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Evaluating the Benefits of Solvents and Flow Control Devices (FCDs) for Thermal Production: Public Report

C-FER Technologies
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Canadian Natural Resources Limited
Imperial Oil Resources Limited

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January 2022
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REVISION HISTORY

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NOTICE

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EXECUTIVE SUMMARY

Steam-assisted gravity drainage (SAGD) operators are evaluating various enhanced oil recovery processes that utilize solvents and/or non-condensable gases to reduce or eliminate the volume of steam required to mobilize bitumen in the reservoir. Research and field pilots of these processes to-date indicate reduced energy intensity, greenhouse gas emissions, and water use; and increased ultimate oil recovery when compared to conventional SAGD.

To further enable and optimize these enhanced recovery processes, SAGD operators are interested in fully quantifying the potential benefits and risks of utilizing inflow control devices (ICDs). Therefore, several SAGD operators, C-FER Technologies (1999) Inc. ("C-FER"), and Alberta Innovates collaborated to upgrade C-FER's ICD Characterization Flow Loop to enable characterization testing of ICDs using solvents and to complete some initial "screening tests" on various vendor-supplied ICD architectures to identify the designs that show the most promise in becoming fully qualified for these applications.

This report describes the current challenges facing the industry with improving environmental and economic performance, some of the work already done with improving the efficiency of SAGD wells through the use of ICDs, and the knowledge gap still facing the industry with recovering bitumen using solvents and non-condensable gas (NCG) injection. It then explains how the initially proposed flow loop operating capabilities associated with testing using propane and butane were expanded to also include the ability to test with diluent and oil. Finally, the results obtained and the lessons learned through the design, construction, and initial "screening" testing of many ICD geometries are described in detail.

Overall, the project was a success. A new, independent test facility is now available for ICD technology to be tested in an efficient and safe manner, which should help to further accelerate a transition from SAGD to solvent and NCG applications. Several ICDs have also been identified as promising technologies to be evaluated as part of a future work scope. This project, as well as the continued work that is expected to occur using this new facility, should lead to the application of ICD technology from Alberta vendors in thousands of future wells, which will further lead to improvements in operational efficiency, economics, and environmental performance for oil and gas operators in Alberta. This will result in long-term sustainability of the industry in Alberta, which will further result in high-paying jobs for Albertans and increased royalty revenue for the Government of Alberta.

ACKNOWLEDGEMENTS

C-FER Technologies (1999) Inc. ("C-FER") would like to acknowledge the technical guidance and financial contributions from Suncor Energy Oil Sands Limited Partnership, Cenovus Energy Inc., Canadian Natural Resources Limited, and Imperial Oil Limited, who helped to make the project possible and ensure that the project objectives were achieved. C-FER would also like to acknowledge the contributions of the inflow control device (ICD) vendors, who contributed ICDs for testing.

Finally, C-FER would like to acknowledge the funding contribution provided by Alberta Innovates, the Ministry of Economic Development and Trade, and the Government of Alberta, as well as the project oversight provided by Alberta Innovates, which also helped to make this project possible.

1. INTRODUCTION

1.1 Steam-assisted Gravity Drainage Background

Approximately 80% of Alberta’s proven oil sands reserves (1) are too deep to mine and, therefore, require in-situ recovery processes. Steam-assisted gravity drainage (SAGD) is the most common in-situ recovery process in Alberta. This process utilizes two horizontal wells or a well-pair, where a lower well (the producer) is near the base of the bitumen and an upper parallel well (the injector) is approximately 5 meters above the producer. During “conventional SAGD”, steam is injected into the reservoir through the injector well, creating a “steam chamber” in the reservoir. The heat transferred from the steam chamber, primarily latent heat from the condensation of the steam contacting the bitumen, causes the bitumen temperature to increase and the viscosity to decrease. This decrease in viscosity improves the bitumen mobility, resulting in a mixture of bitumen and condensed water flowing to the producer well, which is due to the combined effect of gravity and the pressure gradient between the injector and the producer. The utilization of an artificial lift system in the producer allows the bitumen-water mixture to be produced to surface. Figure 1.1 shows the orientation of the injector and producer well used in the typical SAGD process.

There are several challenges associated with recovering Alberta bitumen compared to other world crude oils, including higher capital and operating costs, the use of fresh water, generation of greenhouse gas (GHG) emissions due to steam generation, and issues with transportation and market access (2). One of the key technical issues is the efficiency and energy intensity of SAGD, which is driven by the generation of steam and how efficiently it can be utilized in the reservoir to uniformly create the steam chamber and heat the bitumen as efficiently as possible. This energy intensity is commonly reported in terms of how many barrels of steam must be injected for every barrel of bitumen recovered, or the steam-to-oil ratio (“SOR”).

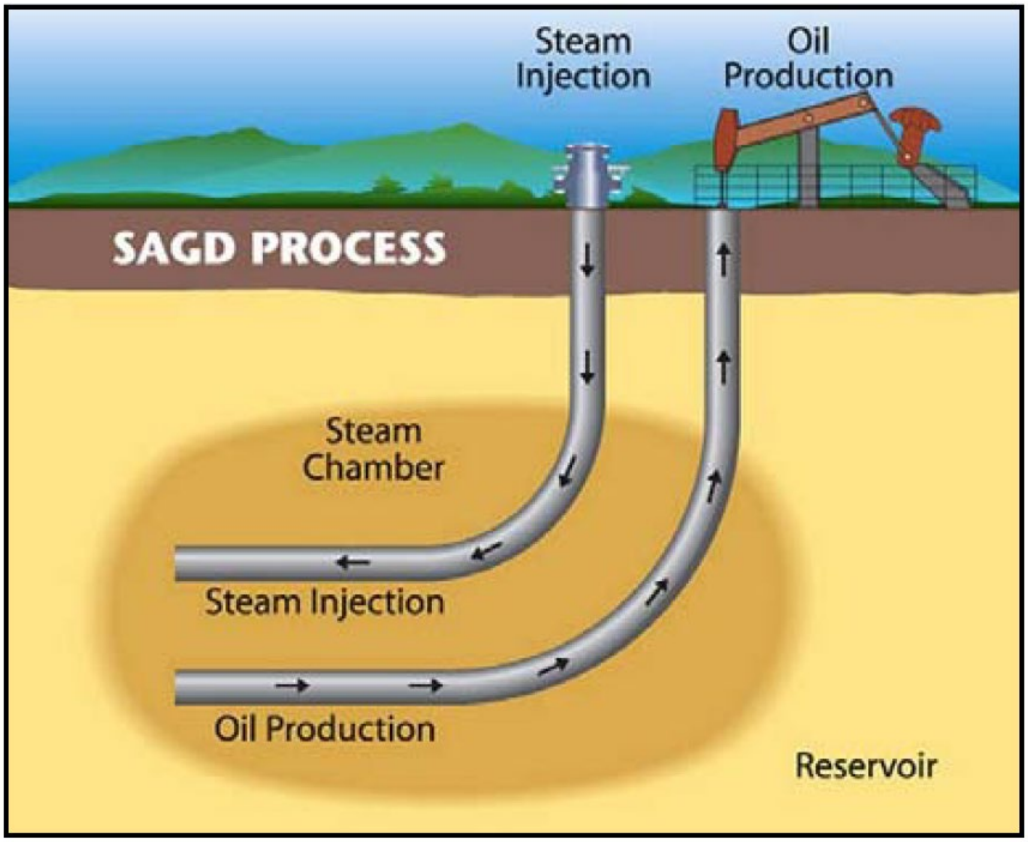

Figure 1.1 SAGD Process Well-Pair (1)

Steam chamber growth is typically uneven due to a number of factors, including the impact of permeability heterogeny and the pressure drop along the horizontal section of the wells. The latter can create a situation where fluid injection or production is preferentially biased towards the "heel" and "toe" of the well-pair. Additionally, lateral variations in the reservoir net pay height and permeability can negatively impact the lateral temperature (steam) conformance, creating production well "hot spots" or steam breakthrough points that will limit the recovery rate and can lead to resource recovery limiting well failures.

A significant challenge for oil and gas operators is identifying and maintaining a uniform steam chamber along the horizontal, as well as the optimum height of the liquid trap over the producer well. This fluid level directly correlates to how close the fluid at the producer well is to its saturation temperature, or "subcool". If the subcool is too high, the fluid level is also high above the producer, and the well will recover bitumen at a lower rate; therefore, operators ideally want to keep the subcool values as low as possible. However, if the subcool is too low, the liquid-steam interface could reach the producer, allowing the injected steam to directly enter the producer and short circuit back to surface. This not only results in inefficient use of the steam and increased energy intensity and production cost of the bitumen, but it can also lead to well failure due to the high velocity of produced droplets and quartz particles entering the producer along with the steam. Therefore, it is important that operators continually maintain the optimum subcool to maximize production while minimizing the risk of a well failure.

1.2 Past Flow Control Device Work and Technology Gap for Steam-assisted Gravity Drainage

Flow control devices (FCDs) are throttling devices installed as part of well completions to add some additional flow restriction between the well and reservoir. This helps to compensate for some of the existing variations in flow restriction along a well, either due to pressure drop along the horizontal or differences in reservoir permeability. For SAGD applications, FCDs can be installed in either the injection well, where they are referred to as outflow control devices, or in the producing well, where they are referred to as inflow control devices (ICDs). ICDs used for SAGD may similarly be designed to add some additional flow restriction to promote uniform inflow into the producer, but are typically designed to restrict inflow of fluids containing the vapour phase.

ICDs were first used in conventional oil reservoirs to promote uniform production and to prevent breakthrough of unwanted gas or water, but their application in SAGD was not as well understood due to performance uncertainty when operating near water saturation conditions. The presence of steam or low subcool water passing through an ICD in typical SAGD operating conditions can cause some of the water to flash to steam, resulting in a significant additional volume of steam passing through the device and a corresponding change in the hydraulic performance. Accurate prediction of pressure drop across ICDs is a key aspect of a SAGD completion design utilizing ICDs to ensure operators can accurately model the reservoir and wellbore, maximize production, and reduce wellbore integrity risks.

Figure 1.2 shows field data released by ConocoPhillips (3) where a trial of a single SAGD well with ICDs showed improved steam chamber conformance, higher bitumen production rates, and reduced SOR compared to nearby, similar wells. However, predictive models did not exist to explain the performance of the ICDs and to predict whether they would prevent steam breakthrough. Furthermore, available testing facilities at that moment were not capable of operating in these challenging conditions.

