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Analysis of Downhole Data from Installation of Lower Completion in Long Horizontal Wells at Ivar Aasen

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ABSTRACT

In recent years, there has been a significant development in logging tools designed to acquire information of the downhole events during drilling operations. This development has not been as significant in completion operations, making it difficult to analyze successes and failures that occur downhole due to the lack of data. The i-Con Drill String Dynamics Logging Tool has been developed by Trican Completion Solutions to be used for downhole data acquisition in wells during completion operations. It contains sensors that measure downhole parameters such as pressure inside the installation string, annular pressure, torque, temperature and axial loads.

As of June 2016, the i-Con tool has been run during the installation of lower completion in five wells at the Ivar Aasen Field. The wells are all long, horizontal oil producers from 4600 m MD to 6200 m MD, completed with sand screens. During the installation, the tool was located directly above the liner hanger running tool as this was the main point of interest in the well.

The downhole data acquired by the tool in the five oil producers was analyzed, with particular attention payed to five specific downhole events:

1 - Installation of the lower completion
2 - Anchoring the lower completion
3 - Circulation through the lower completion
4 - Isolating the lower completion
5 - Pressure testing the lower completion

The goal of this analysis was to determine the typical fingerprint behavior for each event, and to evaluate areas of improved visibility that appear when using downhole data in addition to surface data. In order to achieve this, plots were made in Microsoft Excel. Some plots show all data from the lower completion installations, while others only display relevant data for each downhole event.

The main findings based on the analysis include that there are clear fingerprint behaviors for several variables in many of the downhole events. The acquired downhole data provides new information to draw a more complete picture of the downhole events taking place in the five oil producers at Ivar Aasen. Another more general conclusion is that downhole data sets like these can be used to adjust and optimize future completion operations. It also provides documentation and verification that tools have run through their intended cycles and operations. Verification like this have become more demanded post Macondo.

SAMMENDRAG

De siste årene har det skjedd en enorm utvikling innen loggeutstyr som er designet for å samle informasjon om hendelsene nede i brønnen under boreoperasjoner. En tilsvarende utvikling har derimot ikke funnet sted for kompletteringsoperasjoner. Derfor er det vanskeligere å analysere både vellykkede og mislykkede hendelser som skjer under komplettering på grunn av manglende data. I-Con Drill String Dynamics Logging Tool er utviklet av Trican Completion Solutions med den hensikt å bli brukt for innsamling av borehullsdata under kompletteringsoperasjoner. Toolet inneholder sensorer som måler parametere som trykk inni installasjonsstrengen, annulustrykk, dreiemoment, temperatur og aksiallaster.

Pr juni 2016, har i-Con toolet blitt kjørt under installasjonen av nedre komplettering i fem brønner på Ivar Aasen feltet. Alle brønnene er lange, horisontale oljeprodusenter mellom 4600 m MD og 6200 m MD, komplettert med sandskjermer. Under installasjonen var i-Con plassert rett over liner hanger kjøretoolet ettersom dette var det mest interessante punktet.

Borehullsdataen som ble samlet av i-Con toolet i de fem brønnene ble analysert, med særlig vekt på fem konkrete hendelser nede i brønnen:

1 - Installasjon av nedre komplettering
2 - Forankring av nedre komplettering
3 - Sirkulasjon gjennom nedre komplettering
4 - Isolering av nedre komplettering
5 - Trykktesting av nedre komplettering

Målet med analysen var å bestemme om noen av variablene oppførte seg likt for hver hendelse og å vurdere områder med økt synlighet som kommer frem når borehullsdata blir analysert sammen med overflatedata. For å oppnå dette, ble plott laget i Microsoft Excel. Noen plott viser data fra hele installasjonen, mens andre kun viser relevant data for de konkrete hendelsene.

Et av de viktigste funnene som ble oppnådd ved analysen var at mange av de målte parameterne viser en respons som kan bli kalt «fingerprint behavior» i flere av de konkrete hendelsene. Borehullsdataen gir også ny informasjon om hva som skjer i borehullet slik at man får et bedre innblikk i hva som skjer i brønnene på Ivar Aasen. En mer generell konklusjon er at slike sett med borehullsdata kan bli brukt til å justere og optimalisere framtidige kompletteringsoperasjoner. Den kan også bli brukt for å dokumentere og verifisere at operasjonen gikk som planlagt.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1 INTRODUCTION

In a well, the lower completion[1] is the bottom part of the completion located across the reservoir section in production and injection wells. It consists of several components combined in various combinations, and is designed and tailored to every well and reservoir. It is normally set in the producing zone using a liner hanger system. Lower completions also contain other equipment, e.g. Inflow Control Devices, zonal isolation packers, and reservoir surveillance systems.

In the past, lower completions have been installed in wells without available downhole data. Only surface data, such as pressures, rates and weights, have been available. Therefore, downhole events have been hard to analyze and understand. Recently, installations of lower completions have included memory tools that acquire downhole data such as pressures, temperatures, weights, torque, and shock. This allows a much more accurate analysis of downhole events taking place during the installation.

One such recently developed memory tool is the i-Con Drill String Dynamics Logging Tool. The tool is designed to be used in completion and liner hanger operations and was established on the market in 2013 by Trican Well Services. The tool contains several sensors that measure various downhole parameters. These are internal and external pressure, temperature, torque, tension, and compression. The tool does not provide realtime data. The downhole data remains stored in a memory until it is downloaded once the operation is complete and the tool is retrieved from the hole.

Though the i-Con memory tool is relatively new, it has been run 63 times as of April 2016. In 2015 and 2016 the tool was used in the installation of lower completions in five oil producers drilled at the Ivar Aasen Field. Trican considers the logging tool to be an ideal addition when installing lower completions in fields where several wells are to be completed similarly, and where the wells have a similar well path. This was the case with the oil producers at Ivar Aasen. When the downhole data is acquired, unideal variables can be modified for later operations. This provides the basis for optimizing each event and making operations more efficient. Hence, learnings from the earliest wells can be used when performing the same operations at a later stage.

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[1]E.g.: sand screens, liners, gravel packs etc.

The actual usefulness of the i-Con tool and the downhole data it acquires is to be investigated closer in this thesis. In order to achieve this, the field operators, Det norske oljeselskap ASA, provided both downhole and surface data measured during the installation of lower completions in the five oil producers. These two sets of data will then be compared and analyzed for five different downhole events:

1 - Installation of the lower completion
2 - Anchoring the lower completion
3 - Circulation through the lower completion
4 - Isolating the lower completion
5 - Pressure testing the lower completion

The comparison is done by plotting the data in Microsoft Excel to highlight areas of improved visibility from using downhole data in addition to the surface data. Plots are also made in order to determine if the relevant parameters for each downhole event provide a typical fingerprint behavior.

2 i-CON DRILL STRING DYNAMICS LOGGING TOOL

This chapter contains a short section on the producers of the logging tool studied in the thesis, as well as information on the tool itself. This information includes reasons for development, general information and applications, technical information and finally future improvements.

2.1 TRICAN WELL SERVICES

Trican is an oilfield service company which is headquartered in Calgary, Canada. Although it started up earlier, the company went public in 1996 as a cementing company. Over the next years, the company began and continued to expand nationally. Trican also began operations in the United States and Russia under Liberty Pressure Pumping and Newco Well Service respectively. The expansion continued, and today Trican is an international pressure pumping company with 42 operation facilities and approximately 5 800 employees worldwide.

The oilfield service company i-TEC Well Solutions was established in Stavanger, Norway in 2006. It was a completion and intervention focused company, where the core business was sliding and frac sleeves and supporting equipment. In January 2013, Trican Well Services acquired i-TEC Well Solutions. This event marked the expansion of Trican's Completion Solutions and Downhole Tool service line. Today, Trican Completion Solutions is a growing oilfield service company focused on specialized completion and intervention solutions. Their core products are still sliding and frac sleeves, and in 2014 Trican's TriFrac-MLT™ won the ONS New Technology award. However, the company has also developed new technologies, such as the i-Con Logging tool, which has evolved to become an important asset.

Figure 2-1: i-Con Logging Tool (Trican Well Solutions)

2.2 DEVELOPMENT

The i-Con Drill String Dynamics Logging Tool is one of the newest additions to Trican Completion Solutions' portfolio of completion and intervention related tools. The development of the tool began in i-TEC Well Solutions at an early stage, and over the years, several prototypes were developed including i-Con 350, 450 and 550. These prototypes are considered segments in the development of the current two types of the tool: i-Con L and i-Con XL.

While there has been a vast development in the application and quality of logging tools used in drilling operations, a similar development has not occurred within completion operations. In drilling, the use of logging tools in the drill string has been introduced as a standard in recent years. This is because the value of the downhole data gained by the logging tools has been recognized as vital in order to understand the successes and failures that occur downhole. After the implementation of logging tools in drilling operations the success rate has been greatly increased, and the execution of operations has become more efficient and time saving.

Within completion operations, the need for downhole data was not recognized to be great enough to force a similar development. However, engineers at i-TEC Well Solutions saw the potential of a downhole data acquisition tool tailored to completion operations. This was because the only available data for these operations was surface data which was often found to be insufficient when detailed analysis of downhole conditions were required. Therefore, it was thought that a logging tool providing downhole data would be a valuable contribution during well completion operations.

The goal of the tool development team was that data provided by the tool could be used to improve the way completion and liner hanger operations were being performed. The result of this idea was the i-Con Drill String Dynamics Logging Tool. The first prototype was run in 2009, but the current versions of the tool were completed during the summer of 2013. October the same year, i-Con was run for the first time.

2.3 GENERAL INFORMATION AND APPLICATIONS

2.3.1 GENERAL INFORMATION

The i-Con Logging Tool is a battery operated memory-based monitoring sub. It is a drillpipe mounted dynamics logging tool that records internal[2] and external[3] pressure, temperature, torque, tension and compression at a predetermined frequency between 1 Hz and 20 Hz. The tool can also measure gyro and vibrations though this has not been used frequently on previous runs.

The logging tool can be used in several different ways, but is mainly used for downhole data gathering in completion operations. In these cases, it is located in the installation string at a strategic position. This depends on where the point of interest is in the well, hence where the need for information is the greatest. In the case of installation of lower completion, it is often located directly above the liner hanger running tool in order to be able to gain more information on the actual well conditions and loads at that particular point. Once the operation is completed and the tool is retrieved from the well, the acquired downhole data is downloaded via a data port.

i-Con is designed to be a robust tool which provides valuable downhole data while avoiding any interference with operations and downhole flow restrictions. It has drillpipe style connections (see Table 2-1) and a full bore ID which ensures that the tool does not constitute the weak point in the work string, while it is simple to integrate. The logging tool's robustness enables it to be handled as a regular drill pipe pup joint when shipped offshore. Hence, it is a low risk tool to integrate into the work-string, as the driller does not need to take into account limits of the logging tool when performing the relevant operation, both during the make up of the string and downhole during the operation.

