system is incorporated on ATEX Zone 2-rated industrial computer with integrated HMI, suitable for hazardous environments and capable of running multiple applications simultaneously. This computer is connected to multiple programmable logic controllers (PLCs) and communicates using serial, Modbus TCP/IP, and OPC-UA protocols. The HMI provides operators with intuitive access to system status, control functions, and diagnostics.

The control system is distributed across multiple PLCs, which interface directly with field I/O devices such as encoders, load cells, proportional valve control (PVC) units, and pressure transducers (Fig. 3). These PLCs execute low-level control logic and enforce safety interlocks and sensor alarms based on real-time data and calculated operational limits, ensuring safe and reliable operation throughout the tubing deployment process.

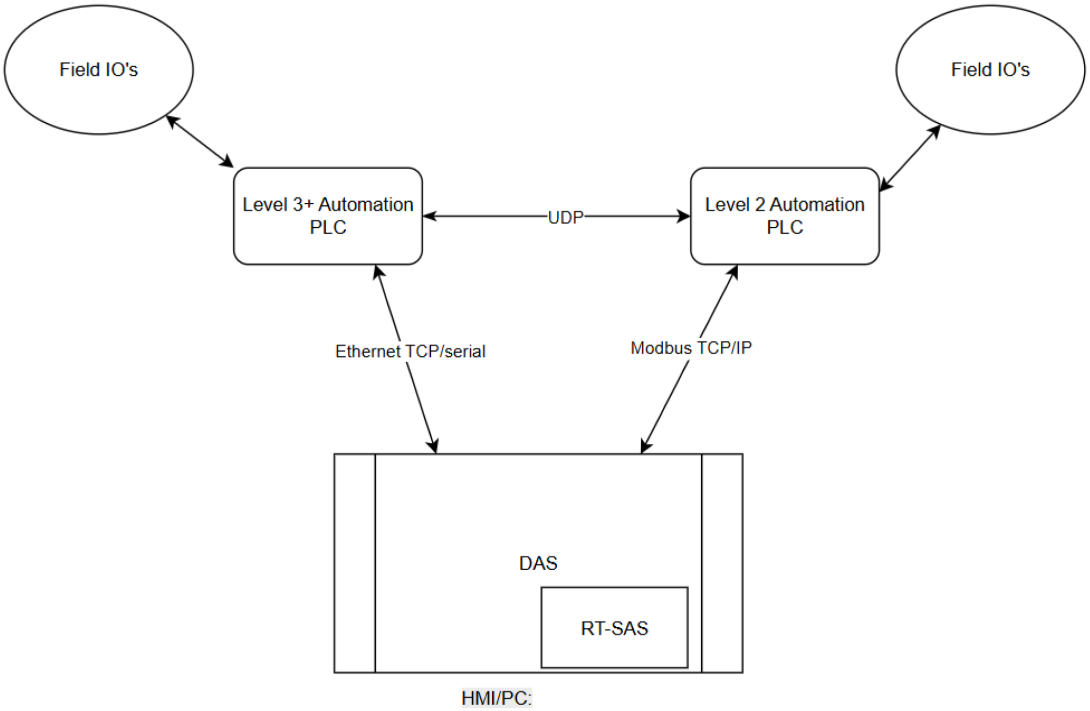

Figure 3—Electronic sensor connection between PLC's, HMI, and DAS

At the core of the electrical system is the PC-based application, which functions as a real-time data acquisition unit. It continuously aggregates live data from the PLCs and calculates critical well parameters using the Real-Time Simulation and analysis software (RT-SAS). These parameters include pull-limit, push-limit, and rate of weight change, which are transmitted to the PLCs as dynamic clip limits. The PLCs use these limits to control the injector head, ensuring safe and efficient movement of the coiled tubing in-hole or out-of-hole.

This architecture enables coordinated execution of control plans, dynamic adjustment of operational parameters, and seamless integration with hydraulic and mechanical subsystems. The modular and scalable design ensures compatibility with future upgrades, including advanced control algorithms, additional sensor arrays, and machine learning-based optimization.

Controls System Design

The newly developed automated control system for the CTU is designed to optimize pipe movement using a combination of cascade PID and fuzzy logic strategies. These controls dynamically manage hydraulic parameters to ensure safe, efficient, and smooth transitions during both RIH and POOH operations.

PID control is used to regulate hydraulic parameters within the injector system. It continuously calculates the error between a desired setpoint and the actual process variable, then adjusts control inputs to minimize that error. The Proportional term reacts to the current error, the Integral term addresses accumulated past errors, and the Derivative term anticipates future trends based on the rate of change. In a cascade PID configuration, multiple PID loops are layered to manage interdependent variables with greater precision and stability.

Fuzzy logic is applied specifically to manage the speed of pipe movement during operations such as Running in Hole (RIH) and Pulling Out of Hole (POOH). Instead of relying on fixed thresholds, fuzzy logic interprets speed conditions using qualitative categories like "too slow," "slow," "fast," and "too fast." Based on these inputs, the system adjusts the PID controller adjust gains dynamically to ensure smooth and safe pipe movement. This adaptive tuning allows the system to respond intelligently to changing conditions, mimicking the nuanced decisions of experienced operators.

By combining fuzzy logic for speed control with cascade PID for hydraulic regulation, the system delivers expert-level performance with minimal operator input. This hybrid control strategy enhances consistency, reduces human error, and empowers less experienced personnel to execute complex sequences reliably and safely.