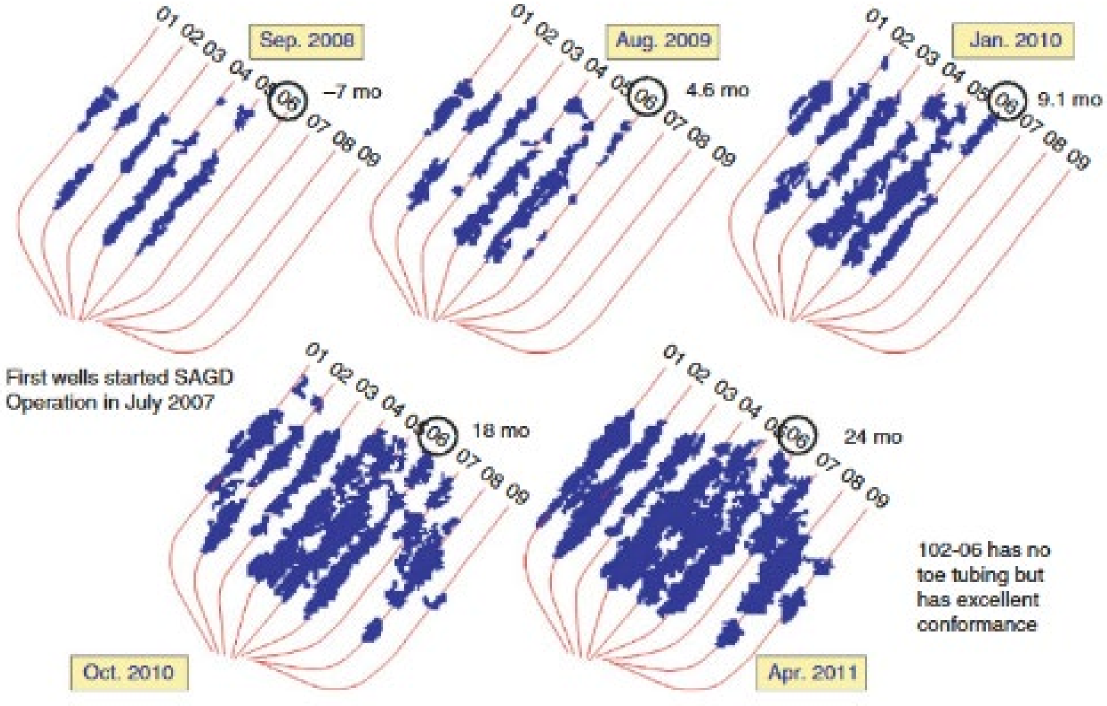

Figure 1.2 Steam Chamber Profile along Horizontal Wellbore (3)

To bridge this technology gap, a new experimental facility, the ICD Characterization Flow Loop (or "ICD Characterization Loop"), was built at C-FER Technologies (1999) Inc. ("C-FER") in 2013, and later operated as part of a Joint Industry Project (JIP) consisting of four Alberta SAGD operators. The facility carried out testing over a five-year period to investigate the hydraulic performance of several ICDs under a variety of operating conditions, including different test fluids with varying levels of subcool, steam/gas fraction, density, viscosity, pressure, and temperature entering the ICD inlet. In 2015, a second facility, the ICD Erosion Apparatus, was also constructed to carry out three-phase erosion testing with water, sand, and gas to assess the long-term reliability of ICDs in SAGD conditions. To-date, operators and technology developers have used the test data generated from these two facilities to design new wells or optimize existing wells, and to improve the technology specific to Alberta's SAGD processes. The original ICD Characterization Loop is shown in Figure 1.3, while the ICD Erosion Apparatus is shown in Figure 1.4.

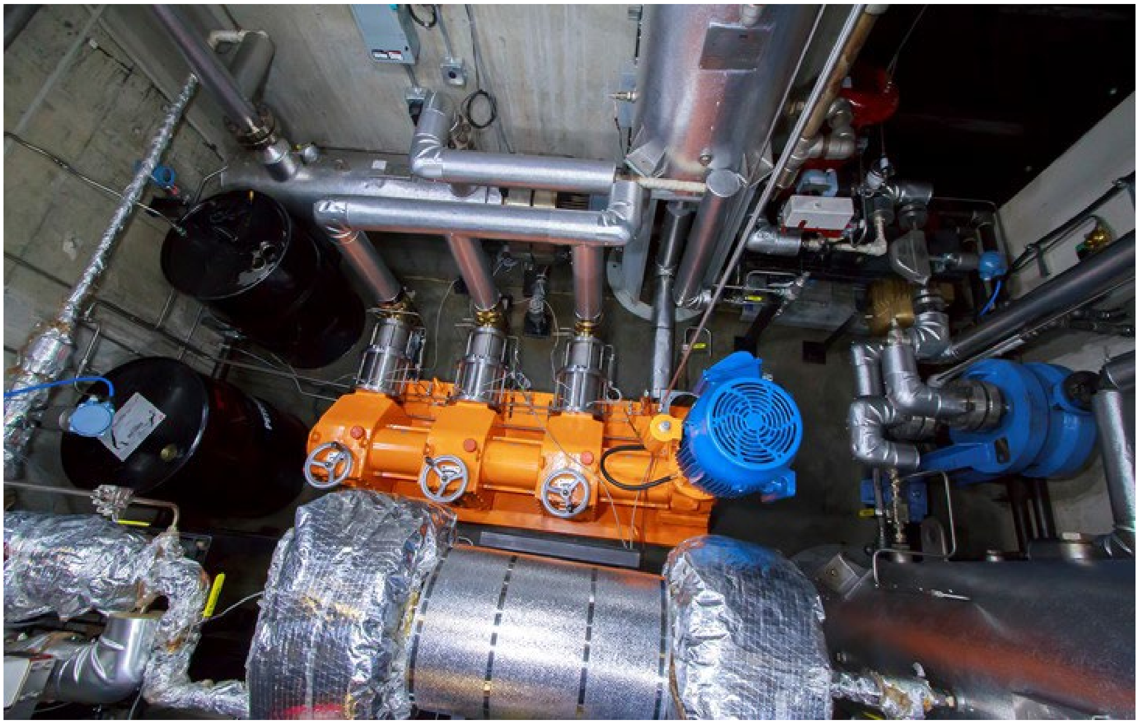

Figure 1.3 Original ICD Characterization Loop

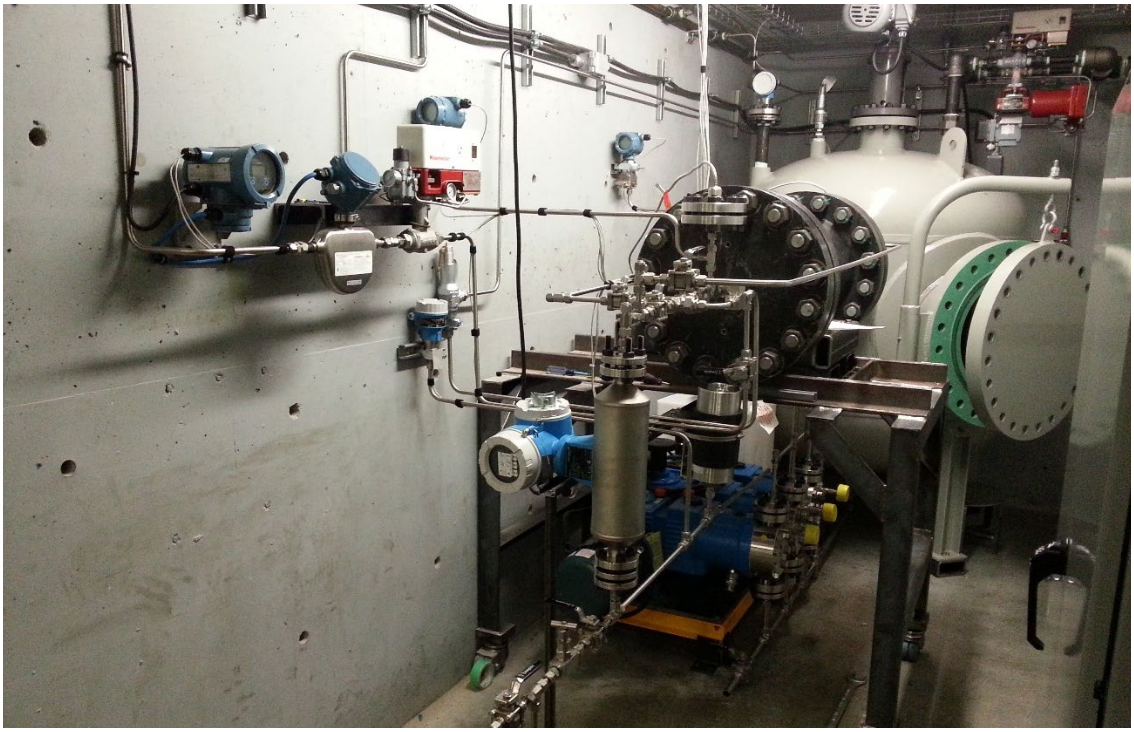

Figure 1.4 ICD Erosion Apparatus

1.3 Solvent Flow Control Device Technology Gap

Several SAGD operators have evaluated or piloted new solvent-enhanced in-situ processes to improve production economics and reduce GHG-emission intensity. These processes use hydrocarbon solvents, potentially with non-condensable gases (NCGs), to supplement or replace the steam used in SAGD. These processes reduce the bitumen viscosity either partially or fully by the diffusion of solvent into the bitumen, instead of relying solely on the addition of heat to reduce the viscosity.

Research and field pilots have indicated that the most effective processes for reducing costs and GHG emissions involved pure solvents or solvents with steam, and that the most effective process for improving existing SAGD fields was steam with solvents added (2). In these processes, the solvent needs to be continuously sourced, treated, or recovered; and heated or vaporized, depending on the process. Thus, just as with steam for SAGD, efficient usage of the solvent and prevention of solvent breakthrough is required to reduce the cost and energy intensity of the process. Figure 1.5 shows an example of a pure solvent recovery process tested by Suncor Energy, the NSOLV process (4).

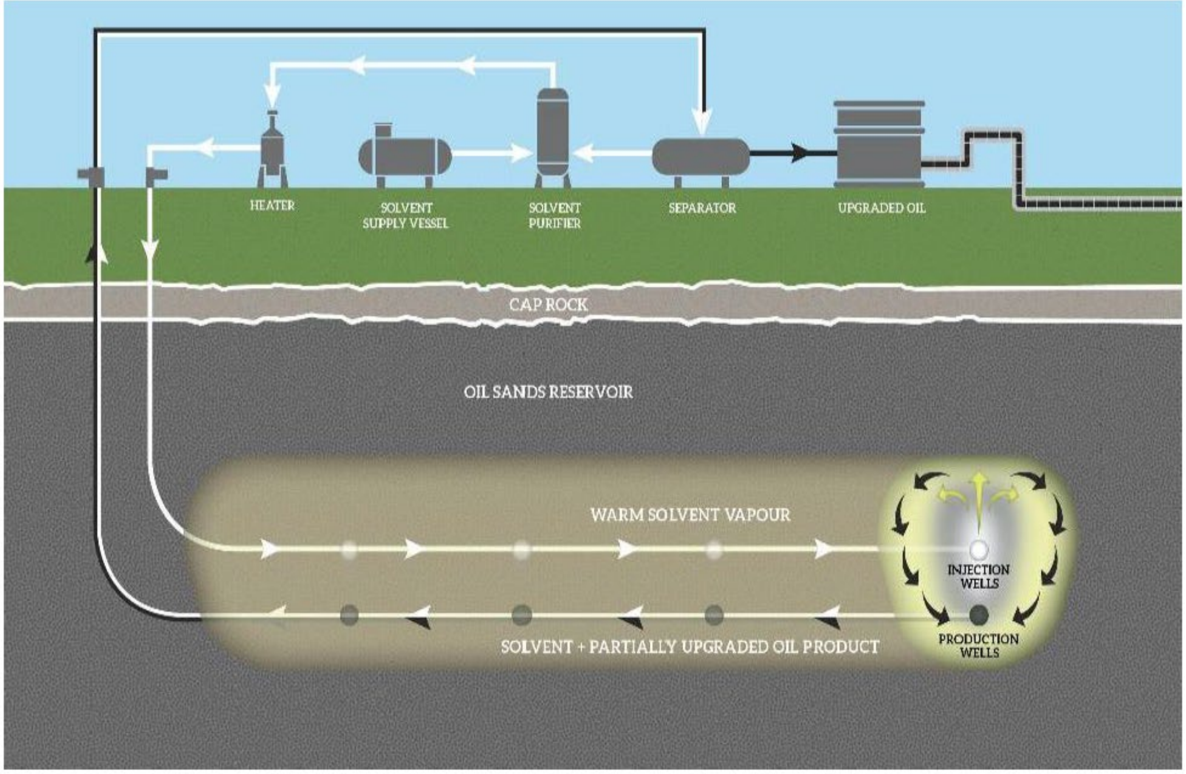

Figure 1.5 NSOLV Recovery Process

It is expected that the challenges faced by solvent-enhanced processes are similar to the challenges with SAGD wells and that they can be mitigated using ICDs. Therefore, accurate characterization of the hydraulic performance of ICDs under these new conditions is essential to effectively design wells for SAGD with NCG injection, steam and solvent, and pure solvent recovery applications.