[2]**Internal pressure**: pressure inside the drill pipe

[3]**External pressure**: pressure in the annulus

Technical Data							
i-Con	Length	OD	ID	Tensile	Pressure[1]	Torque	Threads
	m (in.)	mm (in.)	mm (in.)	Ton (metric) (k lbf)	bar (psi)	N m (lb ft)	
L	2.246 (88.43)	146.05 (5.750)	57.15 (2.250)	191.4 (422.0)	1,034 (15,000)	35,250 (26,000)	Top: XT39 Box Bottom: XT39 Pin
XL	2.580 (101.6)	190.50 (7.500)	76.20 (3.000)	382.8 (844.0)	1,337 (19,400)	107,400 (79,210)	Top: XT57 Box Bottom: XT57 Pin

Table 2-1: Technical Data for the i-Con Logging Tools (Trican Well Solutions)

2.3.2 APPLICATIONS IN THE FIELD

The logging tool is suitable as a surveillance device in most completion operations. However, the main uses of i-Con are in drillpipe conveyed and coiled tubing operations. The downhole data acquired during the operation provides additional information on the events that occur in the well. The only data available without the use of a logging tool is the surface data. Hence, using the tool provides the possibility of analyzing and comparing the two sets of data. This contributes to provide a greater understanding of the downhole events and conditions enabling added knowledge and possibilities of updating procedures for future operations. The logging tool has been run several times on many fields and in various countries, including Norway, Denmark and the UK. As of April 2016, Trican had more than 60 runs offshore.

The operations and wells where using logging tool is most relevant, are those which are to be repeated several times so that a learning from the first wells will provide a great advantage at a later stage. One such case is Ivar Aasen, where i-Con was run when installing the lower completion in five drilled oil producers: D-10, D-11, D-14 T3, D-16 and D-19. The tool was also used on the clean out run prior to running the lower completion in wells D-10 and D-11. As the wells are all long, horizontal producers that are completed in much the same way, the use of the tool provided a greater understanding of what the lower completion equipment was experiencing downhole based on what the surface data showed.

The wells at Ivar Aasen were completed with sand screens[4] which were set by means of a liner hanger. During the installation, the annulus and the drill pipe is pressured up, and weight is set down at various times in order to activate specific equipment. Therefore, it was interesting to gain more information on the downhole conditions, and the actual pressures and loads seen at the liner hanger location. Hence, the logging tool was located directly above the liner hanger running tool. The background for implementing this technology was to increase the success

[4]See *Chapter 4: Lower Completion Designs at Ivar Aasen* for more details on lower completion

rate of the operations and to obtain a better understanding of the downhole events. According to the operators of the field, Det norske oljeselskap, the downhole data was found to add value when challenges were encountered, as it was easier to analyze and investigate the incidents with relevant and higher resolution data available.

On another case the logging tool was implemented on a drill-in liner system for a major operator in the North Sea. Here two separate i-Con tools were implemented in the string with a 750 m distance between them. The idea behind this unorthodox set-up was that the propagation of torque down the string was to be analyzed and investigated. It also enabled a comparison between all data at two different locations in the string which provides a more detailed picture of the downhole conditions and well behavior.

The tool has also been used for other operations. It has been used to calibrate the torque readings on top drives. It can also be useful considering gravel pack operations as the tool can provide information on the success of packer setting, the release of running tools, and the temperature effects of pumping fluids from surface. To this point, the tool has been used for the operations mentioned below as well as those described:

- 4 ½'', 7'', 9 5/8'' liner installations
    - Openhole, cemented and drill-in liners
- Stage cementing operations
- Inflatable packer installations
- Setting and pulling plugs
- whipstock operations
- P&A and slot recovery operations

2.3.3 i-CON VERSIONS

As previously mentioned, there are two versions of the tool: i-Con L and XL. The main difference between these two versions is the size. While the XL tool has an OD of 7.5 inches, the L tool is smaller with an OD of 5.75 inches (see Table 2-2). Despite the different ODs, the producers have designed the two versions so as to be used for the same operations. However, i-Con XL generally has a larger measuring range than the L tool, as shown below in Table 2-2. The larger tool can handle larger loads, pressures and torque. The temperature range, on the other hand, is the same for both versions.

Of the two tools, i-Con XL is the most used. This tool was run 35 times from 2014 to April 2016, while the L tool had been run 20 times in the same timeframe. Trican had a total of 12 i-

Con tools available to the industry until recently. As of April 2016, Trican expanded so that the number of XL tools was doubled. Hence, there are currently 12 i-Con XL and 6 i-Con L tools to the industry.

Measuring Range					
i-Con	**Tensile**	**Compression**	**Pressure**	**Temperature**	**Torque**
	Ton (metric) (k lbf)	**Ton (metric) (k lbf)**	**bar (psi)**	**°C (°F)**	**N m (lb ft)**
L	68.0 (150.0)	68.0 (150.0)	1,034 (15,000)	130 (266)	20,300 (15,000)
XL	217.7 (480.0)	217.7 (480.0)	1,337 (19,400)	130 (266)	81,350 (60,000)

Table 2-2: Maximum Values for the i-Con Logging Tools (Trican Well Solutions)

2.4 TECHNICAL INFORMATION

2.4.1 LOGGING AND BATTERY LIFE

The logging frequency of the logging tool can theoretically be fine-tuned from 1 Hz to 20 Hz to meet the needs for each individual well run. The amount of time that the tool will log depends on the frequency used as shown in Table 2-3. These lifetimes correspond to the time it takes for the memory to be full, at which point the tool will stop logging. Logging with 1 Hz, the tool will log data for 36 days.

Logging Frequency [Hz]	Logging Lifetime [days]
1	36
2	18
4	9
8	4.5

Table 2-3: Logging Lifetime Based on Memory (Numbers from Trican Well Solutions)

Though it is possible to log with 20 Hz, historically the logging frequency used has only varied between 1 Hz and 5 Hz, with about 80% of the jobs recorded with 1 Hz (see Table 2-4). The 5 Hz limit is based on the time it takes for the memory to be filled and the amount of time the operation is expected to last. At the Ivar Aasen field, a frequency of 2 Hz has been used most often. Though 4 Hz has also been implemented, the data files take a long time to process due to the large size. Therefore, 2 Hz is preferred.

i-Con Version	Logging Frequency [Hz]	Number of Times Implemented [-]
All Versions	1	50
XL	2	4
XL	4	8
XL	5	1

Table 2-4: Number of Jobs Run Using the Various Frequencies (Numbers from Trican Well Solutions)

All the logging tools contain four batteries which are all activated during an operation. This is done in order to ensure that the battery life is not the limiting factor considering the amount of time the tool can acquire data. Four batteries also ensure back-ups in case one or more should fail during the job.

The combined battery life when logging with 1 Hz is 47 days, while logging with a frequency of 20 Hz causes a battery life of 39 days (see Table 2-5 for more details). If the gyro or vibration sensors are activated during the job, the battery life of the tool will decrease. This is because the batteries in the tool also power the additional measurements. The activation of these two measuring units also cause the memory of the tool to be filled more rapidly causing the logging lifetime to be less than the numbers provided above.

Sampling Frequency [Hz]	Current Consumption [mA]	Battery Life [hrs]	Battery Life [days hrs]
0.1	11.02	1161	48d 9h
1	11.13	1150	47d 22h
2	11.28	1134	47d 6h
4	11.52	1111	46d 7h
5	11.63	1100	45d 20h
10	12.25	1044	43d 12h
20	13.48	949	39d 13h

Table 2-5: Theoretical Calculations for Sampling Frequency vs Battery Life for an i-Con tool containing 4 batteries

2.4.2 ACCURACY AND CALIBRATION

i-Con contains several different sensors in order to provide the various measurements. These sensors are all (re)calibrated regularly in order to ensure that the tool is accurate, and provides correct and reliable measurements. The accuracies of the tool measurements are presented in Table 2-6.

Sensor	Accuracy
Internal Pressure	±0.1%
External Pressure	±0.1%
Torque	±0.3%
Axial Loads	±0.3%
Temperature	±0.4°C – ±0.95°C

Table 2-6: Accuracy of Sensors (Trican Well Completions)

The sensors have their own calibration procedures with various requirements for sample points and sample point accuracies, as shown in Table 2-7. The acceptance criteria in the table represent the difference between the measured sensor value and the calibration unit value. The location of the calibrations varies in order to ensure that the best possible calibration takes place to make the measurements accurate. Pressure and temperature is calibrated at the Trican workshop, torque is calibrated at IOT[5] and the axial load sensors at IRIS[6]. More information on the calibration procedures and sensor accuracies is provided in Appendix B.

Sensor	Sample Points (90°C)	Sample Points (ambient temp)	Acceptance Criteria
Internal Pressure	-	45	±0.3%
External Pressure	-	45	±0.3%
Torque	45	45	±1.5%
Axial Loads	45	45	±1%

Table 2-7: Required Sample Points and Acceptance Criteria for Sensor (Re)Calibration

2.4.3 TEMPERATURE EFFECTS

The values for battery life provided in Table 2-5 will vary with temperature. From the datasheet of the batteries that are used in the tools (see Appendix A), it can be seen that the operational temperature range of the batteries lies between -40°C and +150°C. However, this temperature range is smaller for the logging tool itself, which is rated from standard conditions up to 130°C. This is because the limiting factor of the tool is not the batteries, but the materials used. At any temperatures above the maximum temperature rating, the materials will begin to deform and melt causing the physical properties to change. These materials include the rubber holding the battery pack in place, glue used to hold wires etc. in place, and tape.

While the tool can handle temperatures above the rating for a limited time, this causes a strain which may dramatically shorten its lifetime. This implies that the time at which the end of the product lifetime occurs will be sooner than expected. This effect can be illustrated using a *bathtub curve* as shown in Figure 2-2. This is the most basic illustration of product reliability, and describes the variation of product failure rates with time. Putting a strain on the product causes the end of the product lifetime to shift from $t_{initial}$ to $t_{modified}$. What makes this effect particularly undesirable is that the value of Δt is unpredictable so there is no way of knowing when the tool will fail if exposed to conditions outside the range specified in the datasheet.