The sequency of operations during RIH, after operator disengaging the reel and injector brakes switch at control panel and system switch to auto-mode. The pipe-in servo is initially set to initial pilot pressure to disengage the counterbalance valve. It then increases injector motor pressure to match surface weight and gradually ramps up pipe-in pressure to reach target speed. If actual speed is not achieved and weight exceeds the critical snub threshold, the system increases injector motor displacement or pressure. If the operator manually increases motor pressure (independent circuit), the system compensates by reducing displacement or pipe-in pressure based on conditions (Fig. 4).

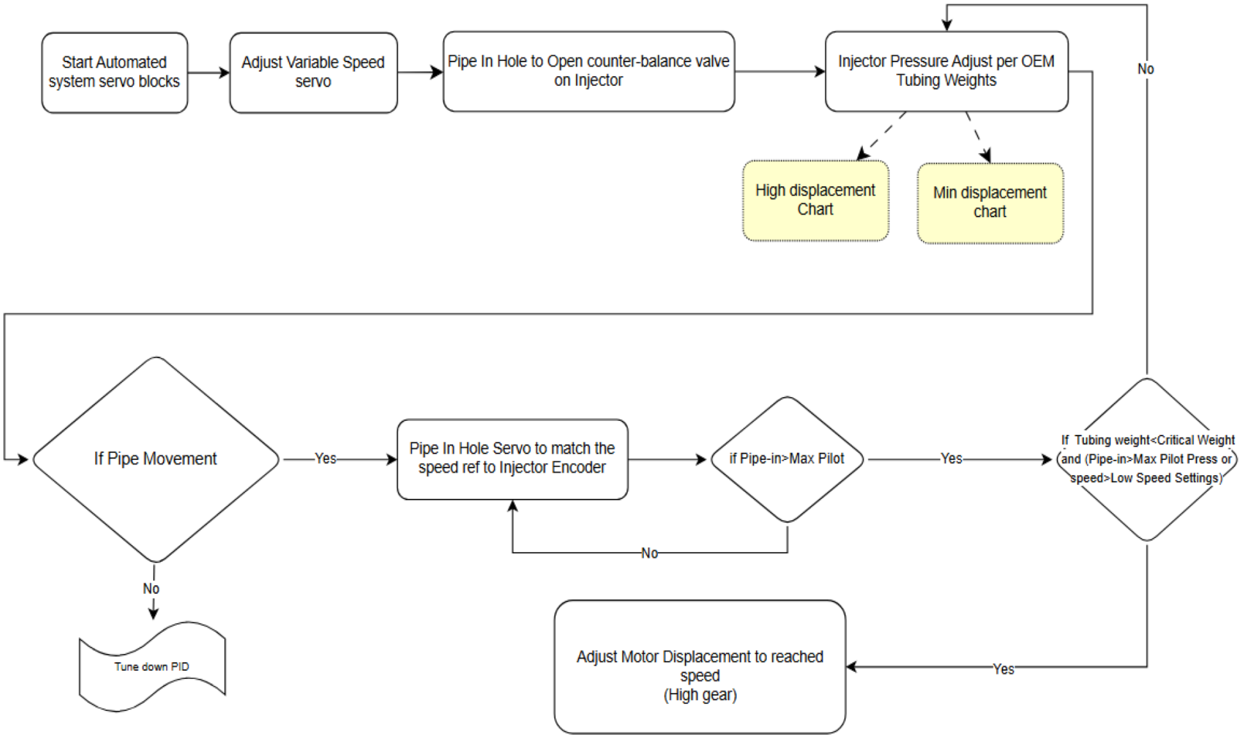

Figure 4—RIH flow chart for injector Control Start

For POOH, the system follows a similar sequence of operations. After brakes disengagement and system switch to auto-mode, it sets reel tension to a minimum setpoint and then pipe-out servo to initial pilot pressure to disengage the counterbalance valve. Injector motor pressure is then increased based on surface weight, followed by a gradual ramp-up of pipe-out pressure to reach target speed. If weight is below the critical pull threshold and speed is not met, the system increases displacement (per injector config). If the operator increases motor pressure, the system compensates by reducing displacement or pipe-out pressure (Fig. 5).