This project addressed the knowledge and technology gaps that existed for the use of ICD technology in SAGD with NCG injection, steam and solvent, and pure solvent processes. First, there was a knowledge gap associated with understanding how the hydraulic performance of ICDs will change in multi-phase conditions, with the addition of a variety of hydrocarbon solvents being considered for these processes. The technology gap addressed included ICD technologies that were being optimized for SAGD conditions, but were not optimized for solvent processes. An infrastructure gap was also present in that facilities did not exist for safely testing ICD technologies with solvents and for generating the data needed to address the knowledge and technology gaps.

2. PROJECT DESCRIPTION

The project initially had two primary objectives. The first was to bridge the infrastructure gap by designing, constructing, and commissioning a new facility capable of testing ICD technology under full-scale conditions representative of enhanced SAGD or pure solvent recovery processes. The second objective was to bridge the knowledge and technology gaps by characterizing the performance of existing ICD technology with NCGs and solvents in the new facility. To ensure that the project objectives would be met, the project was to be supervised and guided by two committees: a technical committee consisting of various oil and gas operators (i.e. the industry partners); and a project steering committee consisting of representatives from C-FER, Alberta Innovates, and one of the technical committee industry partners.

The first project objective was carried out in two phases. Phase 1 focused on finalizing the requirements and conducting the necessary detailed design work for the new test facility. Phase 2 consisted of the teardown of the existing ICD Characterization Loop and procurement of any needed additional equipment to enable C-FER to construct and commission the new facility. The new facility was required to retain the original ICD Characterization Flow Loop capabilities for testing with oil, water, steam, and nitrogen gas, but also be capable of the following:

- Testing ICDs with high-temperature steam and vaporized solvents or NCGs representative of enhanced SAGD processes; and
- Testing ICDs with lower temperature solvents, which would be representative of new pure solvent recovery processes that do not require the use of steam.

For both processes, the tests were to be conducted using either propane or butane as the hydrocarbon solvent.

The requirements associated with the first objective were updated when the JIP Participants directed C-FER to expand the work scope to include an additional solvent recovery process that used diluent as the solvent. Including diluent added some new challenges to Phases 1 and 2 due to the diluent being a multi-constituent hydrocarbon fluid, where: the properties of the diluent are more difficult to determine and model; the diluent properties can change over the course of testing; and various hazardous compounds may exist in the diluent including some aromatics (e.g. benzene) and the possibility of hydrogen sulfide (H_2S). In addition to this, Phases 1 and 2 were further updated due to the development of a more efficient testing process involving plumbing multiple ICDs into the new flow loop, and testing one right after the other to minimize the number of fluid changes.

The second project objective was carried out in Phase 3 of the project, which focused on testing ICDs and collecting hydraulic performance data in the new facility. This objective originally included testing of up to four ICDs, which would be fully characterized with a detailed test matrix for each of the recovery processes. In consultation with the industry partners and the steering committee, this objective was changed to test eight ICDs instead of four, with a reduced testing scope for each ICD. This allowed for more technologies to be “screened” for the new solvent processes, while minimizing the amount of time spent testing technologies that may not be suitable for a given solvent process. Instead of collecting enough data to fully characterize and model the ICDs, the objective was revised to achieve the following goals:

1. Identify the ICD technologies that are the most suitable for solvent processes,
2. Provide the technology developers with some test data from the screening tests and an opportunity to further optimize their designs, and
3. Define a plan to conduct more comprehensive testing for the best-performing ICD geometries as part of a future work scope.

The technical committee also identified Phase 3 as an opportune time to capture acoustic test data generated from each of the ICDs so that the acoustic output from an ICD under known operating conditions could be used to better interpret the downhole condition along any producer well equipped with distributed acoustic sensing (DAS) fibre. Therefore, a third-party vendor installed DAS fibre and the associated data acquisition and recording equipment so that this data could be captured while screening tests occurred. Processing the acoustic data will be conducted by this third-party at a later date, outside of the scope of this project.

Since C-FER is not a developer or end user of the technology, it would have been difficult for C-FER to have project performance metrics that focused on specific thresholds related to technology implementation by industry; however, C-FER is able to indirectly contribute to the continued development of this technology by ensuring that there is success with meeting the immediate project objectives and by keeping a functional ICDs & Solvents Flow Loop available for the industry to access going forward. A summary of the main performance metrics associated with this project are listed below.

- Successful completion of an upgraded flow loop that is capable of hydraulically characterizing ICDs across a wide range of operating conditions, including the use of propane, butane, diluent, water, nitrogen gas, and mineral oil.
- Development of a team of highly skilled personnel who are able to operate and maintain this new facility so that the industry can gain value from it in the future.
- Participation of four ICD vendors, primarily Alberta small to medium enterprises (SMEs), and three end users of the technologies (i.e. operators).
- Development of any required testing procedures followed by successful completion of initial “screening” testing of eight ICD geometries, with the primary goal of identifying the ideal geometries for enhanced SAGD and pure solvent recovery applications.

- Release of at least one publication that showcases the project work and associated benefits for the industry and the Province of Alberta.
- Outfitting of one JIP Participant's SAGD production well with one of the tested technologies within three years.
- Completion of the project without any recordable safety incidents (e.g. serious injury, lost time, medical aid).

Some of these performance metrics are explored in more detail in Section 4.

3. METHODOLOGY

3.1 Original ICD Characterization Flow Loop

The original ICD Characterization Flow Loop was capable of testing with oil, water, steam, and nitrogen gas at conditions representative of SAGD. The operational limits of the original facility are provided in Table 3.1. The high pressure and temperature capabilities of the equipment meant that much of the original facility could be utilized in the upgraded facility, with some limitations.

Some of the key components of the original flow loop that were utilized as part of the upgraded flow loop include:

- *Injection Pump*: a positive displacement metering pump with variable frequency drive (VFD) used to control the liquid flow rate of water or oil at high pressures and temperatures. Since this is a piston-style pump that is unable to fully seal the process fluid from the surrounding atmosphere, it could be used for high-temperature water in the new facility but not for safely pumping liquid solvent.
- *Make-up Water Pump*: a high-pressure positive displacement pump with VFD used to add more distilled water into the facility to replenish any water that exits the facility as a vapour during testing.
- *Coriolis Flow Meters*: three meters used to measure the flow rate of liquid and gas entering the ICD and exiting the separator vessel.
- *Instrumentation*: high-accuracy pressure and temperature transmitters used to determine the fluid properties at various locations throughout the flow loop.
- *Control Valves*: remote-actuated valves used throughout the flow loop to control system pressures and gas flow rates, and to flash steam at the ICD inlet. High-temperature steam-service manual valves were also used throughout the loop for isolation or bypassing of sections of piping.
- *Pressure Vessel*: a stainless-steel pressure vessel used for pressure control in the original ICD Characterization Loop that was repurposed for storing flammable solvents at high pressure to enable injecting solvent into the process during high-pressure testing with steam.
- *Data Acquisition System and Software*: collection of hardware and signal conditioning equipment for over 50 sensors, and control systems to allow for remote and unattended safe operation of all process equipment and control valves in the flow loop. It also included the previously developed software used for calculating key variables of interest, such as fluid properties, volume flow rates, and gas fractions.

System Variable	Operational Limits	
	Minimum	Maximum
ICD Inlet Pressure	100 psig	925 psig
ICD Inlet Temperature	20 °C	270 °C
Liquid Volume Flow Rate	0 m3/d	25 m3/d
Nitrogen Gas Flow	0 kg/min	1 kg/min
ICD Inlet Steam Quality	0%	10%
ICD Differential Pressure	0 psig	150 psig

Table 3.1 Original ICD Characterization Loop Capabilities

3.2 Methodology for Design Challenges

The two primary challenges during the design phase included safely incorporating the addition of a second pump capable of pumping high-temperature solvent in parallel with the already existing pump, and safely managing waste solvent vapours. For each of these challenges, safety was a key factor in the design solution, and all the relevant standards were followed to ensure a safe design.

3.2.1 Facility Containment Location

The original intent of the initial project proposal was to redesign the flow loop to be housed within C-FER's Special Environment Chamber (SEC), which is situated inside of C-FER's Special Environments Laboratory (SEL). This would enable C-FER to utilize existing infrastructure for handling hazardous materials, as shown in Figure 3.1, and to assemble the flow loop equipment inside the SEC such that the equipment could be blanketed with nitrogen to create an inert atmosphere. In the event of a solvent leak from the process, there would be no potential for an explosive atmosphere to be present.

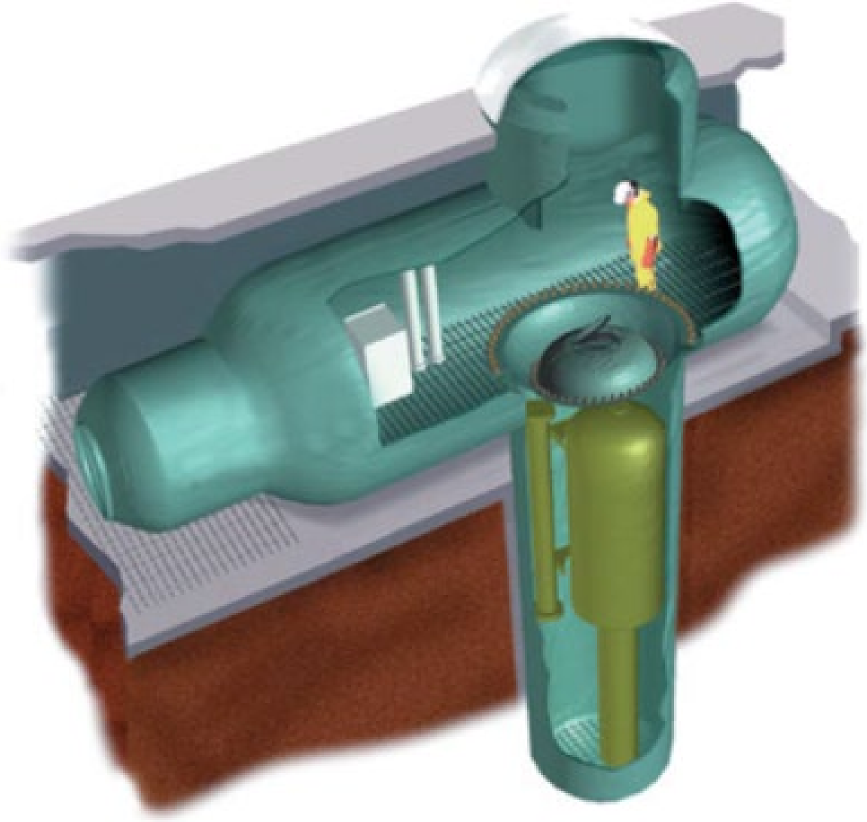

Figure 3.1 C-FER's Special Environments Chamber (SEC)

As part of the detailed design process, the facility location was reassessed and C-FER found that there were several significant benefits associated with using a separate containment location outside of the SEC, including the following:

- There is a safety risk associated with employees working in the SEC, as it must be treated as a confined space.
- There are cost savings associated with not needing to work within the difficult access confines of the SEC.
- There is more flexibility with designing features of the containment system, such as ventilation and access points.
- It would be easier to accommodate modifications to the facility at a later date.

C-FER chose to design a new outdoor structure in C-FER's yard to contain the facility and minimize the risk of exposure to personnel. The structure consists of a heavily modified storage container (or "seacan"), shown in Figure 3.2. Key features of the structure include insulation and heating appropriate for outdoor conditions; generous access doors for easy access to setup, maintenance, and testing; ventilation with redundant back-ups; and a rooftop platform for holding equipment. An extra layer of containment in the event of a failure is provided by a wall of concrete blocks assembled around three walls of the structure, while the driveway in front of the structure has access restricted during testing.