[5]Independent Oil Tools AS

[6]IRIS AS - International Research Institute of Stavanger

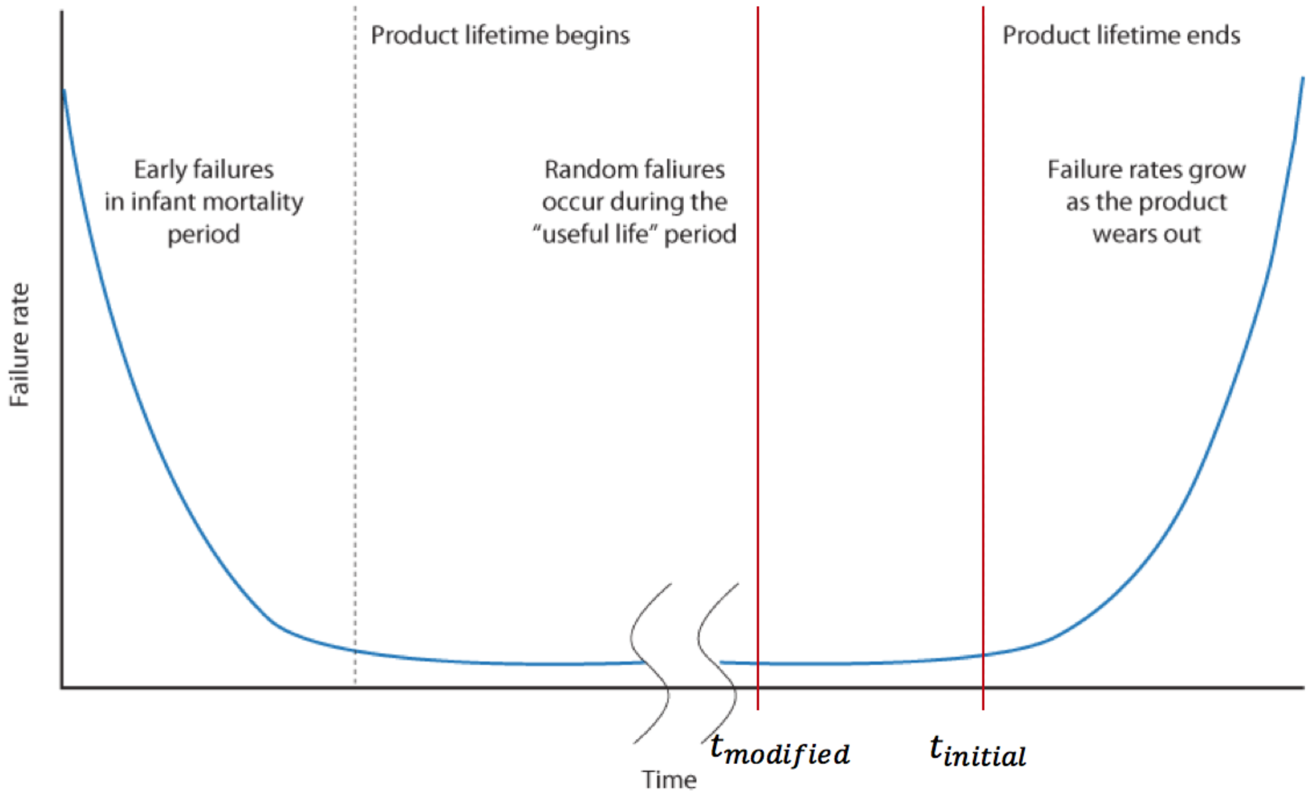

Figure 2-2: The Bathtub Curve of an Electronic Product (Based on conversation with Ole Martin Borsheim, Trican Well Solutions)

As of June 2016, the highest temperature that the tool has been operated at is 139°C, while the temperatures seen at Ivar Aasen are below 97°C. Therefore, there are no issues with the logging tool and the measurements with regards to temperature effects.

2.5 CURRENT DATA PROCESSING METHOD

2.5.1 ONSHORE PREPARATION OF LOGGING TOOL

After each operation where the tool has been run, it is sent onshore for a thorough examination. Before the tool arrives at the Trican workshop, a third party base receives the tool before it is transported to the Trican workshop where further work is done. The tool is cleaned and thoroughly checked for any external damage, as well as damage to vital equipment and threads. Next, relevant equipment can be replaced and the sensors recalibrated. The tool is then redressed for the next job.

Picture 2-1: i-Con Memory Tool at the Trican Workshop, Stavanger (N.E. Wanvik, February 2016)

2.5.2 TOOL ACTIVATION AND DATA DOWNLOAD

Before a job, the logging tool is dormant, meaning it will not record any data, until it is activated. This activation can occur in one of two ways:

1. Logging can be started onshore, either in the Trican workshop or at the customer base. The tool can then be shipped to the well location and be handled as a regular pup joint. If the batteries run out while the tool is still in the well, the recorded data will be stored in the memory until it is downloaded. This occurs once the tool has been shipped back to Trican.
2. Logging can be started at the well site. The i-Con tool is shipped in dormant mode and a Trican technician, or other personnel with the necessary knowledge, will connect the i-Con laptop to the tool in order to start the data acquisition prior to deployment in the well. The responsible personnel can also download the acquired data once the tool is retrieved from the well.

2.5.3 DATA PROCESSING

Once the downhole data has been downloaded, the processing commences. First, the data is processed to remove any irrelevant data (e.g. data recorded while shipping), and imported into Microsoft Excel. The data is then sent to the i-Con Analyzing Team for further processing and analysis. Various data from other sources are then collected, such as daily drilling reports (DDRs), the rig file with the available surface data, well schematics, and well completion/installation string tally.

An Excel sheet including all downhole and rig data is created to allow a graphical representation of the relevant operation. When this is done, specific parts of the operation are analyzed in detail. These focus areas are determined in communication with the operator/client, and by considering the main events as described in the DDR. A PowerPoint Presentation is created, which includes the main conclusions from the analysis. This presentation is sent and presented to the client to visualize the data that the tool has recorded.

2.6 FUTURE IMPROVEMENTS OF LOGGING TOOL

The most obvious future improvement of the tool would be to modify it to become a real-time logging tool instead of a memory logging tool. This would provide an incredible opportunity where it is possible to act on the specific downhole situations immediately, and would provide a more effective method of understanding the occurrences downhole while performing the operations. This improvement would also open up a new market where the tool can be used and provide the same value in all wells; exploration wells and production wells. Modifying the tool to provide real-time data would provide immediate knowledge of the downhole conditions. Hence, the operational parameters could be adjusted and optimized directly instead of optimizing afterwards for future repeated operations.

Currently, research is being done to develop new ways to increase the ranges the tool can handle. As the conventional and simple oil fields are being depleted, more challenging fields are being discovered and developed in order to meet the international demand for petroleum. These fields often have harsher conditions such as higher temperatures and pressures. Though the logging tool can handle elevated pressures, the temperature range limits it from being used in certain downhole conditions. Hence, a vast development area for the tool is to increase this temperature range to allow it to be used in elevated temperatures. The goal is being able to use it in HPHT wells[7].

Another development area for i-Con is the logging lifetime. As mentioned, the current logging time is 36 days using 1 Hz until the memory is filled. This lifetime has been sufficient up to this point. However, in the future there may emerge a market or project where a longer lifetime is required, or a higher frequency is required for an extended period of time. Therefore, increasing the logging lifetime of the tool is a relevant development area. Trican's current solution is to activate and deactivate the tool at the well site, should one of these events come up.

The logging tool also contains sensors that can measure vibrations and gyro. However, these sensors have not been used very often historically speaking, and the measured data is incoherent. Therefore, this needs to be studied and improved in order to offer the clients all the features that the tool is meant to provide. The vibration measurements could be a source of helpful information, particularly when closing the formation isolation valve as little verification of the success of this event was provided by the other downhole measurements.

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[7]**HPHT Wells**: Wells with temperatures above 150°C and pressures above 690 bar/10 000 psi

The tool also contains another latent feature related to the activation. This is that the tool can be activated when it sees a weight of 20 tons instead of being manually activated prior to deployment in the well. However, this feature has not been tried on a job. If it reaches a stage where it can be offered to the clients, it would save a lot of logging time, and provide a simple and elegant way of activation, according to Trican.

Lastly, an area of improvement of the tool would be to provide the possibility of changing the logging frequency while in the hole. This could be relevant for example if the tool was to be used in a fracking operation, where the critical point would be when actually fracking the formation. While this occurs the tool could log with 20 Hz, while the rest of the well could be logged with 1 Hz. This would open up new markets and new uses for the logging tool.

3 IVAR AASEN

The data processed in the thesis was provided by Det norske Oljeselskap ASA. The data was acquired during lower completion installations and related operations performed in five oil production wells at the Ivar Aasen Field. This chapter will describe the field including the discovery, the development and the well designs of the oil producers in question.

3.1 GENERAL INFORMATION

The Ivar Aasen development comprises of three field discoveries; Ivar Aasen, West Cable and Hanz. The fields are located in the northern part of the North Sea, about 175 km off the coast of Karmøy as shown below in Figure 3-1. The discoveries are developed as a unified field, but in two phases. Ivar Aasen and West Cable will be developed first, while Hanz will be developed as a part of the second phase.

The Ivar Aasen field is Det norske's first major development project as an operator. The drilling of pilot wells commenced in the first quarter of 2015, and the planned start-up date of the production of the field is near the end of 2016, in the fourth quarter. At this point in time, the production will only be from the first phase of the development, with production from the second phase expected in 2019.

The water depth of the field is approximately 112 m. The total reserves of the fields are estimated to be about 23.6 MSm^3 of oil equivalents. 19.3 MSm^3 of these are expected to be oil while the rest (5.3 MSm^3) are oil equivalents of gas. The expected economic lifetime of the field is 20 years.