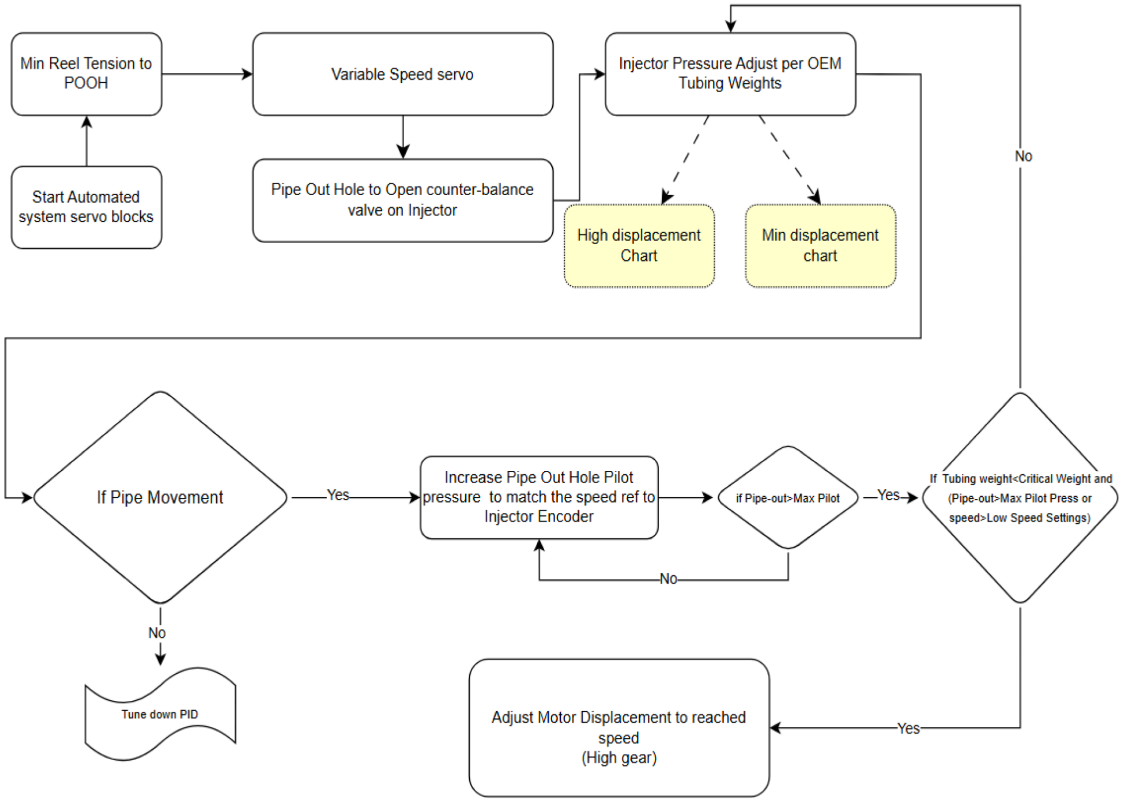

Figure 5—POOH flow chart for injector Control Start

To stop the CTU system, the controls gradually reduce motor displacement, pipe-in/pipe-out pressure, and injector motor pressure until speed drops to ~too Slow speed. Then brings motor pressure to zero and safely shuts down all critical controls (Fig. 6). Traction and tension are maintained within operational limits throughout.

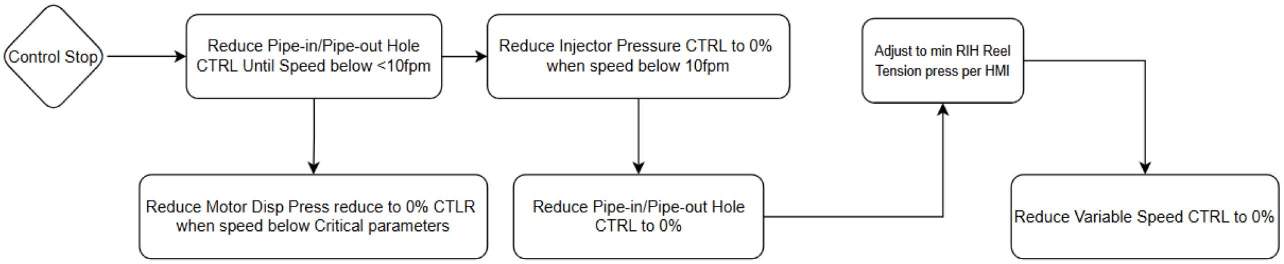

Figure 6—Flow chart for injector Control Stop

The system includes alarms and interlocks running in parallel with process logic and I/Os. If any critical parameter exceeds thresholds in the RT-SAS environment, a Safety Stop is triggered, halting operations and transitioning the system to a safe state (Fig. 7). This architecture enables coordinated control execution, real-time parameter adjustment, and seamless integration with hydraulic and mechanical subsystems. To manage the complexity of multiple subsystems working together—such as pipe-in/pipe-out pressure, injector motor pressure, and motor displacement—the control system uses fuzzy logic to replicate the decision-making behavior of an experienced operator. Each subsystem influences injector speed differently and often non-linearly:

- Pipe-in/Pipe-out pressure moves the hydraulic valve to allow fluid into the motor in one direction or another.

- Injector motor pressure drives the pipe-in circuit and provides the base hydraulic force.
- Motor displacement is adjusted to trade off torque for speed when needed.

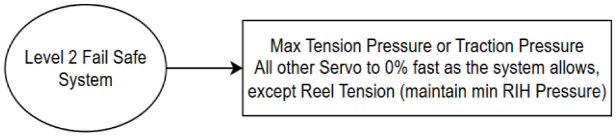

Figure 7—Level 2 Fail safe System Critical Stop

In parallel, PID control loops are used to fine-tune system response. However, when working with hydraulic systems, noise and offset must be considered to maintain stable control. During low-speed operations—where only the pipe-in/pipe-out circuit is active—the system experiences a noise band of ±3 ft/min. When motor displacement is introduced to increase speed, the hydraulic complexity increases, and the noise band widens to ±5 ft/min. To compensate, the PID controller dynamically adjusts its offset based on the system detected noise. This ensures that the system does not overreact to transient fluctuations and maintains smooth, predictable movement. Fuzzy logic complements this by interpreting the system state in linguistic terms (e.g., "slightly fast," "moderately high pressure") and applying adaptive rules that balance speed, torque, and hydraulic stability. Together, fuzzy logic and PID coordination allow the control system to behave like a seasoned operator—making nuanced decisions in real time while maintaining safety, responsiveness, and adaptability to changing wellbore conditions.

Controls Testing and Integration

The development of the control system for the CTU automation used a simulation-driven approach from the outset, enabling early validation and refinement of control strategies. Software-in-the-Loop (SIL) simulation played a critical role in shaping the system architecture—particularly in the conceptual design and tuning of fuzzy logic algorithms and PID controllers. By simulating real-world hydraulic and mechanical behaviors, we were able to evaluate various control scenarios, evaluate system responses, and fine-tune parameters before any physical hardware was involved. This early-stage simulation not only accelerated the design cycle but also helped us identify potential integration challenges and edge cases that could impact field performance.