C-FER also worked with the City of Edmonton to review the structure design with an Edmonton Fire Marshall and a fire protection engineer before acquiring a building permit and completing a formal inspection.

Figure 3.2 ICD Solvent Testing Facility

3.2.2 Hazardous Location Design

The use of propane, butane, or diluent as test fluids in the facility, and the move from the SEL with the nitrogen atmosphere, meant that there was potential for an explosive atmosphere to form in the event of process leaks or a piping failure. Following the requirements of the Canadian Electrical Code and Alberta Occupational Health and Safety Code, the facility was designed as a Class 1 Zone 2 hazardous location. This included ensuring that there was sufficient ventilation to prevent the buildup of flammable vapours inside or around the seacan, and that all electrical equipment to be used was approved for this hazardous zone classification.

A thorough review was carried out of all the existing electrical equipment and instrumentation to ensure suitability for hazardous location use and, in certain situations, new equipment was sourced to ensure all required equipment had the required approvals. The new equipment required for the hazardous location included specialized electrical circulation heaters, a replacement motor for a positive displacement pump, resistance temperature detector (RTD) probes, and appropriate sealing glands and cables for all instrumentation being utilized in the facility.

C-FER, with the help of an electrical engineer from Innotech Alberta, prepared a detailed electrical design package including the hazardous zone classification, hazardous zone locations, specification of equipment inside the zone, and electrical barriers outside the zone. This design package was reviewed and approved by this third-party electrical engineer, an electrical permit was issued, and a final inspection of the system was completed.

3.2.3 Storage and Handling of Solvent Test Fluids

Before the solvent test fluids could be sourced, C-FER needed to ensure that procedures were in place for the safe storage and handling of the solvents. This was especially important for ensuring that the solvents could be safely transferred into the flow loop.

Propane and butane were both sourced in cylinders that were outfitted with a unique dual-port valve: one port connected to a dip tube that extended to the bottom of the cylinder, and one port connected to a gas headspace at the top of the cylinder. The top of the cylinder was pre-charged with inert nitrogen. A statically grounded hose bonded the cylinder to the flow loop to minimize the potential for sparking while the hose was connected or disconnected. A second statically grounded hose was then connected to the cylinder to pressurize the cylinder gas headspace using C-FER's nitrogen supply, which displaced the liquid solvent through the dip tube, through the hose, and into the flow loop solvent injection vessel. Two pictures showing the solvent supply cylinder and the solvent storage vessel are shown in Figure 3.3.

For high-temperature steam tests with vaporized solvent, the solvent would be pushed from the solvent storage vessel using a nitrogen gas cap so that it would flow into the tubing upstream of the ICD inlet. For low-temperature pure-solvent tests, the solvent would be fully pushed from the solvent injection vessel through the flow loop tubing and into the main separator vessel, so that the pumping systems could then circulate it.

Figure 3.3 Solvent Cylinder (Left) and Solvent Injection Vessel (Right)

Diluent was provided to C-FER in barrels by one of the industry partners. The diluent was sourced directly from one of their diluent supply pipelines so that it was representative of the multi-component mixture that would be used in the field with a diluent-based solvent process. Since there was a possibility of the presence of H_2S, C-FER established a procedure to assess the H_2S concentration using an appropriate respirator, personal monitor, and probe. After finding a small amount of H_2S, C-FER sourced an H_2S neutralizer and established a procedure to add the neutralizer to the diluent and monitor H_2S concentrations until they were confirmed to be zero. Once the diluent was free of any remaining H_2S, it was then pumped from the barrels into the flow loop using a dedicated diaphragm pump.

3.2.4 Designing for Diluent

The expansion of the project scope to include diluent testing added additional design challenges. C-FER's typical testing procedure involves venting the generated vapours in an open loop while the liquid is recirculated via the pump in a closed loop. The multi-component mixture of diluent would result in the lighter components venting first, thus changing the composition of the diluent left in the flow loop.

In consultation with the JIP Participants, it was determined that a significantly higher cooling capacity heat exchanger would be needed to cool and condense any vaporized diluent to minimize the amount of vapour that would be released from the system. Calculating the flashing and condensing behaviour of the diluent was difficult without proprietary software; therefore, C-FER worked with a third-party consultant and one of the industry partners to complete some modelling surrounding the diluent process requirements and potential release rates to ensure that the fluid properties would remain consistent enough over the course of a test and that the release of any of the hazardous constituents that made up the diluent would remain below allowable release levels. C-FER used these modelling results to ensure that an appropriate plate-style, dual heat exchanger system was procured for the facility.

3.2.5 Vapour Disposal

C-FER reviewed the project plan with Alberta Environment and Parks and received guidance surrounding allowable release limits from the “Alberta Ambient Air Quality Objectives and Guidelines Summary” document (6). Using this information, C-FER designed the system to ensure that the amount of solvent vapour released would be below the allowable release concentrations through minimizing the concentration of solvent vapours leaving the system through vapour dilution and further diluting any released gas with the surrounding air by discharging the diluted vapours as high as practicable and with a high discharge velocity. The high gas velocity would result in significant mixing and dilution of the vapours in the surrounding air.

3.3 Major New Equipment

Some of the key components of the new flow loop that were procured by C-FER include:

- *Solvent Pump*: a positive displacement diaphragm metering pump with “remote heads” and a VFD to control the liquid solvent flow rate at high pressures and temperatures. Unlike the piston pump used for pumping water or oil, the solvent pump uses diaphragms that maintain sealed pump heads, as well as remote heads that keep the high-temperature process fluid from directly contacting the diaphragms.

- *Separator Vessel:* a horizontal separator vessel allowed sufficient fluid residence time for effective separation of water and hydrocarbons to allow for testing of water/hydrocarbon mixtures. A nitrogen gas cap in the vessel was also used to control the system pressure.

- *Exhaust Fan:* a large blower fan, or “dilution blower”, used to dilute any released vapours with the surrounding air. Additional dilution of the air/vapour mixture into the surrounding air also occurred due to the high discharge velocity from the exhaust fan stack.

- *Knockdown Vessel:* a large, vertical separator installed between the horizontal separator and exhaust system for two purposes: to allow some liquids to be knocked-out before heading to the exhaust system, and to act as a dampener in the event of a large solvent vapour release by capturing the vapours in the vessel so they could be released slowly to the ambient.

- *Heat Exchangers:* a dual-heat exchanger with an intermediate oil circulation loop that allows heat to be removed from the flow loop process line to a high-rate cooling water system located inside of the C-FER building.
- *Instrumentation*: liquid level sensors, lower explosive limit sensors, a benzene detector, RTDs, and other instrumentation with Class 1 Zone 2 certification.

The installation and use of this equipment, along with the final flow loop capabilities and specifications, are provided in more detail in Section 4.

4. PROJECT RESULTS

4.1 Phase 1: Project Planning and Detailed Design Results

The initial project planning activities from this first phase of the project yielded several key results that set the requirements of the testing program and the facility design. The detailed design activities proceeded in parallel, using the results from the detailed design work to inform the project participants of cost and schedule implications. The final results of the project planning included an updated test facility operational window, a modified testing strategy, and a new proposed test matrix.

The testing strategy was updated to test up to eight ICDs, rather than four, with a reduced number of screening tests to be conducted one each ICD before selecting a subset of ICDs for more in-depth testing as part of a future work scope. This strategy enabled more manufacturers' technologies to be evaluated and a greater opportunity to identify technologies with promise for use in different solvent applications. The reduced testing scope still captured enough data to identify technologies with promise, but minimized the cost of testing additional technologies that were found to not be well suited to solvent applications. Furthermore, the testing strategy was modified from fully testing one ICD at a time with a sequential change between test fluids to testing all the ICDs with a given test fluid before switching fluids. This allowed for greater testing efficiency.

The potential range of operating conditions for an ICD in the field was first established for each of the recovery applications to help identify the operating range of the new flow loop. The final screening test matrix is described below, with values referring to the operating conditions at the ICD inlet:

- *Single-phase Water*: establish a baseline hydraulic performance curve with only liquid. This was conducted at 40 °C and 1.8 MPa with four volume flow rates per ICD.

- *Pure Propane*: evaluate ICD performance for pure solvent recovery applications with propane. This testing was conducted at 60 °C, pressures ranging from 2.1 to 3.1 MPa, and a mass flow rate of 4.51 kg/min. Eight test points per ICD simulated five subcool conditions (specified by degrees Celsius below saturation, ranging from 0 to 20 °C) and three vapour mass fractions (ranging from 1% to 5% vapour fraction, by mass).

- *Pure Butane*: evaluate ICD performance for pure solvent recovery applications with butane. This testing was conducted at 60 °C, pressures ranging from 0.6 to 1.0 MPa, and a mass flow rate of 5.46 kg/min. Eight test points per ICD simulated five subcool conditions (specified by degrees Celsius below saturation, ranging from 0 to 20 °C) and three vapour mass fractions (ranging from 1% to 5% vapour fraction, by mass).

- *Water with Nitrogen Gas Injection*: evaluate performance for solvent-enhanced SAGD and late-life SAGD recovery using nitrogen gas injection. This testing was conducted at 220 °C, pressures ranging from 2.2 to 3.3 MPa, and a mass flow rate of 8.65 kg/min. Eight test points per ICD ranging from 20 °C subcool to 5% vapour mass fraction, with an additional 12 test points including the injection of varying rates of nitrogen gas, for a total of 20 test points per ICD.

- *Water with Propane Vapour Injection*: evaluate performance for solvent-enhanced SAGD with non-condensable solvent vapours using propane injection. Conducted at 220 °C, pressures ranging from 2.2 to 3.3 MPa, and a mass flow rate of 8.65 kg/min. Six test points per ICD ranging from 20 °C subcool to 3% vapour mass fraction, with an additional 12 test points including the injection of varying rates of propane gas, for a total of 18 test points per ICD.

- *Water with Butane Vapour Injection*: evaluate performance for solvent-enhanced SAGD with non-condensable solvent vapours using butane injection. Conducted at 220 °C, pressures ranging from 2.2 to 3.3 MPa, and a mass flow rate of 8.65 kg/min. Six test points per ICD ranging from 20 °C subcool to 3% vapour mass fraction, with an additional 12 test points including the injection of varying rates of butane gas, for a total of 18 test points per ICD.

- *Water and Diluent with Low Water Cut*: evaluate performance for pure solvent recovery applications involving steam and diluent. Conducted at 101 °C, pressures ranging from 0.5 to 0.8 MPa, and a mass flow rate of 5.56 kg/min. Eight test points per ICD ranging from 20 °C subcool to 5% vapour mass fraction.

- *Water and Diluent with High Water Cut*: evaluate performance for pure solvent recovery applications or enhanced SAGD with diluent injection. Conducted at 149 °C, pressures ranging from 1.5 to 2.2 MPa, and a mass flow rate of 8.5 kg/min. Eight test points per ICD ranging from 20 °C subcool to 5% vapour mass fraction.

The detailed design work was important for preparing the necessary design documentation to guide the construction of the facility. Specifying appropriate equipment and estimating equipment costs were completed for several major facility design options to help the JIP Participants agree on a final work scope that provided the most value in a cost-efficient manner. Process design deliverables that were developed included a Process Flow Diagram showing process equipment, control layout, and instrumentation; and a facility plan view for the process equipment. Additional key design activities focused on ensuring safe operation, including the new facility containment barriers and location, requirements for disposal of waste solvent vapours, and the electrical design package specifying the hazardous zone classification, electrical connection locations, and electrical equipment requirements.

One of the important philosophies during the design process was to maximize the operational flexibility of the system for future testing. This was not only meant to ensure that it could be used for the full range of operating conditions that would be required to fully characterize an ICD, but to further expand the operating window to enable testing to occur at higher pressures, temperatures, and gas fractions, as well as for a wider range of flow rates. In addition, the flow loop was designed to allow testing with mixtures of oil and water, and potentially mixtures of bitumen, solvent, and water, to further investigate the impact of fluid viscosity, emulsions, and gas exsolution from oil on ICD performance.