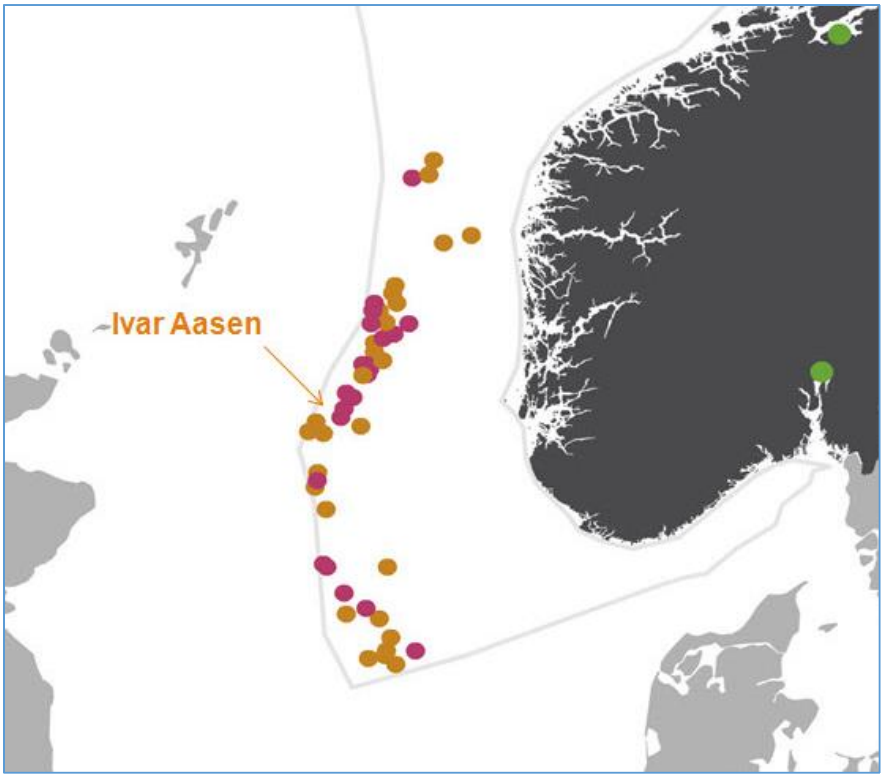

Figure 3-1: Ivar Aasen Field Location in the North Sea

The Ivar Aasen development consists of resources from five different fields: PL 001B, PL 028B, PL 242, PL 338BS, and PL 457. All the discoveries are located within Blocks 16/1 and 25/10 in the North Sea. The five licenses signed an agreement to develop the discoveries as a unitized field. The partnership, which has been committed for the development of the Ivar Aasen field, is as shown below in Table 3-1.

COMPANY	OWNERSHIP PERCENTAGE
Det norske oljeselskap	34.7862 %
Statoil Petroleum	41.4730 %
Bayerngas Norge	12.3173 %
Wintershall Norge	6.4651 %
VNG Norge	3.0230 %
Lundin Norway	1.3850 %
OMV Norge	0.5540 %

Table 3-1: Committed Partnership for Ivar Aasen Field Development

3.2 THE FIELD DISCOVERY

Det norske discovered Ivar Aasen in 2008 when drilling an exploration well on the Draupne prospect. Four years later, in 2012, the discovery in license 457 was made. Both West Cable and Hanz were discovered by Esso E&P Norway in 2004 and 1997 respectively. The Hanz discovery is not included in the current unitization of the field as shown in Table 3-1. Therefore, Det norske is the operator with a 35 percent ownership interest. The partners in this license are Statoil with 50 percent, and Bayerngas with 15 percent ownership interest.

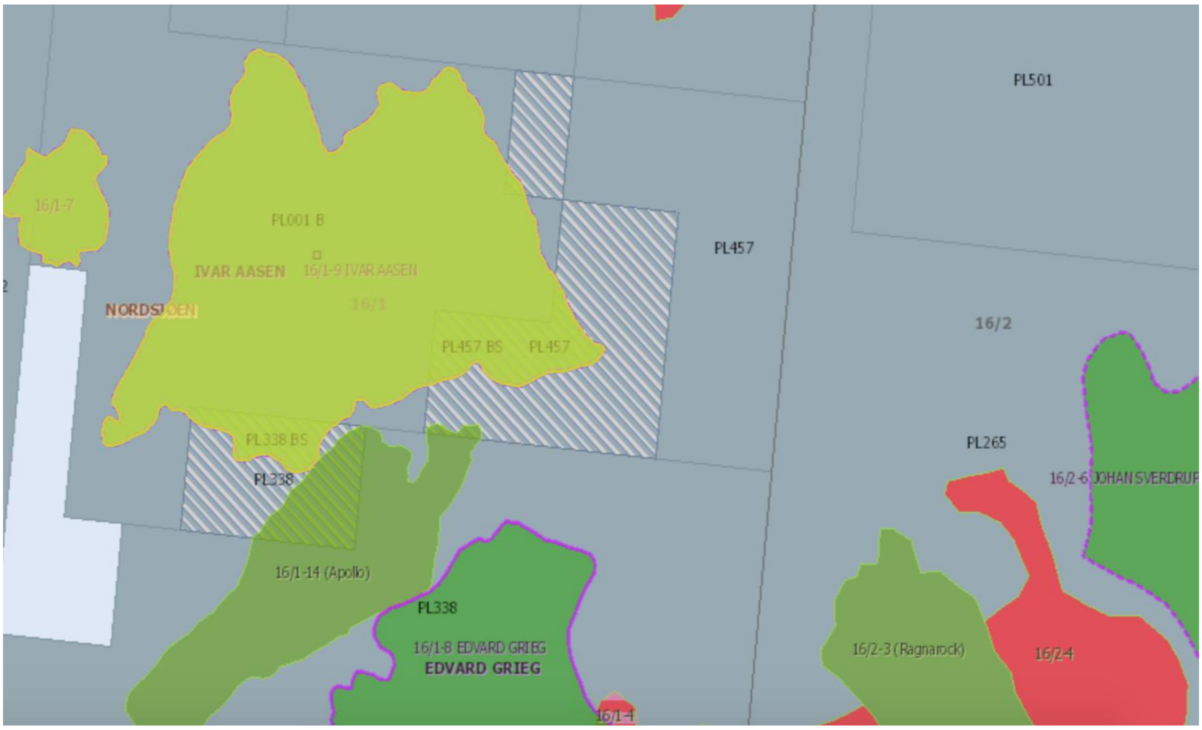

Figure 3-2: Field Map of Ivar Aasen (Norwegian Petroleum Directorate, 2015)

Oil at Hanz was discovered in sandstones from the Middle Jurassic and Paleocene age. At Ivar Aasen, oil and gas was discovered in the Middle Jurassic and Upper Triassic reservoir sandstones: The Hugin, Sleipner and Skagerrak formations. The West Cable discovery is located west of the Ivar Aasen discovery, and this discovery is a Mid-Jurassic sandstone reservoir, namely the Sleipner Formation.

3.3 THE IVAR AASEN DEVELOPMENT

All three discoveries will be developed as one field in a joint development project, as previously mentioned. The development of the field will take place over several years from 2015 to 2019. It is divided into two phases where the first phase involves the development of West Cable and Ivar Aasen, while the Hanz discovery subsea development will take place in phase 2.

The Ivar Aasen platform is located above the Ivar Aasen reservoir and is used to produce the field. This is a manned production platform containing dry wellheads, flow measurement functionality, one-stage separation and processing capacities, and water-handling facilities. The wells are drilled by a heavy-duty jack-up rig, Maersk Interceptor, drilling in cantilever-mode above the Ivar Aasen platform. Both the production and injection wells for the Ivar Aasen and West Cable discoveries are drilled from this rig. Hanz will be developed by subsea wells, and the wells will be tied back to the Ivar Aasen platform through a flow line and umbilical system. Figure 3-3 displays the development solution for the field.

The development of Ivar Aasen is coordinated with the development of Lundin's Edvard Grieg field in license PL 338. The production platform at Edvard Grieg (to the right in Figure 3-3) will receive the partly processed oil and gas from Ivar Aasen for further processing and export. This platform will also provide lift gas and electricity to Ivar Aasen.

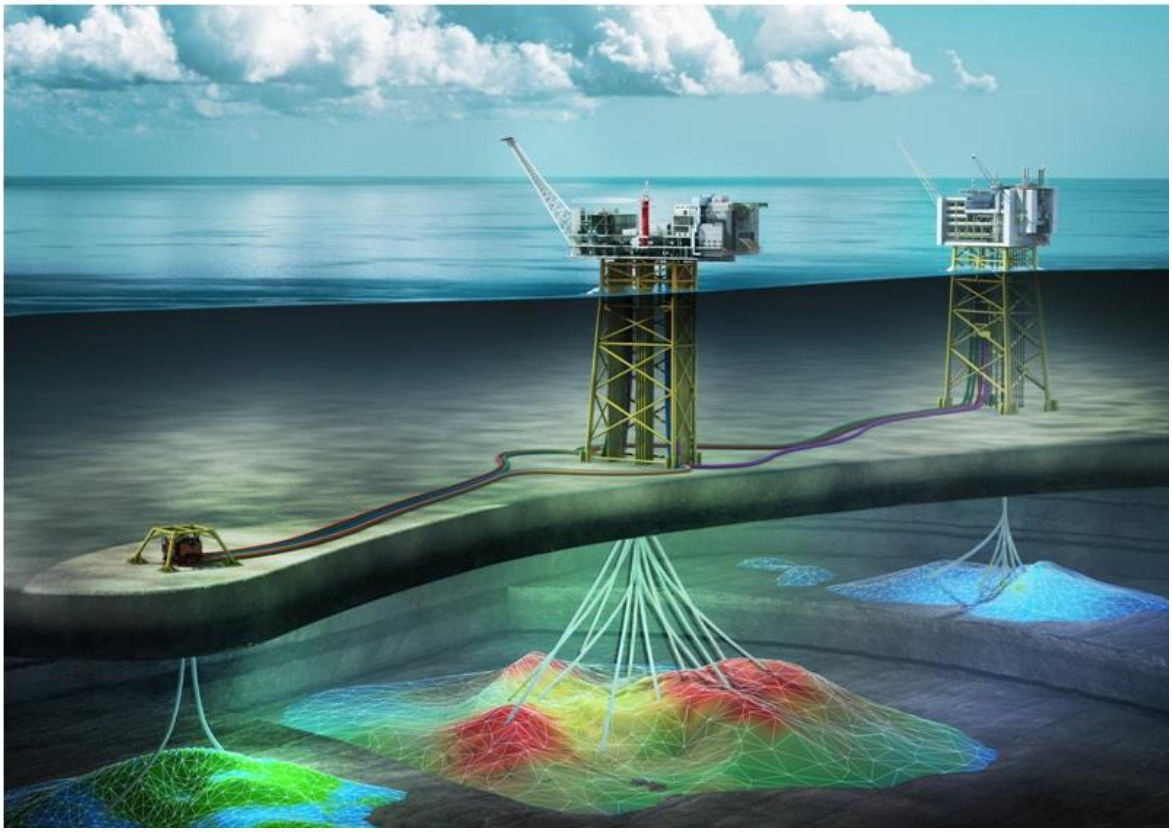

Figure 3-3: The development solution of Ivar Aasen (Det norske oljeselskap ASA, 2016)

3.3.1 DRILLING AND DRAINAGE

The Ivar Aasen field is planned to be developed using a total of 15 wells. 13 of these wells will be dedicated to the Ivar Aasen main field including West Cable, while two wells are dedicated to the Hanz subsea development in Phase 2. The Ivar Aasen discovery is planned to be drained using six horizontal production wells and six S-shaped injection wells, where all injectors are placed near the flank of the field. The planned well locations and well paths are shown in Figure 3-4. The three western wells are planned to mainly drain the Sleipner and Skagerrak Formations, while the three eastern wells are planned to mostly drain the Hugin and Skagerrak Formations. The horizontal producers are spread out in a pattern with the injectors placed between them in order to ensure a thorough flooding of the reservoir. West Cable will only contain one oil producer, and Hanz is planned with one producer and one injector.