As the control logic matured, we used SIL testing iteratively to validate each functional block of the system, including auto-configuration sequences, pressure ramping logic, and safety interlocks. The simulation environment enabled comprehensive testing of RIH and POOH operations under varying load conditions, surface weights, and operator overrides. It also allowed verification of the system's response to abnormal conditions—such as exceeding snub or pull thresholds—ensuring that the fuzzy logic and PID controllers responded appropriately. This rigorous testing methodology ensured that the control system was robust, adaptive, and ready for deployment, with a high degree of confidence in its ability to manage real-time operational dynamics safely and efficiently.

A key aspect of our CTU control system design was ensuring seamless integration between office engineering software and field execution systems. From the beginning, the architecture was designed to support compatibility with legacy Data Acquisition System (DAS) software, Fatigue Lifecycle Management Software (FLCMS), and RT-SAS. This required not only capturing and recording operational data but also building a system capable of real-time communication across multiple platforms. The goal was to create a unified workflow where engineering inputs, control logic, and field execution could operate cohesively—without manual intervention or data translation errors.

Office-engineering tools were heavily relied upon are just as critical as field systems in this workflow. Technical engineers used these tools to gather well profile data and simulate operational scenarios. Once simulations were complete, the software generated critical real-time configuration files—specifically for Coiled Tubing Simulation Software (CT-SS) and FLCMS—which were uploaded to the RT-SAS module within the DAS software. These files contained essential parameters which updates per real wellbore parameter such as critical pull and snub limits, as well as rate-of-weight-change thresholds that the controller used during live operations. The result was a tightly integrated system that bridged design and execution, improved operational efficiency, and ensured the controller was equipped with the necessary limits and logic to respond accurately and safely to real-time conditions.

After completing SIL testing and incorporating feedback from subject matter experts (SMEs) to the project transitioned to full-scale simulation to mimic real-world operations. A complete test setup was assembled (Fig. 8), including hydraulic connections from the HPU to the CTU cabin, and from the cabin to the injector. This physical integration allowed for realistic job simulations, targeting operational speeds during both RIH and POOH. Because of the groundwork laid during SIL, the hydraulics were tuned much faster by reducing what would typically take months to completion within a week. The pre-modeled control framework allowed for rapid adjustments and immediate feedback.

Figure 8—Testing System setup

This full-system integration phase also helped identify and resolve software bugs early in the process, ensuring a smoother transition to field deployment. The system was executed according to the job program and evaluated across a wide range of operational scenarios. These results, along with performance metrics and lessons learned, are discussed in detail in the following results section.

Controls Testing and Integration with actual hydraulics

The system's fuzzy logic controller was named *Ken/Marvel* Control Logic (KMCL), in recognition of two key contributors: *Marvel*, our field supervisor with 27 years of direct CTU experience, and *Ken*, our CT-N_2 SME who has the same years of experience on the manufacturing side. Drawing from both field expertise and manufacturing insight, the development was a creative and practical approach to automating the CTU. Their combined knowledge helped shape the fuzzy control logic to reflect how the CTU behaves in real-world scenarios.

For the initial trial, the system started with the injector motor pressure fully closed to observe how the controller would respond at a given speed. During this phase, it was discovered that the absence of configured noise parameters for hydraulic pressure caused oscillations in injector speed (Fig. 9). This led to introducing noise filtering and system tuning using both high and low displacement settings, which helped stabilize the hydraulics.

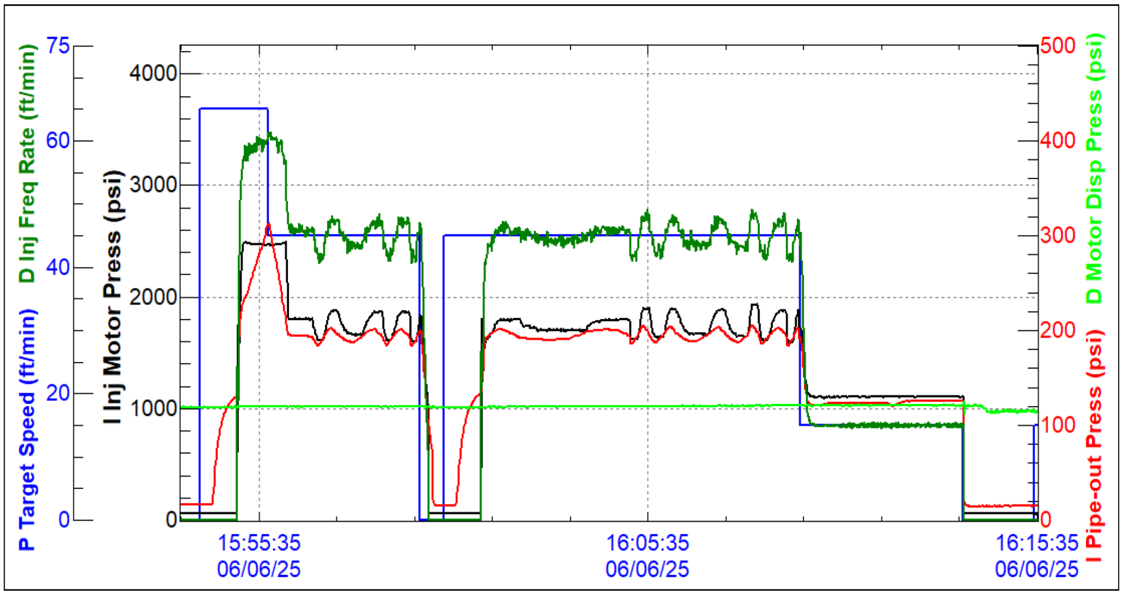

Figure 9—First test out the system with complete close of injector motor pressure