The project success metrics for this phase were completed as expected, including agreement between industry partners and C-FER upon the project work scope, testing strategy, and facility capabilities, as well as completion of the detailed design package to guide the procurement and setup work.

4.2 Phase 2: Procurement and Construction

The overall result of this phase was a fully constructed and commissioned facility with a flow loop capable of operating at the test conditions specified in the previous phase. Achieving this overall result required a number of significant efforts with key results as described below.

- The modified seacan was set up outside of C-FER's building to safely house the facility. Safety systems installed to allow for testing in the facility include electrical heating, container exhaust ventilation, a high-rate exhaust fan to dispose of vapours from the flow loop, a structural platform above the container to support an exhaust fan and prevent the accumulation of snow on top of the seacan, and a concrete blast barrier around the container. Additional setup work was completed to allow for construction and testing activities in the facility, including the installation of cable trays, power, heat exchanger lines, air lines, and pressurized gas lines connecting the container to C-FER's building.

- A building permit and an electrical permit were required for this facility. Obtaining a building permit included reviewing the facility design with a Fire Marshall and fire protection engineer from the City of Edmonton to ensure that the facility met the requirements of the National Fire Code of Canada. Obtaining an electrical permit and completing a formal inspection was important to ensure that all electrical work in the facility met the requirements of the Canadian Electrical Code for a Class 1, Zone 2 hazardous location so that it would safely operate with flammable test fluids.

- A pressure piping system was constructed with threaded, flanged, and tube fitting connections and line sizes from 1/8-in tubing to 3-in pipe. Construction followed C-FER's Pressure Piping Quality Management System to ensure that the system was built in accordance with the Alberta Safety Codes Act, ASME B31.3, and other relevant codes, as required. A key result of this was a set of completed hydrostatic or pneumatic pressure tests for all piping in the facility prior to commissioning.

- Eight ICD test specimens were installed in the flow loop for testing. Four ICD vendors signed agreements with the JIP and C-FER to provide six unique ICDs, while the JIP provided two ICD geometries for comparison. In addition to receiving and installing the ICDs in the flow loop, design drawings were provided by each vendor and reviewed by C-FER, operating limits of the ICDs were confirmed to align with the worst-case operating condition of the flow loop, and a pressure test was completed with all the ICDs to verify the integrity of the ICDs and connected piping system prior to operating the flow loop.

- Instruments, wiring, and data acquisition hardware for over 100 instrument signals were installed and commissioned. This portion of the scope was excluded from the electrical permit for powered equipment; however, it still required significant effort to meet the requirements of a Class 1, Zone 2 hazardous location, including: explosion-proof instrument housings, sealing glands for all wired connections, shielded cables with supports and barriers to prevent damage, and electrical barrier devices prior to the hazardous zone boundary to eliminate the potential for sparking to occur inside the hazardous zone. The result of this effort was a commissioned instrumentation and control system, where each individual instrument signal was formally verified.

There were significant challenges during the construction phase due to the onset of the COVID-19 pandemic. Many equipment suppliers were affected by the challenges of the pandemic as they shifted their workforces to remote work and struggled to procure the necessary specialty parts or raw materials needed to fabricate the equipment. In some cases, the suppliers were facing difficulties operating at normal capacity due to reduced workforces. C-FER also had to adapt by sending many employees home and staggering the work hours for the remaining employees working at C-FER to minimize the risk of COVID-19 transmission. This led to some additional time spent by C-FER, and associated costs, to complete this phase of work.

Despite these challenges, Figure 4.1, Figure 4.2, and Figure 4.3 show the successfully constructed and commissioned flow loop, capable of testing ICDs within the following operating ranges:

- Temperature: 20 to 270 °C;

- Pressure: 0 to 6 MPa;

- Flow rates: 0 to 30 kg/min (~ 0-48 m^3/day);

- Liquid Density: 400 to 1,000 kg/m^3;

- Liquid Viscosity: 0 to 100 cP;

- Water Cut: 0 to 100%; and

- Steam/Gas Fraction: at a minimum, 5% (by mass) at the ICD inlet, but as high as 10% by mass if operating in specific portions of the flow loop operating window.

Figure 4.1 Completed ICD & Solvents Flow Loop

Figure 4.2 Internal View of the Facility

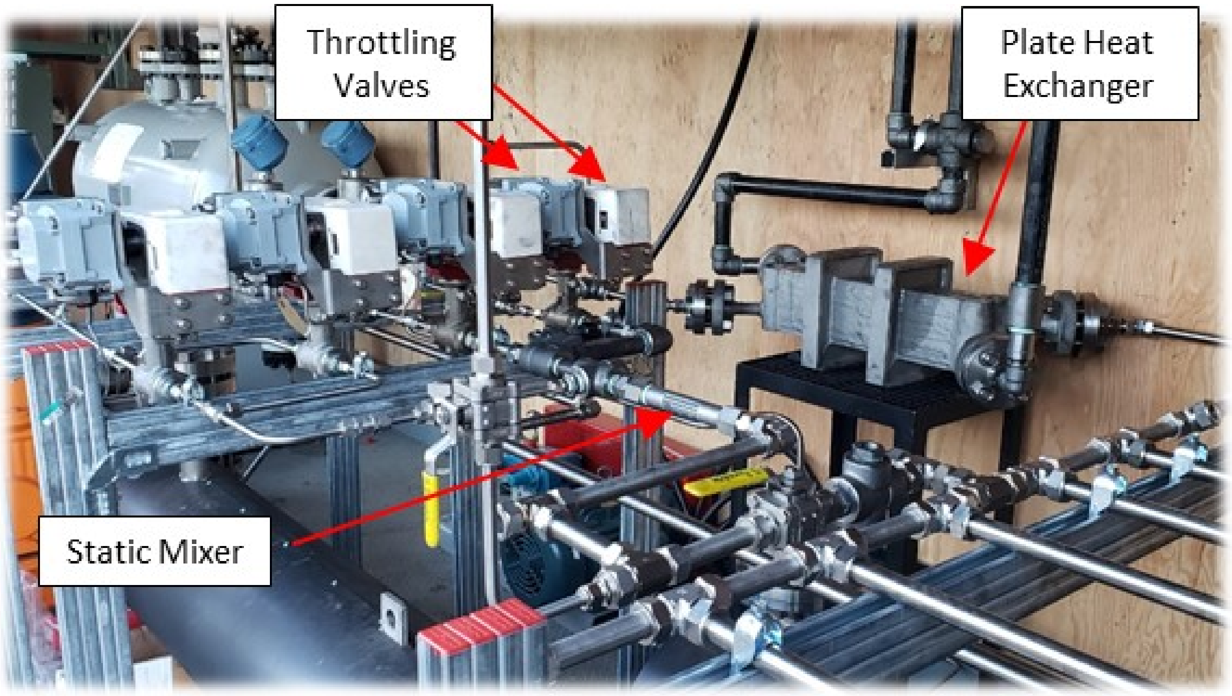

Figure 4.3 Key Design Components in the Facility

4.3 Phase 3: Inflow Control Device Screening Testing

Screening testing of the eight ICDs was successfully completed with test data captured at the test conditions outlined in Section 4.1. As previously described, the testing strategy proceeded with one test type and fluid at a time for all ICDs before progressing to the next test type (and corresponding test fluid). The chronological progression of testing and the importance of the results are described in this section.

Testing began with the single-phase water tests at 40 °C before progressing to testing water with nitrogen gas injection at 220 °C, as both of these tests were similar to previous ICD testing work at C-FER and provided a well-understood trial of the new facility before progressing to testing with hazardous test fluids. The preliminary single-phase water results were communicated to the ICD vendors early as an initial quality check to ensure that the results appeared as expected. Testing with water and nitrogen at 220 °C was the first of the multi-phase tests to explore the sensitivity of the ICD to water flashing to steam or NCG breakthrough. Some sample results for one of the ICDs with water and nitrogen at 220 °C is shown in Figure 4.4, where the key measured variable, the ICD differential pressure, is plotted against two control variables of interest: the amount of injected nitrogen and the initial enthalpy of the water (which is quantified by the subcool or steam fraction upstream of where the nitrogen is added). These test results help to show how restrictive the ICD becomes at different operating conditions involving the production of steam or gas, including the hydraulic difference in performance whether the gas consists of pure steam or is partially composed of an NCG. This was further investigated with the injected propane and butane tests.

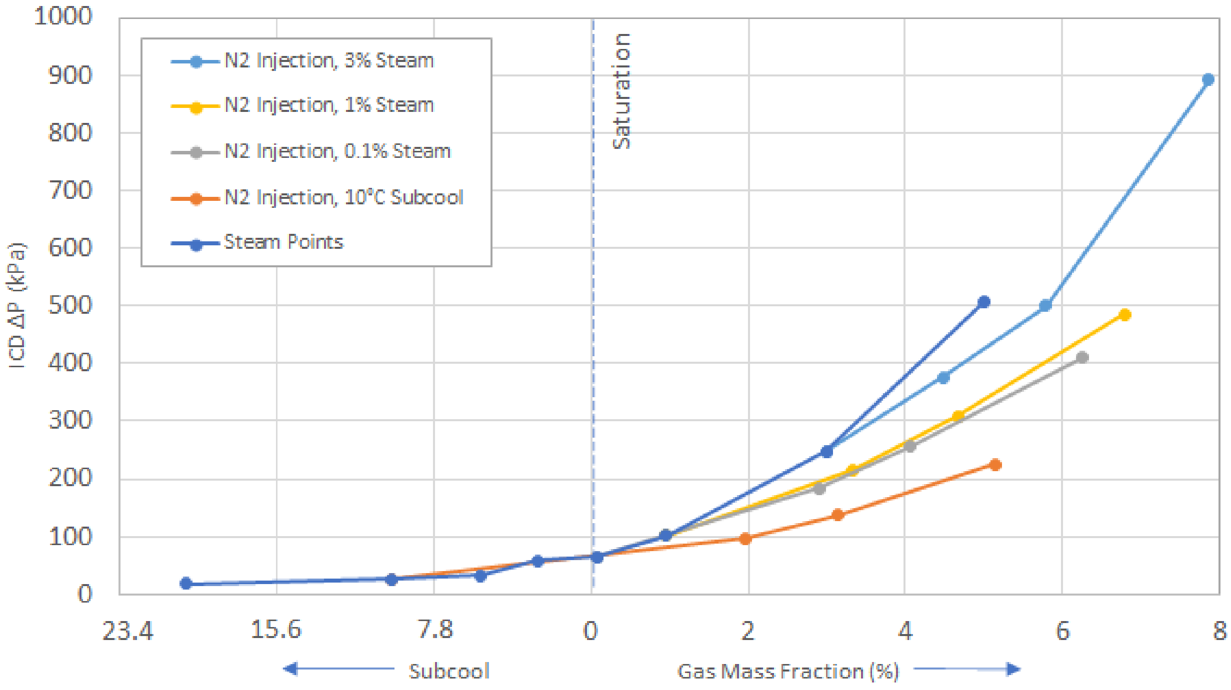

Figure 4.4 Sample Results: Water with Nitrogen Gas Injection

Testing then progressed to water with propane injection and then water with butane injection at 220 °C. These tests were conducted next due to their similarity to the previous tests involving water and nitrogen, and due to their being the next logical step with incrementally testing the new capabilities of the upgraded flow loop with the use of solvents. The goal of these tests was to investigate the impact that various non-condensable solvent gases have on the performance of each of the ICDs. These tests were successfully completed as planned.