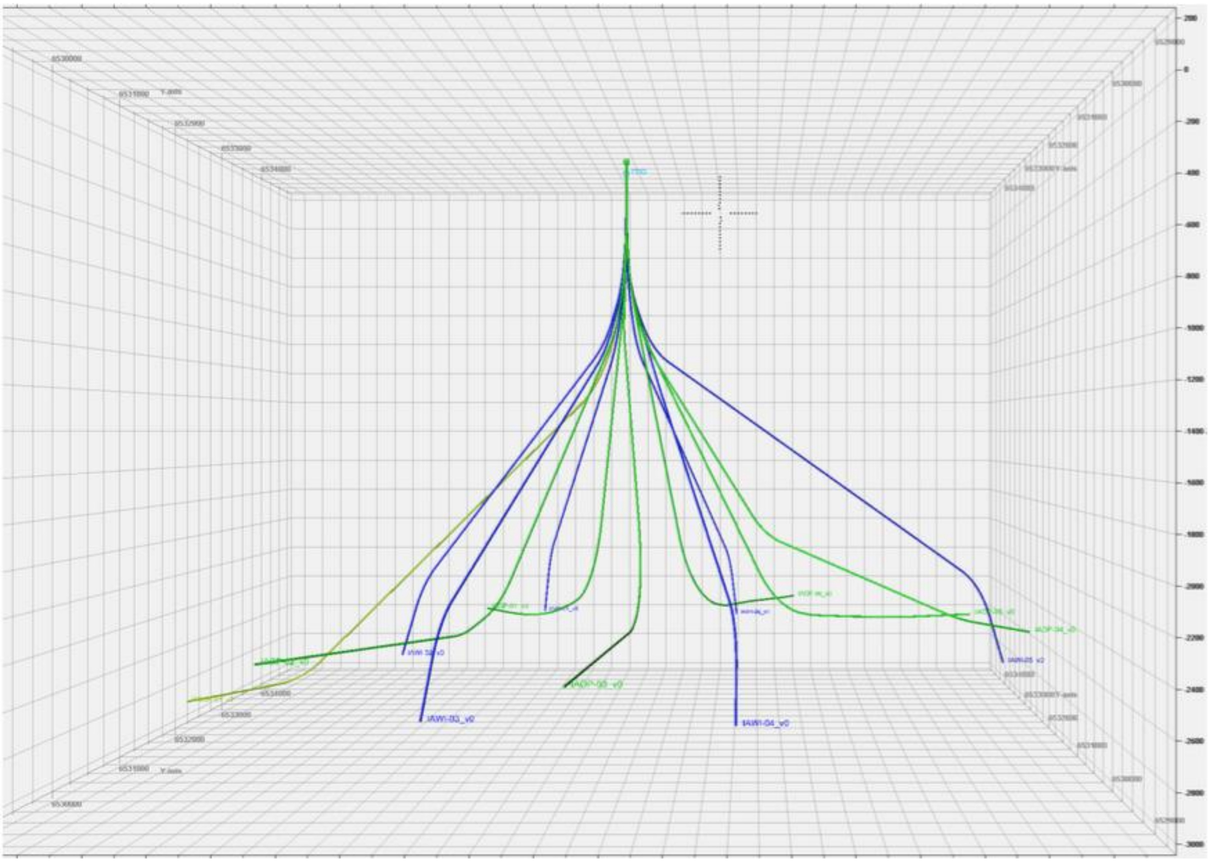

Figure 3-4: Preliminary Well Pattern with Injection (blue) and Production (green) wells per April 2014 (Ivar Aasen – Main Drilling and Completion Program)

The drainage strategy of the field is full pressure maintenance based on injection of water. The typical life of the production wells is expected to be 2-3 years of oil production followed by a gradual water-cut increase to 80%. The production from the last 10 to 15 years is expected to have the water-cut slowly increasing from 80% to 98%. With a water-cut this high, gas lift will be used in order to enable steady production from the wells. In some of the production wells it may be necessary with shut-off plugs in order to reduce the water production and enhance oil production.

The West Cable discovery contains a slightly undersaturated oil which is favorably located, so it is likely it will have good aquifer support. This provides a relatively high recovery factor for the primary recovery stage. The drainage strategy for this discovery includes drilling a near horizontal producer which is meant to penetrate as many geological layers as possible. As the production from West Cable is based on depletion, gas-lift is required at an early stage.

3.3.2 BASIC WELL DESIGNS

The West Cable and Ivar Aasen producers are geosteered horizontally or highly deviated through the reservoir section of the well. Currently, the total depth (TD) of the Ivar Aasen wells range between 4619 m MD RKB and 6590 m MD RKB. The water injection wells are as mentioned planned to be S-shaped with an angle through the reservoir of 20° to 30°. The lengths of these wells vary from 3620 m MD RKB to 5200 m MD RKB.

Figure 3-5 illustrates the preliminary base case well schematic for the oil producers at Ivar Aasen from which the data used in the thesis was acquired. The wells are completed using a lower and upper completion. The lower completion, or sandface completion, contain standalone sand screens, ICDs, swell packers and intelligent tracers, as well as a Formation Isolation Valve and a liner hanger.

Downhole chemical injection is included in the upper completion design. This section of the completion contains gas lift mandrels, and the related necessary equipment[8]. A well schematic of the base case completion design for the Ivar Aasen oil producers is shown in Figure 3-6. In this schematic, the lower completion is the part below the 9 5/8" casing shoe. Both the annulus and the tubing incorporate downhole pressure and temperature gauges (DHPTG) to allow well monitoring.

[8]Related equipment is described in *Subsea Well Completion Design, p. 29 – 31* (Wanvik, 2015)

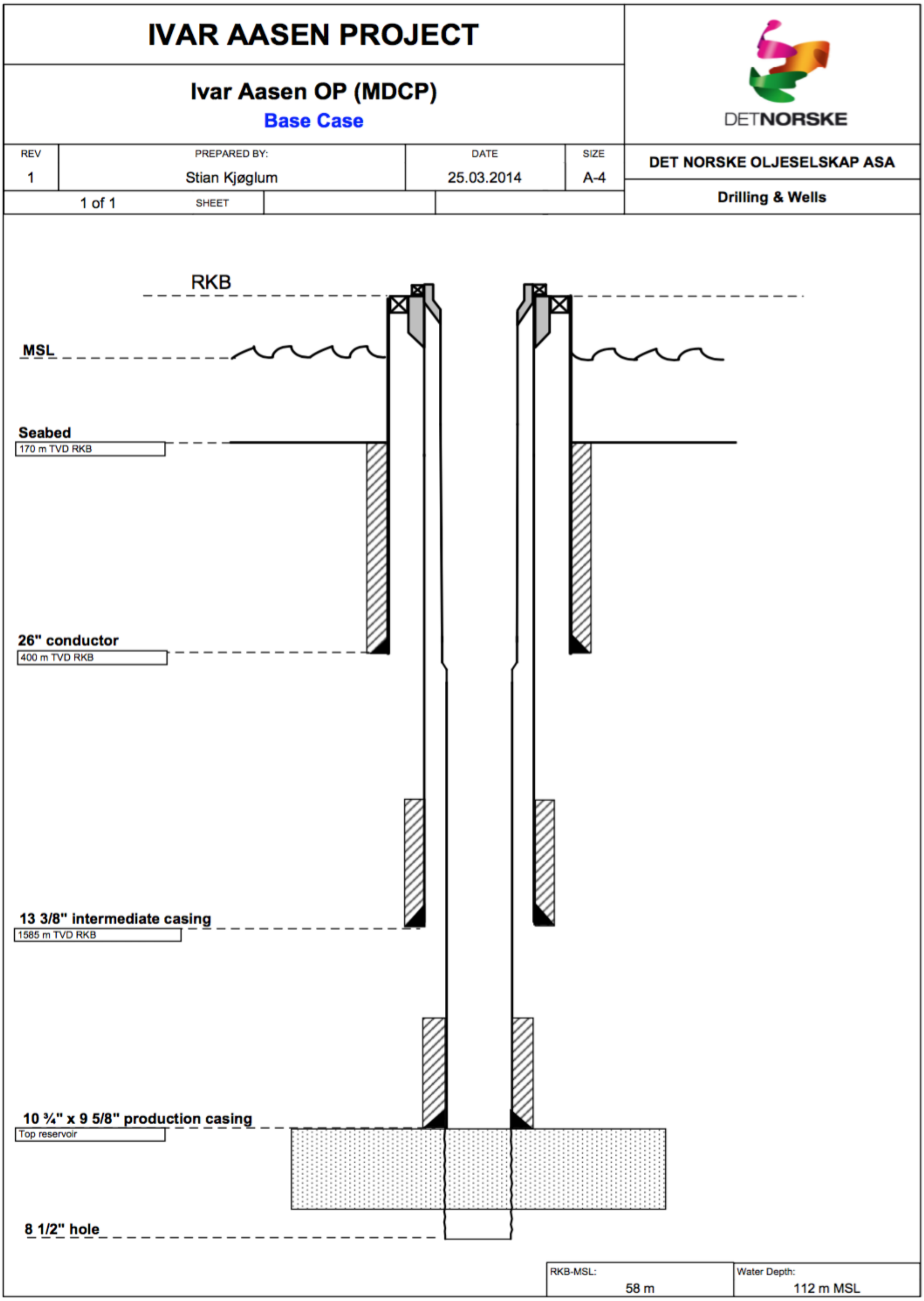

Figure 3-5: Base Case Well Schematic of Ivar Aasen Oil Producer (Det norske oljeselskap ASA, April 2014)