As speed increased, high displacement pressure caused the PID controller and KMCL to overshoot above the setpoint. To compensate, the pipe-in/pipe-out was adjusted, which improved control response (Fig. 10). With further enhancements, better handling of the PID controller was achieved with KMCL by coordinating pipe-in/pipe-out pressure with displacement motor pressure, while maintaining a constant injector load. This approach reduced overshooting but still resulted in a sharp speed drop during controlled shutdowns due to sudden displacement pressure loss (Fig. 11). Additional trials refined the balance between pipe-in/pipe-out, displacement motor, and injector motor pressures. This tuning achieved target speeds more accurately, avoid overshooting, and shut down the system gracefully (Fig. 12 & 13).

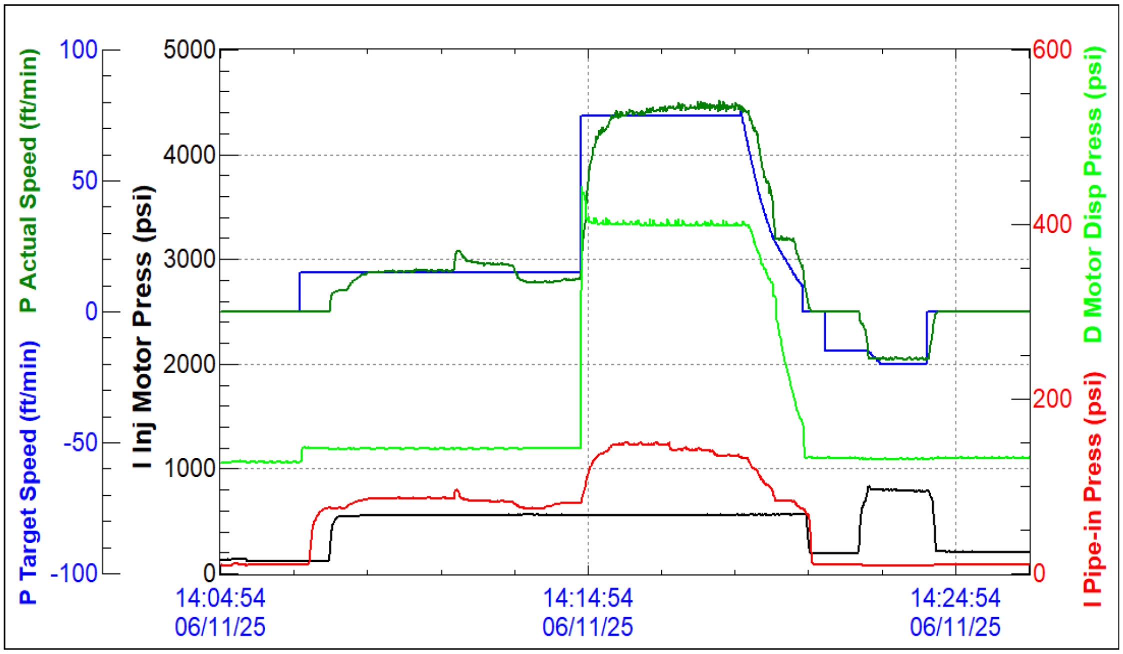

Figure 10—Start tuning the system for noise and adjust the motor displacement pressure

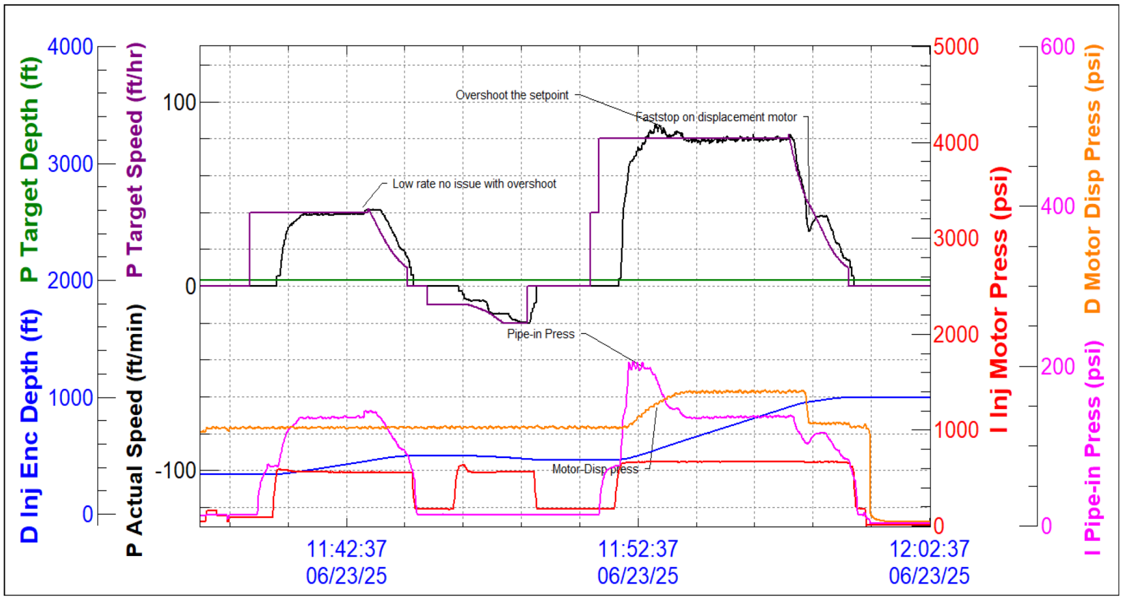

Figure 11—Start tuning the system for noise and adjust the motor displacement pressure