Continuing this risk management strategy of incrementally adding additional complexity and safety risk after successful operation during the previously completed test, the liquid butane tests were completed next due to their relatively low vapour pressure. Once these tests were successfully completed without evidence of solvent leakage from the process, testing then progressed to the use of pure propane (similar to testing with pure butane, but with a much higher vapour pressure). The butane and propane tests were successfully completed as planned; however, an unexpected behaviour occurred in the new facility when the nitrogen gas that was used as an inert gas cap in the separator vessel dissolved into the liquid butane or propane, and then came out of solution at the ICD inlet, as evidenced by an unexpected ICD inlet temperature decrease. The consequence of this dissolved gas was additional gas being present at the ICD inlet with many of the test points, as well as the added complexity of having this gas mixture include a condensable (solvent) and non-condensable (nitrogen) component. To minimize this behavior, C-FER first modified the test procedure to minimize the amount of nitrogen gas that was dissolving. Next, C-FER updated the gas fraction calculations at the ICD inlet and discharge to account for the nitrogen coming out of solution.

The final testing was conducted using water and diluent mixtures, beginning with the low water cut tests at 101 °C. This testing continued to use the modified test procedure from butane and propane to minimize the amount of nitrogen dissolving in the test fluid. This testing was also the first test to utilize the full combination of process equipment in the facility to circulate two parallel fluid streams, water and diluent, and to recondense the multicomponent mixture of the diluent. C-FER used approximate diluent fluid properties obtained from one of the project industry partners to target a range of test conditions and successfully captured data for all eight ICDs. The collected diluent data was then shared with this industry partner so that they could post-process it using their HYSYS software for the purpose of calculating more accurate values for the fluid properties and gas fractions at the ICD inlet and discharge.

Data from each set of tests was summarized into tabular form with a single set of mean measured and calculated properties for each test point. Post-processing of the data included determining the most stable window of data for each test condition, reviewing the thermal stability for the vapour fraction calculations, and updating the fluid property calculations for all tests with dissolved nitrogen (similar to what was done by one of the industry partners using HYSYS software for the diluent tests). These summarized tables and a common set of plots for each test were distributed to the JIP Participants and then to each ICD vendor for their respective ICDs, which included an average of 75 total test points for each ICD tested.

The distribution of summary data and figures was a key result of this phase, which allowed for follow-up discussions with both the JIP Participants and ICD vendors to assess the data and evaluate the technologies tested. First, C-FER facilitated meetings amongst the JIP Participants to review the test data and discuss any key hydraulic performance characteristics. Following this, the JIP met with each individual ICD vendor to discuss these results and potential areas for further development, including more thorough characterization and reliability testing. The JIP Participants ultimately selected three technologies of promise for further testing in a future work scope. The completion of the screening testing, distribution of data, and feedback meetings with vendors completed the technical success metric for this phase.

5. KEY LEARNINGS

5.1 Flow Loop Design

Safety was a key factor in the design. C-FER originally planned to install the new facility inside of one of C-FER's SEC with nitrogen gas flooding inside the chamber to create an inert, non-hazardous atmosphere. Although this was beneficial for ensuring that there would never be the potential of a flammable atmosphere, C-FER reassessed and determined that it would be safer to construct the flow loop in a separate containment box outside of the C-FER building as this would eliminate the hazards associated with employees working in a confined space. The cost savings associated with having the flow loop in this separate containment unit were also advantageous. C-FER used prior experience working in the field in hazardous locations, a thorough review of the Canadian Electrical code, and working with an electrical engineer from Innotech Alberta to design a well-ventilated, accessible, and safe testing facility that would provide maximum flexibility with using and maintaining the facility in the future.

C-FER originally didn’t expect to test with a multi-component fluid mixture, which resulted in some additional challenges associated with safe operation. C-FER approached a third-party consultant to conduct some fluid modelling, and worked with one of the industry partners to calculate the required heating and cooling loads, to ensure that the flow loop could meet all the target operating conditions safely and with minimal solvent vapour release.

5.2 Flow Loop Construction and Commissioning

Prior to constructing this new flow loop, C-FER had implemented a new quality control program to meet the requirements of the Alberta Boiler Safety Association (ABSA) pertaining to the ASME B31.3 code. This was one of the first major projects at C-FER that followed this quality program, which helped improve the overall quality and safety of the new flow loop; however, it unfortunately required more effort than was originally expected. C-FER now has greater knowledge of the implications of constructing a complex flow loop that follows ASME B31.3, as well as how best to fulfill the quality program requirements, which will enable C-FER to conduct this type of work more efficiently going forward (e.g. further upgrading the new flow loop, or creating a new facility for an alternate purpose).

Constructing a flow loop in a Class 1 Zone 2 location also took more effort than originally expected. Although this was identified as a requirement during the detailed design portion of the project, and suitable equipment had been identified for use in the hazardous zone, C-FER was unaware of all the details associated with isolation barriers, cable selection, and cable routing that would only become known once the Phase 2 work commenced. Similar to the lessons related to ABSA, the information and experience gained during this work was important for ensuring that C-FER was able to effectively complete regular project hazard assessments and write appropriate safe work procedures associated with carrying out the Phase 3 work. In addition, this experience will be extremely valuable for executing future work in this area, including working with third-parties, such as electrical engineers, electricians, and the City of Edmonton, during the detailed design phase, to ensure that all the details of the design are finalized and permits are granted before moving to the construction stage.

Finally, working through a pandemic certainly proved to be a challenge in a number of areas. Maintaining regular project communication between project personnel working from home, those working during typical daytime shifts, and those working during evening shifts was the biggest challenge within C-FER; however, various Microsoft Teams features were implemented to enable effective project communication during this time, as well as COVID-19 safe work procedures that enabled the on-site work at C-FER to progress safely and with minimal delays. The use of Teams enabled C-FER to transition to a partially remote project team and to successfully complete the Phase 3 work as it enabled a reduced number of project team members to be present at C-FER during testing (allowing more adequate distancing for the personnel present on-site). A further benefit includes reducing the risk of delays with future projects using this new facility due to continued uncertainty surrounding the pandemic and associated COVID-19 restrictions since a client interested in participating real-time during testing would still be able to do so from a remote location.

5.3 Inflow Control Device Testing

5.3.1 Test Results and Identification of Promising Inflow Control Devices

The primary learning gained from the screening tests was which ICD geometries exhibited the best hydraulic performance characteristics to prevent or minimize the entry of steam, solvent vapours, and NCGs into the production well, while preferentially allowing liquid water, solvent, and bitumen to be produced with minimal restriction. Of the eight ICD geometries tested, the industry partners identified three of the ICDs as being very effective at allowing the production of liquids and restricting production when gases were present, whether the fluid was steam, steam with nitrogen, steam with solvent, or pure solvents. A fourth device also appeared to exhibit promising performance characteristics, but this device was far too restrictive, which limited the number of test points at higher gas fractions that could be captured.

Sample data from one of the promising ICDs is shown in Figure 5.1. This device showed a strong sensitivity to increasing gas production, and the sensitivity increased as a higher portion of the gas passing through the ICD consisted of steam. This aligned with expectations since the total volume of gas passing through the device should increase more with steam than with NCG (i.e. the volumetric contribution of steam to the vapour phase comes from the expansion of the existing steam vapour passing through the device, as well as any additional liquid water flashing to steam as the pressure drops; in comparison, no additional mass of NCG is created as the fluid pressure drops across the device).

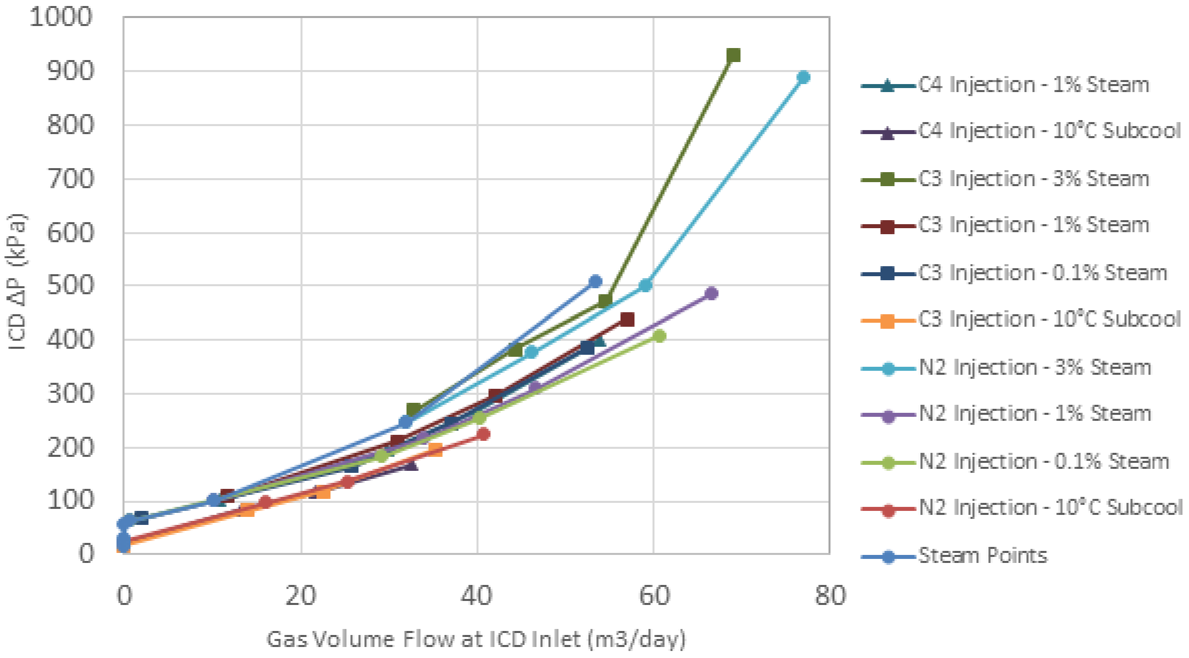

Figure 5.1 Sample Data: Steam with Nitrogen, Propane or Butane Injection, Device #1

One key lesson gained from testing is that the ICD performance with one NCG could be modelled based on the performance of that ICD using an alternate NCG. Sample data showing this behaviour with one of the control ICDs is provided in Figure 5.2, where the performance with nitrogen, propane, and butane appears consistent as long as all other conditions at the ICD inlet are the same. For this reason, future thermal testing to predict the performance of an ICD operating in high-temperature steam and solvent conditions could likely be conducted using only nitrogen gas injection. This learning was extremely important for reducing safety risk and lowering the testing costs associated with future work.

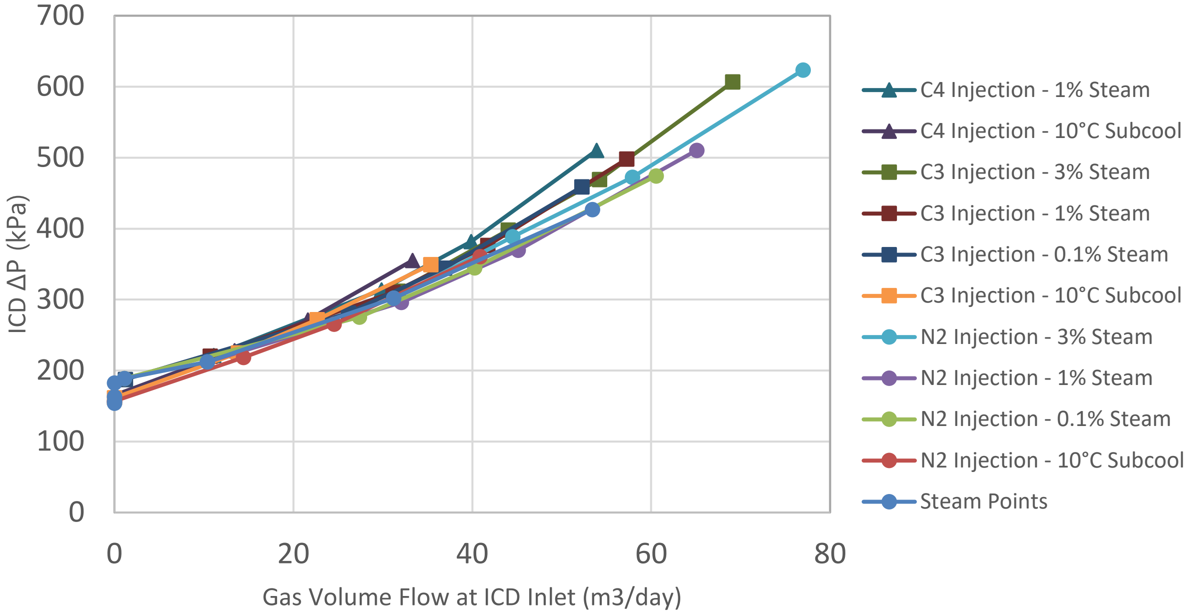

Figure 5.2 Sample Data: Steam with Nitrogen, Propane or Butane Injection, Device #2

In addition to promising performance in thermal conditions involving steam, these same four promising devices exhibited positive performance with flashing butane and a flashing mixture of water and diluent. Some sample data is shown in Figure 5.3. The devices were able to reach a "multi-phase choked flow" condition with 60 °C butane (100% water cut) and 101 °C diluent/water mixture (15% water cut). However, unlike the butane and diluent, pure propane did not show a transition to choked flow during the tests, which was likely due to the propane having a much higher ICD inlet pressure than the butane and diluent/water mixture tests.