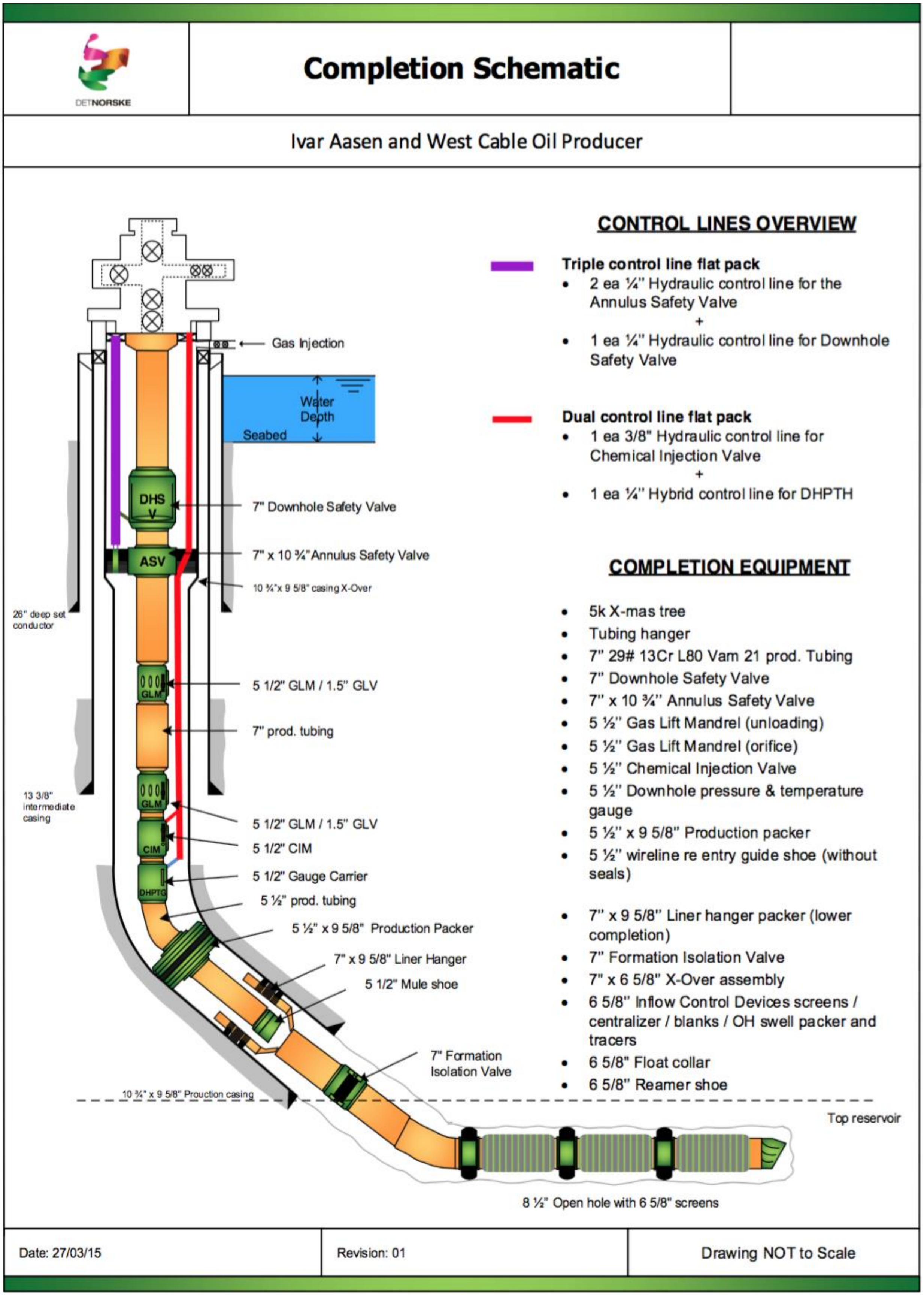

Figure 3-6: Ivar Aasen and West Cable Completion Schematic (Det norske oljeselskap ASA, April 2014)

4 LOWER COMPLETION DESIGNS AT IVAR AASEN

This chapter will describe the main lower completion equipment of the five oil producing wells at Ivar Aasen. The installation sequences that have been implemented in order to install the lower completions are also described. Finally, each of the five oil producers are presented with information on their objectives, drilling summary, and casing and completion equipment depths in order to provide an understanding of the specific well design and the well behavior prior to the completion operations.

4.1 LOWER COMPLETION EQUIPMENT

The wells at Ivar Aasen are completed as standard as possible according to the base case completion schematic shown in Figure 3-6. The lower completion includes everything from the toe of the well up to the liner hanger. During the installation, the i-Con tool was located directly above the liner hanger running tool. This section will describe the completion equipment used and its purpose in the well completion. The relative positioning of the equipment for each well is found in the base case completion schematic in Figure 3-6.

4.1.1 SAND SCREENS

Sand screens are a form of sand control common in wells where sand production is a possibility. The screens sections are normally quite long and are used for the entire length of the reservoir section (at Ivar Aasen the longest is about 2000 m long). There are several types of sand control screen types, where the three main types are:

- Wire-wrapped screens
- Pre-packed screens
- Premium/mesh screens

The type used in the oil wells at Ivar Aasen are 6 5/8” wire-wrapped screens with slot openings of 250 micron. These types of screens consist of a base pipe with pre-drilled holes, longitudinal rods and a single wedge-shaped wire wrapped and spot-welded to the rods. The wire is either welded or gripped by a connector at the ends of the screen. The wedge-shape of the wire ensures that particles bridge off against the wire, or pass through and are produced. The inflow area depends on the wire thickness (thicker wires causes less inflow area), the slot width and the percentage of screen joint that comprises slots. The screens chosen for Ivar Aasen are 12.5 m long with a jacket length of 8 m.

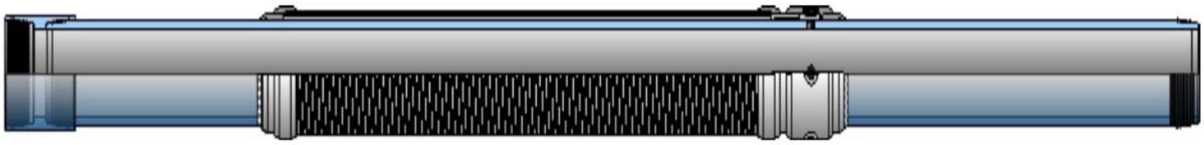

Figure 4-1: 6 5/8" Wire Wrap Sand Screen (Det norske oljeselskap ASA, April 2014)

Figure 4-2: Snap Shot of Reamer Shoe and Sand Screens Downhole (Screenshot from Ridge AS Animation, 2016)

4.1.2 INFLOW CONTROL DEVICES

The sand screens run at Ivar Aasen are also equipped with ICDs (Inflow Control Devices) and swell packers. The ICDs are installed to balance the inflow along the wellbore by exerting higher back pressure in high productivity zones, and vice versa for the low productivity zones. Typically, the zones closer to the "heel" of the well will contribute more than similar zones at the toe. Consequently, low productivity zones are stimulated to produce more than in normal screen completions (Ivar Aasen Field Development - Main Drilling & Completion Program, p. 295).

4.1.3 SWELL PACKERS

Swell packers are rubber elements that begin to swell when in contact with a particular type of fluid. These are often used for zonal isolation between the the selected production sections in the reservoir. This is the reason why they are implemented into the lower completion strings at Ivar Aasen. The swell packers chosen for these wells are ResPack slip-on swell packers with metal end rings. These are planned to be used in the lower completion to isolate sections of the open hole. The packer consists of a steel inner support tube onto which a hydrocarbon swelling elastomer molded on to the external and internal surfaces of the support tube. This swell packer is designed for 8 1⁄2" open hole section. They are integrated into the sand screens and are run in conjunction with the ICDs for zonal reservoir management, and to provide optimal ICD configuration.

Figure 4-3: ResPack Slip-On Swell Packer (Det norske oljeselskap ASA, April 2014)

4.1.4 INTELLIGENT TRACERS

Intelligent chemical tracers combine polymers and uniquely identifiable chemical compounds into a matrix. These resemble strips of plastic which can be formed into a variety of shapes which enables easy integration into common completion equipment such as packers, pup joints, sand screens, and artificial lift equipment. The tracer material is designed to be either water or oil sensitive. If an oil sensitive matrix is in contact with oil, it will release a prescribed amount of its unique chemical fingerprint (tracer). Samples of the produced fluid can then be analyzed for the concentration of each tracer. Analysis of the tracer concentration data will then provide information about the inflow of fluid to the well (Wanvik, 2015).

At Ivar Aasen, compartments for tracers are positioned through the length of the sand screens. The tracers are typically incorporated in one screen joint in 5 to 6 key segments of the horizontal section. The main purpose of the tracers is to monitor the well clean-up and identify the inflow location of oil and water from the segments of the open hole reservoir section. The tracers can also be used for well integrity monitoring, such as a leaking lower completion packer.

4.1.5 FIV – FORMATION ISOLATION VALVE

FIVs are designed to seal the tubing or isolate the reservoir without running plugs. These valves are hydromechanical, and the general principle is that the valves can be closed mechanically with a shifting tool and opened by pressure or pressure cycles. The valves can be positioned in the reservoir section, in the tubing, or below a packer. They are often used in relation to perforations and modern screen completions. Isolation of the reservoir mitigates issues such and losses, well control, and formation damage.

At Ivar Aasen, a Fortress formation isolation valve is run. This is a bidirectional barrier that is run as a part of the lower completion acting as a deep set barrier. The Fortress is a ball valve that was run in hole in an open position by the use of an inner string stung into the valve. The inner string is carefully spaced out to ensure that the shifting tool is below the isolation valve. In order to close the valve mechanically, the shifting tool is pulled past the FIV. The valve can later be opened by pressure cycles, or mechanically, at a later stage.

4.1.6 LINER HANGER AND HANGER PACKER

A hydraulic liner hanger is used at Ivar Aasen to anchor the screens securely to the casing walls. The hanger also incorporates a hanger packer which is set in order to isolate the reservoir section. The hanger is set by dropping a ball and pressuring up the installation string. The packer is set using the setting dogs in the running tool. These are activated once the hanger is set and the running tool is pulled out of the liner hanger. Weight is then transferred on to the PBR and hanger to activate the packer and squeeze it so that it seals the annulus.

4.1.7 PBR – POLISHED BORE RECEPTACLE

A PBR is an expansion device used when liner or lower completion hangers are implemented in a well. The main purpose of PBRs is to enable a seamless transition between the string below and above the hanger. There can be two types of PBRs in a well: one at the hanger of a lower completion and one at the hanger of a drilling liner. The main purpose of the drilling liner PBR is to enable a seamless transition from the liner to the tubing, while the production PBRs enable a transition between the lower completion and the production tubing. The PBR consists of two parts; one male part which may contain seals (Seal Stem) and one female part (PBR). This enables the PBRs to part, making later heavy workovers easier (Wanvik, 2015, p. 14). As the space out of the seal stem into the PBR allows some flexibility, the use of PBR simplifies space out of the production tubing and saves rig time during completions. The seal stem is run as the bottom part of the upper completion (or intermediate completion is used), while the PBR is installed in the top of the liner hanger. At Ivar Aasen, a production PBR is used.