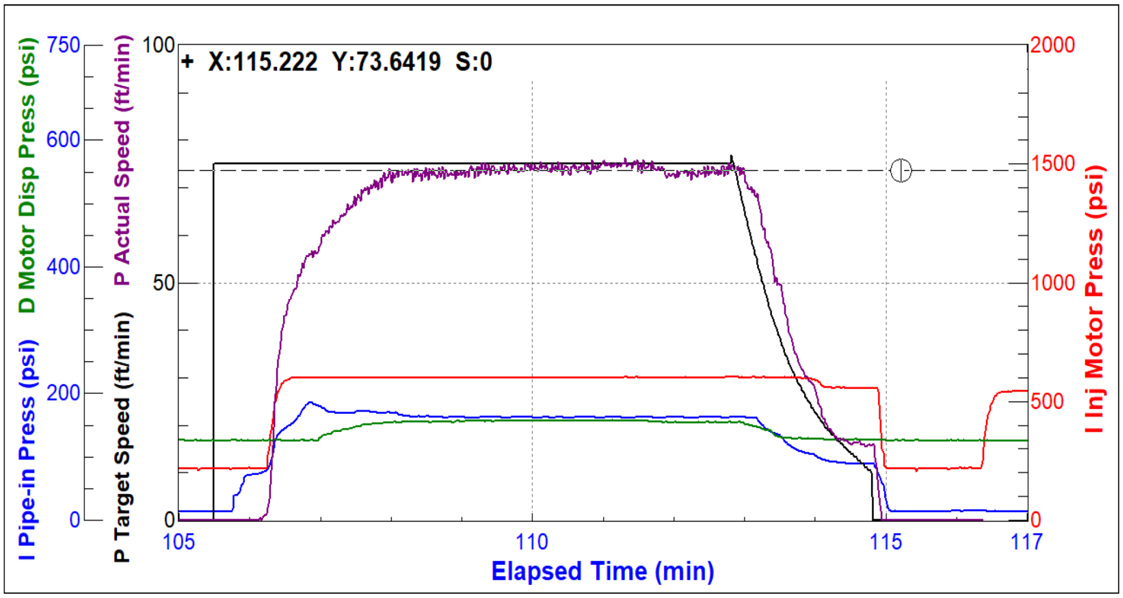

Figure 12—RIH at target speed of 75fpm

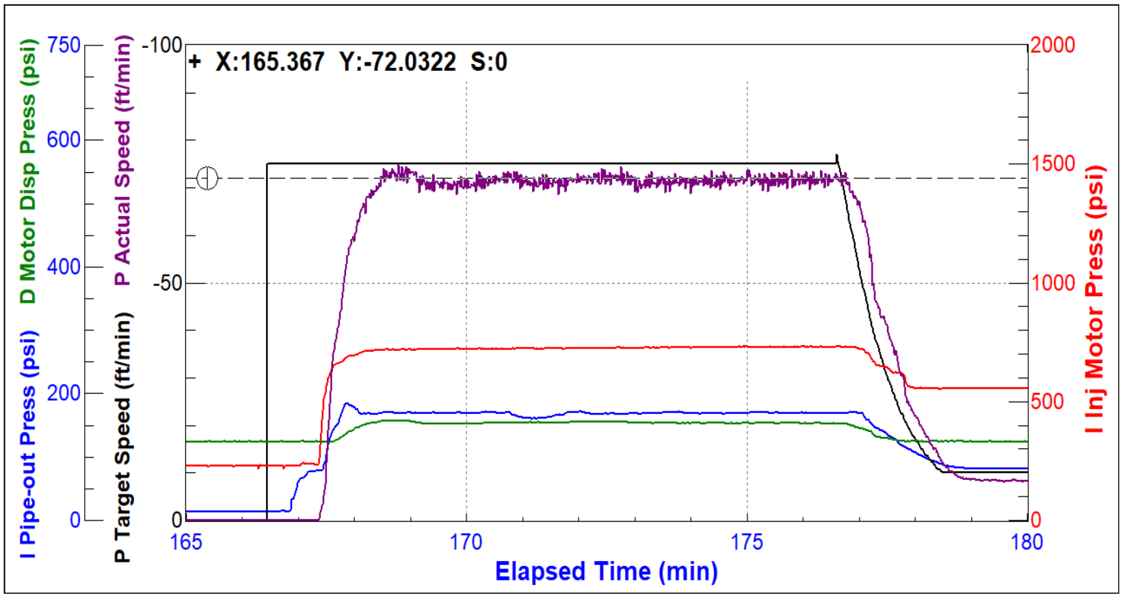

Figure 13—POOH at target speed of 75fpm

A full-scale job simulation with actual hydraulics was executed, running the injector to 2000ft Measured Depth (MD) and performing pull tests every 500 ft for 30 ft interval at -20 fpm (4 total pull tests). A restriction was introduced at 1200 ft to evaluate system behavior. The system successfully slowed down during RIH and POOH within ±50 ft of the restriction zone and between 1150–1250 ft as seen in the chart the actual speed maintaining speeds around 10 fpm ±3 fpm close to target setpoint of 10fpm. Also, the system was configured to maintain 625 psi during RIH and 1200 psi during POOH (Fig. 14). Safety Stop functionality was evaluated by simulating sudden weight changes, which triggered immediate shutdowns of hydraulics (Fig. 15).