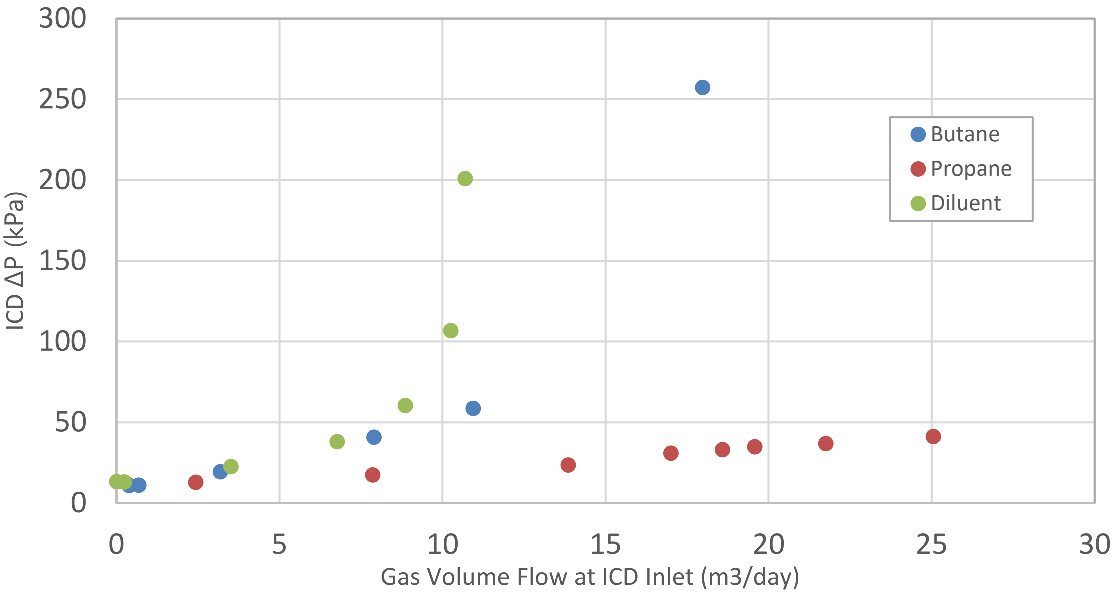

Figure 5.3 Sample Data: Flashing Propane, Butane, and Diluent/Water Mixture (15% Water Cut)

Unfortunately, not all of the ICDs performed as well. One of the vendor-supplied devices functioned similarly to one of the control devices that was tested (i.e. a sharp-edged orifice). The second control geometry provided by the JIP did exhibit better sensitivity to vapours and NCG than the poorly performing vendor device or the control orifice; however, it did not perform as well as the promising devices described above. Therefore, neither of the control ICDs or the above-described vendor-supplied ICD were identified as candidates for future testing.

There was one other vendor-supplied device that exhibited some unique hydraulic behavior, where it was effective at blocking NCGs but ineffective with any of the test fluids that had a portion flash from liquid to vapour. This behaviour was certainly unique compared to the other ICDs, so this device likely has promise in other recovery applications where blocking gas production at lower temperatures is key. Potentially, design optimizations to the device could enable it to effectively block flashing fluids as well. However, the inability of the device to resist production in conditions involving flashing, coupled with a very high flow resistance during testing with unsaturated liquids, resulted in this device also not being selected for future testing.

Based on these results, the industry partners agreed that four of the geometries should be considered for further testing as part of a future project, while four of the geometries should not be considered for future testing. However, since two of the devices that were identified as promising had very similar device architectures, the JIP also decided that it would be best to eliminate one of these two devices. Therefore, a total of three out of the eight ICD geometries that were tested during the screening round were identified as the ideal candidates to undergo more thorough testing in the future.

Overall, the testing was impactful with identifying the most promising devices to be fully characterized as part of a future scope of work outside of this project. In addition, the testing showed that the new test facility will be an important tool to enable the industry to continue developing and de-risking these most promising ICD technologies, as well as other ICD technologies of interest to the industry.

5.3.2 Testing Procedures

There were several key learnings during the Phase 3 work about how the tests were conducted and how the flow loop could be optimized that should help to further improve the efficiency of testing and quality of the generated data.

Testing in cold weather is always a challenge due to the condensation and freezing of released water vapour. This resulted in ice buildup on the dilution blower fan blades, as well as ice plugging of a lower section of pipe exiting from the flow loop on the way to the dilution blower fan. In addition, any activity that required access to the flow loop during cold weather required special considerations to prevent the low-temperature ambient air from flooding the facility and negatively impacting operations.

Going forward, C-FER will likely aim to avoid testing in the most extreme cold weather conditions; however, for situations with mild weather where the temperature does go below freezing, or when there is a significant and unexpected temperature drop during a test program already in progress, C-FER has identified some key facility and operational improvements. Since the release of water vapour can result in a slow buildup of ice on the exhaust fan blades, a safe work procedure was written to pause testing, lock out the exhaust fan, and safely remove any ice buildup off the fan blades. Future upgrades include a piping modification on the exterior of the seacan to prevent potential ice plugs from forming in the piping exiting the knockdown vessel, and to procure flexible coverings that can cover the overhead doors to minimize air exchange with the ambient when seacan access is needed.

The heat exchanger system was sized to accommodate high-rate heat transfer fluid circulation between the seacan and the C-FER building; however, C-FER found one of the heat transfer system pipes entering the building was quite hot. This was caused by natural convection of the circulation oil between the two heat exchangers; therefore, C-FER inserted a manual valve into the oil circulation piping to avoid any undesired natural convection from occurring.

There were some challenges with testing with pure propane and pure butane due to the dissolution of the separator vessel nitrogen gas into the liquid solvent, which came out of solution at the ICD inlet. C-FER has identified three go-forward strategies to manage this added challenge.

First, the testing procedure was modified to minimize this impact by decreasing the system pressure as close to saturation conditions as possible as this would minimize the amount of gas that dissolves in the test fluid. Once reaching this point, the test points were quickly captured, progressing from the highest gas fraction to the highest subcool test point, with the goal of minimizing the amount of time available for nitrogen gas to dissolve in the test fluid as the system pressure increased. Second, C-FER ensured that the gas composition and volume at the ICD inlet, including the contribution of the gas coming out of solution and the creation of any additional steam vapour, was quantified in the test results. Finally, one option that could be investigated in the future would involve substituting the nitrogen gas for an alternate noble gas that is less soluble in the test fluid. This would likely be helium, although the added cost of this gas (which is further exacerbated due to a current global helium shortage) would have to be further investigated.

In terms of ensuring that any future testing utilizing this facility can be completed in as safe of a manner as possible, there were a number of additional lessons learned that will help to guide future testing plans:

- Testing autonomous ICDs that can (expectantly or unexpectantly) “close” during testing can result in a difficulty maintaining a stable, target operating condition at the ICD inlet, or cause a sudden pressure spike upstream of the ICD inlet that could trip a pressure safety valve. Installing an autonomous ICD in parallel with a second “control” device (i.e. another geometry that has already been characterized) is a helpful strategy to mitigate this issue.

- Sealing flanges and piping/tubing connections became more important when dealing with solvents due to the potential for leaking solvent vapours into the hazardous zone. Therefore, it is important to conduct frequent leak checks after the first few thermal cycles to ensure that any leak points that form can be eliminated. As an additional risk reduction strategy, it is best to avoid placing electrical equipment directly under sealing surfaces.

- Despite the diluent Safety Data Sheet stating that it would not be present, or only present in trace amounts, C-FER found H_2S in the diluent at a concentration of approximately 100 ppm. These types of checks are invaluable for protecting the equipment from exposure to harmful chemicals and protecting the health of all project personnel. Therefore, C-FER established a procedure to assess the H_2S concentration using an appropriate respirator, personal monitor, and probe. If H_2S is present, C-FER will add an H_2S neutralizer, then recheck the concentration. The neutralizer will continue to be added (in small amounts, with sufficient waiting periods in between neutralizer additions) until the H_2S concentration is confirmed to be zero before the diluent is pumped into the flow loop.

6. OUTCOMES AND IMPACTS

6.1 Project Outcomes and Project-specific Metrics

Two knowledge and technology gaps were identified at the outset of the project. First, a knowledge gap existed regarding understanding how the performance of ICDs would change with the addition of multi-phase solvents. A technology gap also existed where ICD technologies had been optimized for SAGD production, but did not have design data or optimizations to apply the technology to processes such as solvent-enhanced SAGD, SAGD with late-life NCG injection, or pure-solvent recovery. An associated infrastructure gap was also identified since existing experimental facilities were not capable of testing with solvents.

The first outcome of the project was bridging the infrastructure gap with the successful design, construction, and commissioning of the new test facility that is capable of testing ICDs under conditions representative of the above-described recovery processes. The completed facility included expanded capabilities for testing with various combinations of steam, nitrogen, propane, butane, diluent, and oil for up to eight ICDs, which resulted in increased flexibility with the facility in all following work to address the knowledge and technology gaps.

The subsequent operation of the facility and testing of eight ICDs helped to address both the knowledge and technology gaps previously identified. Testing of the ICDs with the various fluid combinations, including solvents, resulted in several key learnings and knowledge about how different fluids affect the performance of the ICDs. This led to the selection of ICD technologies that showed the most immediate promise for solvent processes and which would be further tested or optimized in the future. The next step involving more detailed testing of a smaller number of ICDs as part of a future scope of work will have the important outcome of developing models for the ICDs, which can be implemented into reservoir and wellbore models of the operators planning development of these enhanced SAGD and pure-solvent recovery processes.

6.2 Clean Energy Metrics

The project investment target was met, which including financial contributions from the Government of Alberta and the industry partners, as well as C-FER's in-kind contribution of the original ICD Characterization Flow Loop, to make this work possible.

A number of project targets relating to highly qualified and skilled personnel (HQSP) in this sector were also met. At least four engineers and seven technologists at C-FER have contributed significantly to the success of the project, where three of these engineers and five of these technologists have become thoroughly knowledgeable about the operation and ongoing maintenance of the facility. This will certainly support C-FER with keeping the facility operational and the needed staff available to support the industry going forward. No specific project target was specified for the number of new jobs created, but one technologist was hired at C-FER to assist the Production Operations department, whose primary focus is the construction and operation of experimental facilities.