4.2 INSTALLATION SEQUENCES OF LOWER COMPLETION

This section describes the installation sequences of the lower completions at Ivar Aasen. As the completions are nearly identical in each well, the installation operation is also nearly identical. The general installation sequence for the wells is described as per the DOPs (Detailed Operational Procedures) below in section 4.2.1. This sequence was used for wells D-10, D-11, D-14 T3, and D-19.

As D-16 had such a long screen section, the installation procedure was slightly different with two runs. The first run dropped off a sand screen section of about 1000 m, and the second run contained the rest of the lower completion. This second completion string was attached to the dropped off screen section. The installation sequence is described in section 4.2.2

4.2.1 GENERAL INSTALLATION SEQUENCE

1. Activate i-Con tool on pipe deck
2. Rig up screen handling equipment
3. Pick up and run reamer shoe assembly
4. Pick up and run screens with ICDs, tracer screens, slip-on swell packers, as per tally
5. Pick up and make up Fortress barrier valve assembly
6. Rig up a false rotary and run 3 1/2" inner string with Fortress shifting tools past the Fortress reservoir barrier valve
7. Pick up screen hanger with packer, PBR and running tool
8. Remove c-plate and make up the screen hanger to the blank pipe
9. Pick up and run i-Con logging tool assembly
10. RIH screens to planned setting depth on landing string with closed end displacement. Fill the running string every 5 stands
11. Drop setting ball. Pressure up DP to set screen hanger
12. Pressure up DP to disconnect screen hanger running tool. Blow ball seat.
13. Pump base oil into OH. Pump 90% of net open hole volume at 500-1000 lpm. Displace with OBM.
14. Pick up approx. 3 m with setting dogs above PBR. Set down weight on top of PBR to set liner hanger packer
15. Close BOP and pressure up annulus to 70 bar above leak off pressure and to pressure test the packer integrity
16. POOH running tool (about 10 m) and close FIV reservoir barrier valve
17. Close the BOP and pressure up the well to 70 bar above leak off pressure to test liner hanger packer and FIV
18. POOH with running string. Download i-Con data

4.2.2 INSTALLATION SEQUENCE WELL D-16

4.2.2.1 Installation Run 1

1. Activate i-Con tool on pipe deck
2. Rig up screen handling equipment
3. Pick up and run reamer shoe assembly
4. Pick up and run screens with ICDs, tracer screens, slip-on swell packers, as per tally
5. Pick up and Run the Scoop head assembly (Drop off system)
6. Pick up and run i-Con logging tool assembly
7. RIH lower completion (first run) to setting depth
8. Pressure up to 131 bar to release the Running Tool from the Scoop head
9. POOH with running string
10. Download data from i-Con logging tool
11. Delete i-Con logging memory from run 1

4.2.2.2 Installation Run 2

1. Dress Franks equipment for 4 ¾”
2. Pick up the 4 ¾" Seal assembly
3. Pick up and make up X-Over assembly
4. Dress Franks equipment for 6 5/8"
5. PU 6 5/8" screens with ICDs, tracer screens, swell packers as per the tally
6. Pick up and make up X-Over assembly
7. Pick up and make up Fortress barrier valve assembly
8. Rig up false rotary and run inner string with Fortress shifting tools past the Fortress reservoir barrier valve
9. Pick up screen hanger with packer, PBR and running tool
19. Make up inner string. Remove c-plate and make up the screen hanger to blank pipe
20. Pick up and run i-Con logging tool assembly
21. RIH screens to planned setting depth on landing string with closed end displacement. Fill the running string every 5 stands
10. Sting into the PBR and observe for the shroud to shear.
11. Drop the setting ball and connect top drive to pressure up
12. Pressure DP to 182 bar to disconnect screen hanger running tool. Blow ball seat with 280 bar
13. Pump circa 62 m^3 base oil into OH. Pump 90% of net open hole volume at 500-1000 lpm. Displace with OBM.

22. Pick up approx. 2.5 m with setting dogs above PBR. Set down 30 T weight on top of PBR to set liner hanger packer
23. Close BOP and pressure up annulus to 70 bar above leak off pressure and to pressure test the packer integrity
24. POOH running tool (about 15 m) and close FIV reservoir barrier valve
25. Close the BOP and pressure up the well to 70 bar above leak off pressure to test liner hanger packer and FIV
14. POOH with running string. Download i-Con data

4.3 COMPLETION DESIGN IN WELL 16/1-D-10

4.3.1 WELL OBJECTIVE

Well 16/1 D-10 was the first producer drilled and completed on Ivar Aasen. The objective of the well is to produce the northwest area of the Ivar Aasen field with a planned oil rate of 1500 Sm^3. The production will come from the Skagerrak 2 and Sleipner Formations, and it will receive pressure support from the north and south. It is completed to act as a swing producer in order to manage the required field GOR.

4.3.2 WELL COMPLETION

The well is completed according to the base case schematic shown in Figure 3-6. The depths of the well sections and relevant lower completion equipment are displayed in Table 4-1 and Table 4-2. The heel of the well is planned to be located in the gas cap, and this section is originally isolated, with the potential of producing from the section at a later time.

Casing Size [in.]	Casing Shoe Depth [m MD]
26”	434
13 3/8”	1 494
10 ¾” x 9 5/8”	2 746
8 ½” OH	4 664

Table 4-1: Casing Sizes and Depths at D-10

Completion Equipment	Depth [m MD]
Top PBR	2 669
Liner Hanger	2 676
FIV	2 697
Reamer shoe	4 467

Table 4-2: Completion Equipment and Depths at D-10

The logging tool was run with a 4 Hz logging frequency in well D-10. It was located above the liner hanger running tool as per the MDCP. The tool was in the well for 2 days, and a total of 14 774 400 data points were gathered.

4.4 COMPLETION DESIGN IN WELL 16/1-D-11

4.4.1 WELL OBJECTIVE

Well 16/1 D-11 was the second oil producer drilled and completed at Ivar Aasen. The objective of D-11 is to drain the Vestland Group (Sleipner Formation) in the eastern part of the structure. The well mainly passes through the Sleipner and Hugin formations, where Sleipner is the main contributor to oil production.

4.4.2 WELL COMPLETION DESIGN

The well completion design is identical to the basic well completion design proposed by the MDCP as shown in Figure 3-6. The depths at which some of the most important components are located are shown below in Table 4-3 and Table 4-4.

Casing Size [in.]	Casing Shoe Depth [m MD]
26”	448
13 3/8”	1 637
10 ¾” x 9 5/8”	3 065
8 ½” OH	5 090

Table 4-3: Casing Sizes and Depths at D-11

Completion Equipment	Depth [m MD]
Top PBR	2 747
Liner Hanger	2 754
FIV	2 775
Reamer shoe	4 862

Table 4-4: Completion Equipment and Depths at D-11

In D-11, the logging tool was also run with a 4 Hz logging frequency. It was located above the liner hanger running tool as per the MDCP during the lower completion installation. The tool was logging for the 2 days it was in the well and acquired 18 662 400 data points.

4.5 COMPLETION DESIGN IN WELL 16/9-D-14 T3

4.5.1 WELL OBJECTIVE

Well D-14 was the third oil producer drilled and completed at Ivar Aasen. The objective of this particular well was to drain the southwest area of the Ivar Aasen field. The goal is to produce from the Sleipner and Skagerrak Formations with a planned oil rate of 1500 Sm3/d. D-14 is intended to be a swing producer to manage the required field GOR.

4.5.2 WELL COMPLETION DESIGN

The well completion design is identical to the design proposed by the MDCP (Figure 3-6). Some relevant depths in the well are shown below in Table 4-5 and Table 4-6. The heel of the well completion will be located in the gas cap. This particular section (about 600 m) will initially be isolated, with the possibility of producing the gas cap at a later stage (after 2022).

Casing Size [in.]	Casing Shoe Depth [m MD]
26”	434
13 3/8”	1 446
10 ¾” x 9 5/8”	3 108
8 ½” OH	4 619

Table 4-5: Casing Sizes and Depths at D-14

Completion Equipment	Depth [m MD]
Top PBR	2 861
Liner Hanger	2 871
FIV	2 896
Reamer shoe	4 535

Table 4-6: Completion Equipment and Depths at D-14

During the installation of the lower completion, the tool was installed in the string directly above the liner hanger running tool. It was logging with 2 Hz causing a total logging lifetime of 12 days including the gyro data. The duration of the job was only one day, causing the a total of 4 123 116 data points to be acquired.

4.6 COMPLETION DESIGN IN WELL 16/9-D-16

4.6.1 WELL OBJECTIVE

The fourth oil producer at Ivar Aasen was well 16/9-D-16. It is located in the southeastern part of the field, and its objective is to drain the Hugin and Sleipner Formations in the last part of the 8 ½" reservoir section. The Skagerrak and Statfjord Formations are also penetrated by this well.

4.6.2 WELL COMPLETION DESIGN

The well was planned to be 5998 m MD, though it was drilled farther. It is completed according to the MDCP, with a few additional features. This well was run with a sand screen drop-off system from Halliburton in order to maximize the chance of getting the screens to TD. This was decided based on the complicated well path of the well, and the fact that the open hole section was over 2000 m long. The first section of the lower completion was about 1000 m long. A few depths at which various completion equipment is located in the well are shown below in Table 4-7 and Table 4-8. The installation sequence implemented on this well was as described above in INSTALLATION SEQUENCE WELL D-16.

Casing Size [in.]	Casing Shoe Depth [m MD]
26"	447
13 3/8"	1 526
10 ¾" x 9 5/8"	3 912
8 ½" OH	6 217

Table 4-7: Casing Sizes and Depths at D-16

Completion Equipment	Depth [m MD]
Top PBR	3 845
Liner Hanger	3 862
FIV	3 872
Drop off Scoop head	5 375
Reamer shoe	6 216

Table 4-8: Completion Equipment and Depths at D-16

The same logging tool was included for both runs of the lower completion installation in this well. In the first run it was located right above the sand screen drop-off system (scoop head), and in the second run it was located above the liner hanger running tool. During both runs the tool was logging with 2 Hz. The first run lasted for 2 days and 16 447 068 data points were gathered. The second run lasted 2 days with a total of 6 196 950 data points.

4.7 COMPLETION DESIGN IN WELL 16/9-D-19

4.7.1 WELL OBJECTIVE

Well D-10 was the fifth producer completed at Ivar Aasen. It is located in the southern part of the field, and its 8 ½" reservoir section will penetrate the Skagerrak Formation which is the main target of the well. However, the Sleipner and Hugin Formations will also be penetrated.

4.7.2 WELL COMPLETION DESIGN

The planned total depth of the well was 4859 m MD. It was planned to run the lower completion in two stages (like well D-16), but this was not done. The 8 ½" OH reservoir section of the well was drilled to a TD of 4861 m MD, but the sand screens were only run to 4507 m MD and the entire lower completion was installed in one run. Table 4-9 displays the casing sizes and depths in the well. Various completion equipment and their corresponding depths in D-19 are shown below in Table 4-10.