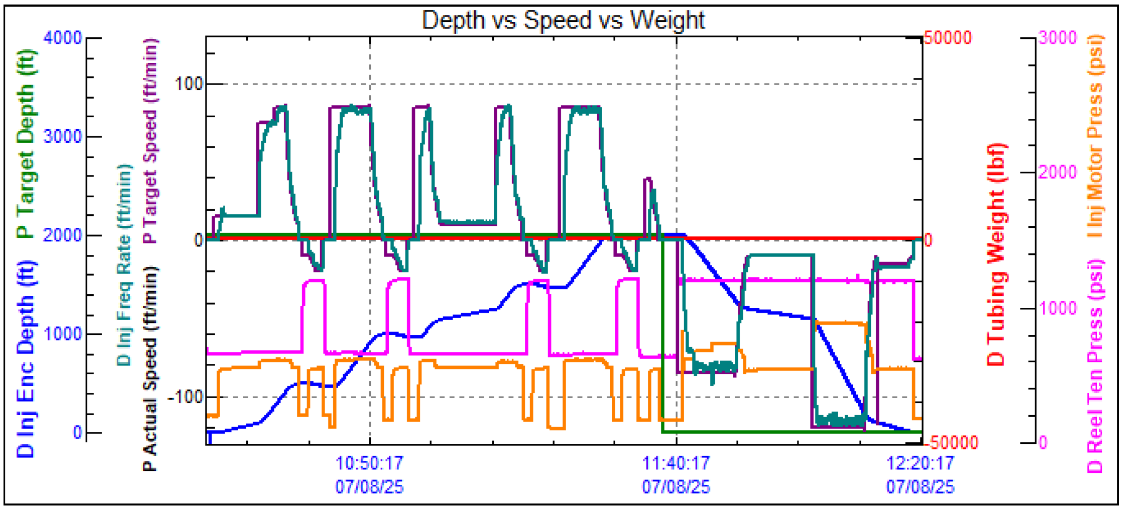

Figure 14—Full well scenario testing

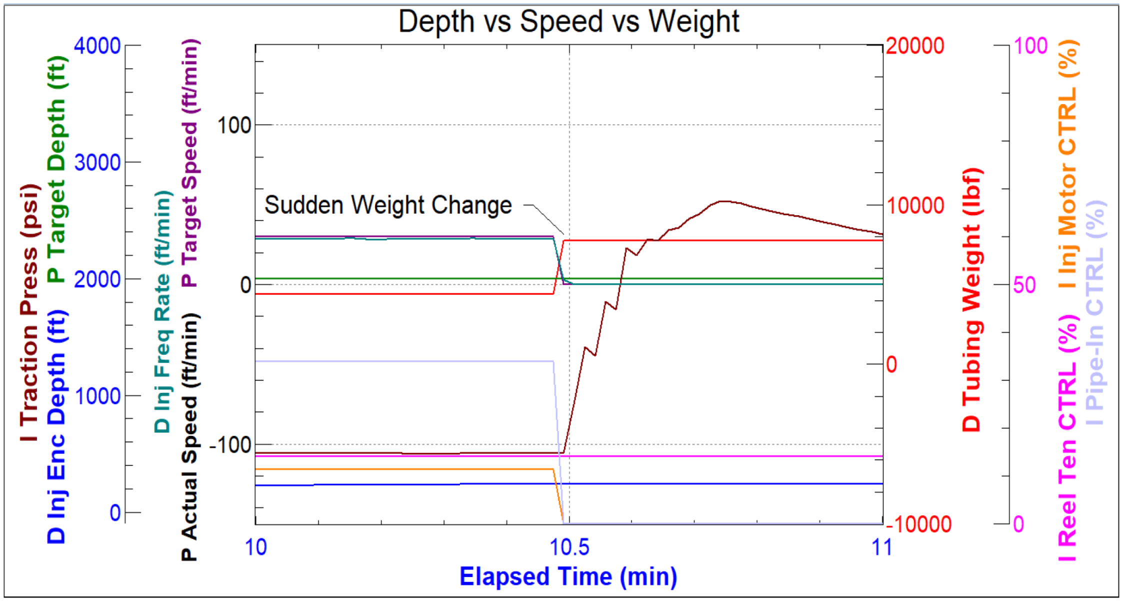

Figure 15—Automated Safety-Stop

To evaluate emergency response, a run-away scenario was conducted by disengaging automated control and handing over to manual operator control while maxing out traction pressure (Fig. 16). In this test, the system immediately reversed the motor direction to catch the tubing, simulating a real-world emergency. Although such an event would expect cause damage to the injector and hydraulic system, this was done using part of function test to validate the logic. This scenario was executed in a controlled environment, where we pre-dialed manual setpoints and activated the run-away switch during POOH. The system responded by switching motor direction and applying maximum traction pressure.