The main clean energy metrics for this project focus on implementation of the commercial technologies and the ensuing benefits, with the main project success metric having one JIP Participant install one of the tested ICDs in a field trial within 3 years. Further work is needed by both C-FER and the JIP Participants in this area, specifically with ensuring that some follow-up testing work of the most promising devices is completed so that detailed transient wellbore and reservoir models can be constructed. Other metrics associated with the future implementation of ICDs, which would occur once the ICDs begin to be installed on a bigger scale, include GHG-emission reductions in solvent-enhanced SAGD and pure-solvent recovery processes (2), and new jobs created for the manufacturing and installation of ICDs for future implementations.

6.3 Program-specific Metrics

The program-specific metrics for the project included the number of end users participating, with a target of at least three JIP Participants, and participation from enough vendors to test four unique ICDs. This metric was exceeded, with the participation in the project expanding to four JIP Participants, and with four vendors contributing six ICDs for testing.

Implementation of the commercial technologies in solvent processes has not yet occurred; however, these technologies should help to de-risk these other recovery processes, accelerating the transition to these new recovery processes, and to lead to corresponding reductions in cost, energy, and GHG intensity per barrel of produced bitumen.

6.4 Project Outputs

The project target of generating at least one publication was met with C-FER and the JIP co-authoring and co-presenting two presentations at industry events: one at the Inflow Control Technology (ICT) forum in 2020, and one at the Society of Petroleum Engineers' (SPE) and Canadian Heavy Oil Association's (CHOA) Slugging it Out Conference in 2021. Further publications are expected in the future from the JIP Participants or individual ICD vendors, including a presentation at the SPE Canadian Energy Technology Conference in 2022.

7. BENEFITS

7.1 Economic

The direct economic benefits of the project include employment over the course of the project with completing the planned construction and testing work. Of course, this employment will continue in the future as C-FER works to keep the facility maintained and operational to enable future testing to occur.

The more impactful economic benefits are associated with understanding how ICD technology can work effectively to help de-risk solvent-enhanced SAGD, SAGD with late-life NCG injection, and pure-solvent recovery applications. This should help the industry to accelerate adapting existing fields to enhanced SAGD processes, as well as initiate more field trials with processes involving pure solvents, to help enable the industry to take advantage of the longer-term economic benefits associated with these more efficient recovery applications (2). In addition, the improved efficiency and environmental performance due to reduced methane combustion and GHG emissions will likely help with increasing the volume of bitumen exported from Alberta. This will result in an increase in royalties for the province and attraction of investment for new projects.

Finally, it is expected that the use of ICDs will assist local oil and gas equipment suppliers, including their engineering and manufacturing teams, with designing, manufacturing, and deploying this technology. The Alberta Energy Regulator forecasted there may be 1,100 new SAGD well pairs in Alberta over the next 10 years (1). At 65 to 85 ICDs per production well, and assuming a unit price of CAD3,500 per ICD, the market value of these devices could range between CAD250M to CAD327M over the next 10 years.

7.2 Environmental

There are approximately 1,990 current and active SAGD well pairs in Alberta, as well as plans to build 1,100 more over the next 10 years (1). Each SAGD operation utilizes fairly similar downhole completions, meaning that ICD technology and a solvent-enhanced recovery process could potentially be combined in most SAGD operations in Alberta.

Environment Canada indicated that the total GHG emissions from the oil and gas industry in Canada may reach 200M tonnes of CO_2-equivalent per year in 2020, where the in situ oil sands production (almost exclusively in Alberta) is expected to account for ~25% of this total (5). SAGD production accounts for over 70% of all in situ production, so it is reasonable to expect that the widespread adoption of solvent-enhanced recovery technologies with ICDs would certainly be impactful on Alberta's total GHG emissions.

Baseline emissions for a SAGD well in Alberta have been estimated at 60 kg CO_2e/bbl (2). In the same source, the relative reduction in GHG emissions for various technologies was also considered, where steam solvent-enhanced processes had some of the best GHG reductions from the baseline at approximately 70% (i.e. down to only 20 kg CO_2-equivalent per bbl of bitumen).

There was no data found on the combined GHG impact of a solvent-enhanced thermal recovery process coupled with "ideal" ICDs. Although ICDs are expected to help further improve the efficiency of a well using NCGs and solvents, the main reduction in GHGs may not be due to the incremental reduction in GHGs from the use of ICDs, or even their ability to potentially deplete a well at a faster rate (i.e. slightly shortening the well life and the amount of time injecting steam); instead, their most important contribution may be as an enabling technology that helps operators reduce the overall risk associated with well control or integrity in these new recovery processes. Therefore, the primary benefit of ICDs may be a reduction in overall process uncertainty that helps enables operators to accelerate the move from conventional SAGD to the use of these more enhanced recovery applications.

Solvent-enhanced thermal recovery processes with ICDs should be able to be implemented in new developments and by converting existing SAGD operations. These are expected to proceed at different rates, with solvents/ICDs being implemented in new developments more rapidly than in existing wells. It was estimated that the annual GHG-emission reductions from the use of ICDs and solvent-enhanced thermal recovery may add to over 4M tonnes per year of CO_2e by 2027.

In addition, ICDs in these enhanced recovery processes will also help reduce water consumption by reducing the cumulative steam-to-oil ratio or, in the case of pure-solvent recovery, potentially eliminate the use of water altogether. This benefit will occur as soon as ICDs are implemented and last for the life of the well.

7.3 Social

The primary social benefit of this work is strongly tied to the environmental benefit: by reducing GHG emissions and water use at Alberta oilsands operations, these processes become far more sustainable. With this increased sustainability, there is also increased confidence for external investment to further expand the sector, corresponding to increased, long-term employment of HQSP in areas of engineering, manufacturing, and field services.

8. RECOMMENDATIONS AND NEXT STEPS

The significant potential economic and environmental targets associated with reducing operating expenses, energy consumption, and GHG emissions, and potentially even unlocking new heavy oil resources, depends not on just the commercialization of the ICD technology being tested, but the commercialization of the enhanced in-situ processes, such as solvent-enhanced SAGD and pure solvent. Successful implementation of the knowledge gained from this project and the ICD technologies tested is seen as an important component with de-risking these enhanced processes and achieving the associated economic and environmental benefits over the long term.

The next step towards implementing these technologies commercially is the development of more comprehensive hydraulic performance models of the most promising ICDs. The developed ICD models would then be included in reservoir and wellbore modelling software used by the JIP Participants to model the in-situ recovery processes. Further work utilizing the models would then be required by the JIP Participants to optimize the processes and identify opportunities for field trials or commercial implementations.

Further testing work to support the development of these ICD hydraulic performance models is the next action to be taken by C-FER, the industry partners, and the ICD vendors to advance this technology. Based on the key learnings identified from the testing conducted in this project, three unique ICD geometries were selected for this further testing work. One of the selected ICD geometries was found to be too restrictive to collect the full target range of test data, so one of the first steps is to work with the ICD vendor to modify the device arrangement to be compatible with the full range of test conditions. The selected ICDs will next be tested in more detail following a comprehensive test matrix. This future testing work will be supported by the facility and test procedure learnings identified in this project, such as only using nitrogen as an NCG test fluid for high-temperature steam and solvent tests. Additionally, it is expected that this future testing will be followed by erosion resistance testing of the ICDs in a separate facility to evaluate the long-term reliability of the ICD geometries and how the hydraulic performance of these devices may vary over long-term field operation. It is expected that this further work will continue to be advanced in partnership with the JIP Participants and the ICD vendors.

Of course, this upcoming characterization and erosion testing work with the three promising ICDs identified at the end of Phase 3 is not the end of ICD development in Alberta. Potential partnerships being explored include working individually with additional ICD vendors, specifically Alberta SMEs that were not involved in this project, to advance their new technology as well. This will help to provide additional, novel ICD technology options to the industry that will help to further optimize solvent-enhanced recovery, SAGD with late-life NCG injection, and pure-solvent recovery processes.

9. KNOWLEDGE DISSEMINATION

This project was setup as a partnership between the Government of Alberta, C-FER, ICD vendors, and ICD end users to help progress the development and implementation of this technology for the long-term benefit of the industry and the Province of Alberta. Therefore, it is important to ensure that the results of this work are effectively communicated to all impacted parties to maximize the project value.

The primary means of disseminating the project knowledge is by C-FER compiling data sets consisting of detailed hydraulic performance data that will be shared with the project participants. ICD vendors will use the test data associated with the ICD(s) they contributed to the project to help them better understand the hydraulic performance of their ICDs in scenarios involving flashing fluids, which will enable further design modifications and optimization. The oil and gas operators will use the test data to compare the performance of the devices to select the best ICDs for their applications, as well as to build accurate, transient reservoir models to ensure that the designs of future wells using these ICDs are optimized. Once received by the project participants, this information is expected to be shared with their respective teams.

The industry has been made aware of this project work through two main communications to-date. The ICT Network is a group of oil and gas operators, ICD vendors, researchers, and academia who regularly meet to create awareness of ICD technology, hold forums to present and discuss on ICD-related topics, and write standards related to testing ICDs. C-FER presented at an online forum held in August 2020 about the current environmental challenges with bitumen recovery, the opportunity to improve environmental performance using solvents, and the industry's plans to construct a unique test facility to test many devices. The SPE "Slugging it Out" conference is a one-day event where professionals in the heavy oil industry come together to discuss the biggest challenges the industry is facing. C-FER and one of the industry partners presented on the current challenges, how the transition to solvents will be part of the solution, and how the work being conducted under this project will help further enable this transition to occur.

Additional presentations and publications are also expected. An abstract has already been submitted for the Canadian Energy Technology Conference in Calgary, happening in March 2022. Some of the ICD vendors will likely also publish results specific to their own ICDs.

10. CONCLUSIONS

The objective of this project was to help bridge a key knowledge gap pertaining to the implementation of ICDs in applications involving the use of NCGs or solvents. This was conducted in two key stages: upgrading C-FER's ICD Characterization Flow Loop, and then conducting screening tests on many ICDs of interest to identify the most promising devices for these applications.

To accomplish these objectives, significant engineering work was conducted to determine how to upgrade the ICD Characterization Flow Loop so that the new facility could be operated in the most effective and safest manner as possible. Instead of constructing this flow loop in C-FER's SEL, as per the originally proposed plan, it was designed to reside inside of a seacan situated outside of the C-FER building. Key components for this upgraded flow loop came from the original ICD Characterization Flow Loop (e.g. water pump, instrumentation, control valves, vessels, data acquisition equipment), and a number of items were purchased from a variety of suppliers (seacan, solvent pump, separator vessel, instrumentation, and a high-rate dilution blower). The upgraded flow loop was then used to perform preliminary screening tests with eight ICDs of interest. These tests showed which ICDs seemed to be effective at resisting the production of unwanted gas, whether steam, NCG, solvent vapour, or gas combination.

Aside from identifying three promising ICDs during the screening testing, there were also many key learnings that will help to improve the efficiency and safety of future testing programs. These learnings include using nitrogen gas for future tests involving steam and NCGs, removing propane from future detailed testing plans, and incorporating nitrogen exsolution into any calculations used to determine how much of each gas, whether flashed, injected, or coming out of solution, are present at the ICD inlet. Another key learning gained was that an ICD previously designed for use in more conventional applications is not necessarily going to be effective in a situation where fluid flashing may be present; therefore, it is important that any ICDs that could be used for these applications should be tested in conditions that are representative of the conditions present in the target recovery application to confirm that they are suitable for this application. These lessons should greatly benefit the industry partners and ICD vendors as plans are made for more detailed characterization testing of the most promising devices.

This work should not only lead towards a reduction in GHG emissions per barrel of oil, but also will help the industry to bridge the knowledge gap about how best to design wells with ICDs that utilize solvents and NCG injection; this should help accelerate the transition from typical SAGD to these more efficient recovery processes. This will not only provide more certainty regarding the sustainability of the industry in Alberta over the long term, but provide significant benefits to the Province of Alberta in terms of increased employment and government revenue.

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