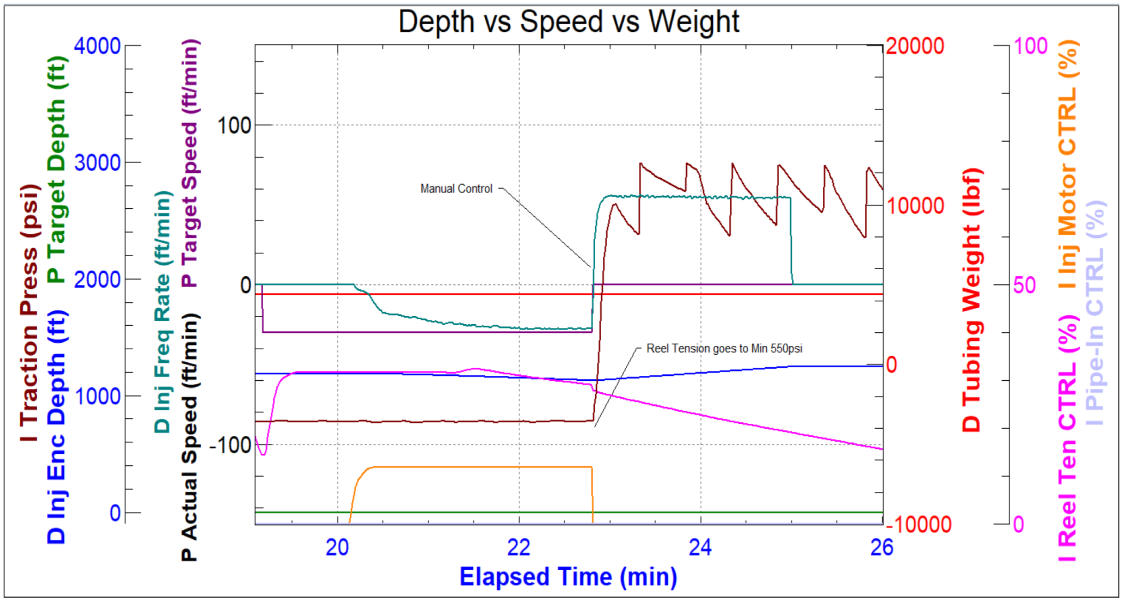

Figure 16—Ran-away scenario

Operational Benefits and Client Value

The deployment of the automated intelligent injector control system is a significant advancement in coiled tubing operations, delivering measurable improvements in safety, consistency, and operational efficiency. By automating critical sequences and keeping key operational parameters, the system reduces reliance on manual intervention and mitigates risks associated with operator variability—particularly in environments where experience may be limited.

Unlike traditional systems that rely on operator judgment and reactive safety mechanisms, this automation framework proactively manages execution through real-time control logic. It continuously checks surface weight, tubing tension, and speed, adjusting dynamically to ensure operations stay within safe and predefined boundaries. This enhances safety by preventing overpull, excessive snubbing forces, and tubing buckling, while also improving job repeatability and reducing the likelihood of equipment damage or unplanned shutdowns.

The system uses real-time wellbore conditions, calculated and updated continuously via the RT-SAS, to guide operational decisions. These dynamic parameters—such as clip limits for pull, snub, and rate-of-weight change—are derived from actual wellbore data and ensure that the control system responds accurately to changing conditions throughout the job. This enables the system to keep best performance and safety without requiring manual recalibration or intervention.

From a client perspective, the system delivers substantial value through reduced downtime, optimized execution, and enhanced reliability. By integrating intuitive interfaces, intelligent automation, and real-time decision support, we enable less experienced operators to perform with the confidence and precision of seasoned experts—enhancing productivity, reducing errors, and improving overall system reliability. The automation of routine and high-risk tasks leads to more predictable job outcomes, lower non-productive time (NPT), and improved asset use.

Clients receive help from higher service quality, increased operational transparency, and greater confidence in execution. The system's ability to adapt to real-time wellbore conditions and support control across a wide range of scenarios ensures that interventions are completed efficiently and safely. This translates into long-term cost savings, improved field performance, and stronger client satisfaction.

In summary, the automated intelligent injector control system not only bridges the experience gap but also redefines CT operations as a more controlled, consistent, and client-focused process—delivering measurable improvements across safety, efficiency, and reliability.

Conclusion

The development and validation of an automated intelligent injector control system was designed to address long-standing challenges in coiled tubing operations—specifically the widening experience gap, variability in service delivery, and the need for improved HSE performance. By transitioning from passive safety systems to active, real-time automation, the system enables consistent execution of critical tasks while keeping operational boundaries derived from real-time wellbore conditions.

The automation framework not only enhances safety and reduces non-productive time (NPT) but also empowers less experienced operators to perform as a traditionally associated with decades of field experience. This is achieved without removing the operator from the loop, but by embedding expert logic into the control system to support decision-making and execution.

The results show that automation is not just a technological upgrade—it is a strategic enabler for improving service quality, reducing operational risk, and meeting client expectations for consistency and safety. As the industry continues to evolve, systems like this will play a vital role in bridging the gap between human ability and digital execution, ensuring that coiled tubing operations stay efficient, reliable, and future-ready.

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Nomenclature

CT	Coiled Tubing
CTU	Coiled Tubing Unit
RIH	Run in Hole
POOH	Pull out of Hole
CT-SS	Coiled Tubing Simulation Software
FLCMS	Fatigue Life Cycle Management Software
RT-SAS	Real-Time Simulation and analysis software
SIL	Software in Loop
DAS	Data Acquisition System
NPT	Non-Productive Time
HIF	High Impact failure
HSE	Health, Safety, and Environment
PID	Proportional–Integral–Derivative
WOB	Weight-on-bit
ROP	Rate-of-Penetration
PLC	Programmable Logic Controller
Modbus	Modular Bus
TCP/IP	Transmission Control Protocol/Internet Protocol
OPC-UA	Open Platform Communications Unified Architecture
HMI	Human Machine Interface
PVC	Proportional Valve Control

I/O	Input/Output
OEM	Original Equipment Manufacturer
SME	Subject Mater Expert
KMCL	Ken/Marvel Control Logic

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