Casing Size [in.]	Casing Shoe Depth [m MD]
26" x 18 5/8"	468
13 3/8"	1 367
10 ¾" x 9 5/8"	2 884
8 ½" OH	4 861

Table 4-9: Casing Sizes and Depths at D-19

Completion Equipment	Depth [m MD]
Top PBR	2815
Liner Hanger	2824
FIV	2850
Reamer shoe	4 507

Table 4-10: Completion Equipment and Depths at D-19

The i-Con tool was also installed in this well, and the logging frequency used was 2 Hz. The duration of the job was 1.1 days, causing the tool to acquire 8 783 568 data points.

5 BACKGROUND INFORMATION FOR ANALYZED DATA

The data provided by Det norske oljeselskap includes downhole data acquired during five lower completion installations at Ivar Aasen. The wells in question are the oil producers D-10, D-11, D-14, D-16 and D-19 mentioned in Chapter 4. The logging tool was as mentioned located directly above the liner hanger running tool during the installations. At this location in the installation string, the tool was able to record downhole measurements which were approximately the same that the liner hanger running tool and the liner hanger itself experienced during operations. In addition to the acquired downhole data, the surface data measured by the rig was provided for each well.

The installation data was imported to Microsoft Excel 2016, where the separate downhole events that were to be investigated further were isolated. These events are:

1 - Installation of the lower completion
2 - Anchoring the lower completion
3 - Circulation through the lower completion
4 - Isolating the lower completion
5 - Pressure testing the lower completion

Event four and five both contain two subevents as the annulus and inside of the lower completion are isolated at separate times. First, the annulus is isolated by the liner hanger packer which is then pressure tested. The inside of the lower completion is later isolated by the FIV. The entire well is then pressure tested. Therefore, these two events are divided as shown:

4 - Isolating the lower completion
    a. Set Liner Hanger Packer
    b. Close FIV
5 - Pressure testing the lower completion
    a. Pressure Test Liner Hanger Packer
    b. Pressure Test Well

Once the data was imported in Excel, plots were created both for the separate downhole events and for the entire installation. For further analysis, more specific and detailed plots were made. The objective of the plots was to determine if the additional downhole information contributes to increased visibility and understanding of the events. Another objective was to determine whether there are any unique variable behavior (fingerprints) specific for each of the mentioned downhole events.

5.1 PRESENTATION OF MEASURED VARIABLES

There were six downhole variables acquired by the logging tool for each installation. The first is the pressure measured inside the installation string (internal), and the second the annular (external) pressure. In the following plots, these pressures are referred to as $i - Con\ Int, P$ and $i - Con\ Ext, P$ respectively. The data also includes the differential pressure between the internal and external pressure which is calculated by deducting the internal from the external. In the plots the differential pressure is titled $i - Con\ Diff, P$. All pressures are displayed in bar. The axial strain that the tool experiences is also measured. It is given in tons and is denoted as $i - Con\ Load$ in the plots. This measurement is positive when the tool experiences tension, and negative when there is compression. The temperature is continuously measured (in °C) by the tool at the current location, and is represented as $i - Con\ Temp$. Though the torque is also measured by the tool, it is not plotted in the following plots as it was found to have little significance when interpreting the downhole events. The color coding used in the plots presented in the thesis is shown below.

$i - Con\ Int, P$

$i - Con\ Ext, P$

$i - Con\ Diff, P$

$i - Con\ Load$

$i - Con\ Temp$

The number of measured variables included in the surface (rig) data provided by Det norske varies between six and seven. These include $Bit\ Depth$ [m MD], $Hook\ Load$ [tons], and $Hook\ Height$ [m]. The bit depth is measured as the equipment enters the hole where the origin is the rig floor (RKB). The stand pipe pressure (SPP) was measured in bar. The pump rate through the top drive was measured in liters per minute (lpm) and is denoted by $Flow\ Pumps$. The rotation measured in RPM was not provided for all five wells, and was therefore never considered in the processing of the data. The torque measured by the surface equipment were provided in the rig data but were not plotted as it was found to be of little interest. The color coding used in the final plots is as follows:

Hook Load
Hook Height
SPP
Flow Pumps

Some of the produced plots contain the same variables from all five wells in the same plot in order to easily compare the behavior of the variables in different wells. In these plots, the color coding used is:

Well D-10 A
Well D-11
Well D-14 T3
Well D-16
Well D-19

5.2 DESCRIPTION OF DOWNHOLE EVENTS

Figure 5-1 displays an overview of the complete lower completion installation performed in the first completed well at Ivar Aasen; D-10. The plot displays data for the entire installation from before the i-Con tool was picked up and until the installation string is pulled out of hole. The downhole events that were analyzed in the thesis are highlighted.

The variables included in the plot are the internal and external pressures, as well as the temperature and load measured by the tool. The stand pipe pressure and the flow rate are also included from the surface data. Similar plots for the other wells can be found in Appendix C.

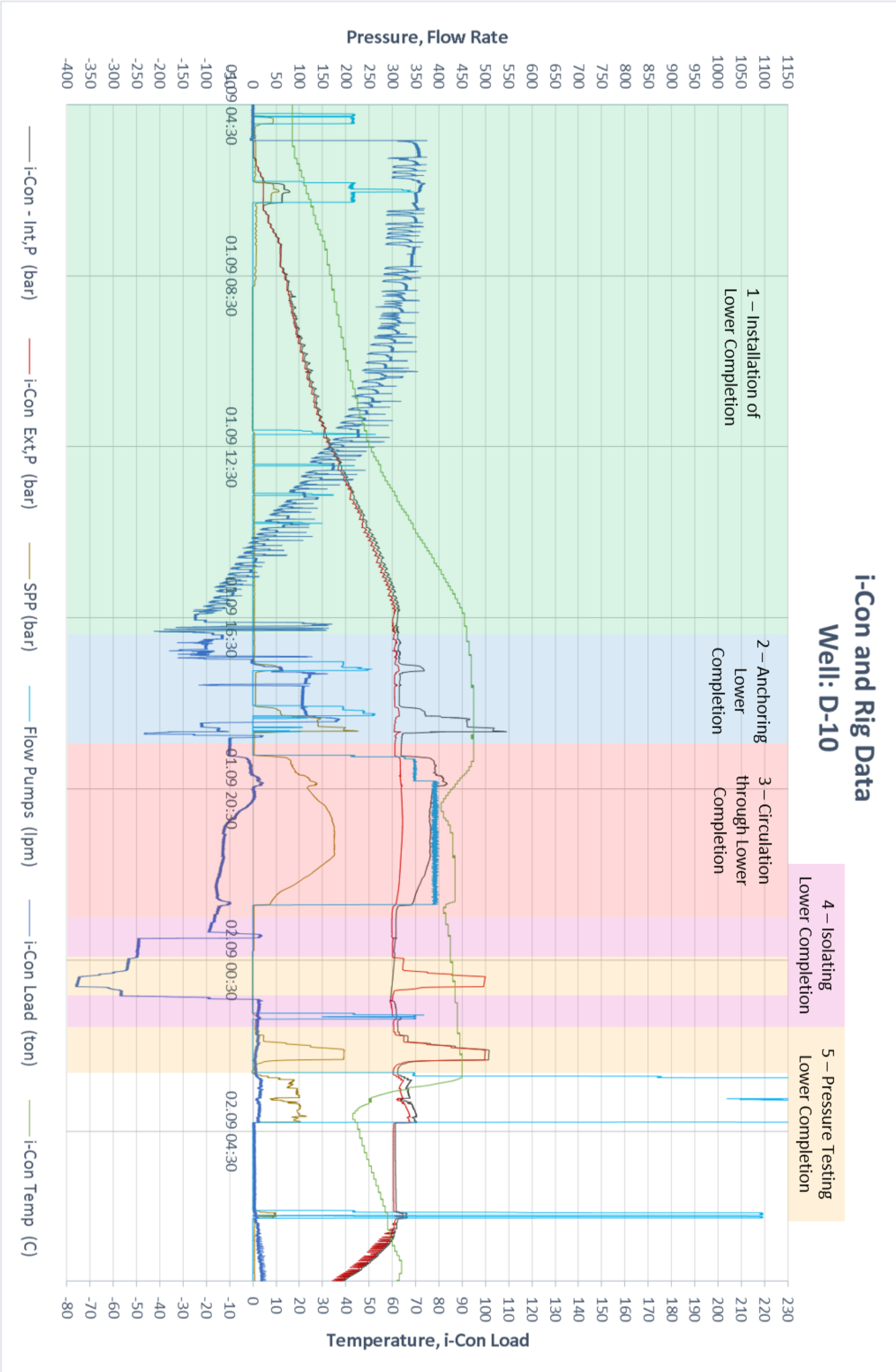

Figure 5-1: Overview of Complete Installation at D-10 and Downhole Events

5.2.1 1 - INSTALLATION OF LOWER COMPLETION

The **installation of the completion** involves running the lower completion to the planned setting depth in the well without string rotation or circulation. This depth is normally planned to be a few meters above the total depth (TD) of the 8 ½" open hole reservoir section. When the desired depth cannot be reached, the lower completion is set as deep as possible.

The data plotted in Figure 5-1 shows that the logging tool is picked up at approximately 05:00 01.09.2015. This can be seen as the axial load measured by the tool suddenly increases from zero to about 60 tons. As the tool is located directly above the liner hanger running tool, the load felt by the tool at this time is the weight of the lower completion[9] and the liner hanger running tool.

Once the lower completion string is made up, it can be run in hole to TD. On the mentioned figure one can see that in the beginning the logging tool registers nearly the same load (approximately 60 tons in tension). This indicates that the string is hanging freely so that the gravitational pull on the string is what the tool registers. However, after a time the measured load decreases. This is due to the fact that the well is deviated. Once the lower completion reaches the deviated part of the well, some of the downward force it exerts is transferred onto the wall of the casing or open hole. This results in less load for a while, but then the amount of force required to run in hole increases due to increased friction forces. At one point, the entire lower completion is pushed into the hole, causing compression of the string rather than tension. This is reflected by the logging tool as the measured values for the axial loads are negative, indicating compression.

When running in hole, there are often restrictions along the way. These may require reciprocating the string in order to work past, circulating while running in hole, or setting down a lot of weight. Once the desired setting depth is reached, circulation is established until returns are seen over the shakers. The up and down weight of the string is then recorded before the installation is complete and the next downhole event commences.

[9]See Section 4.1 for further details on the equipment included in the lower completion

5.2.2 2 - ANCHORING OF LOWER COMPLETION

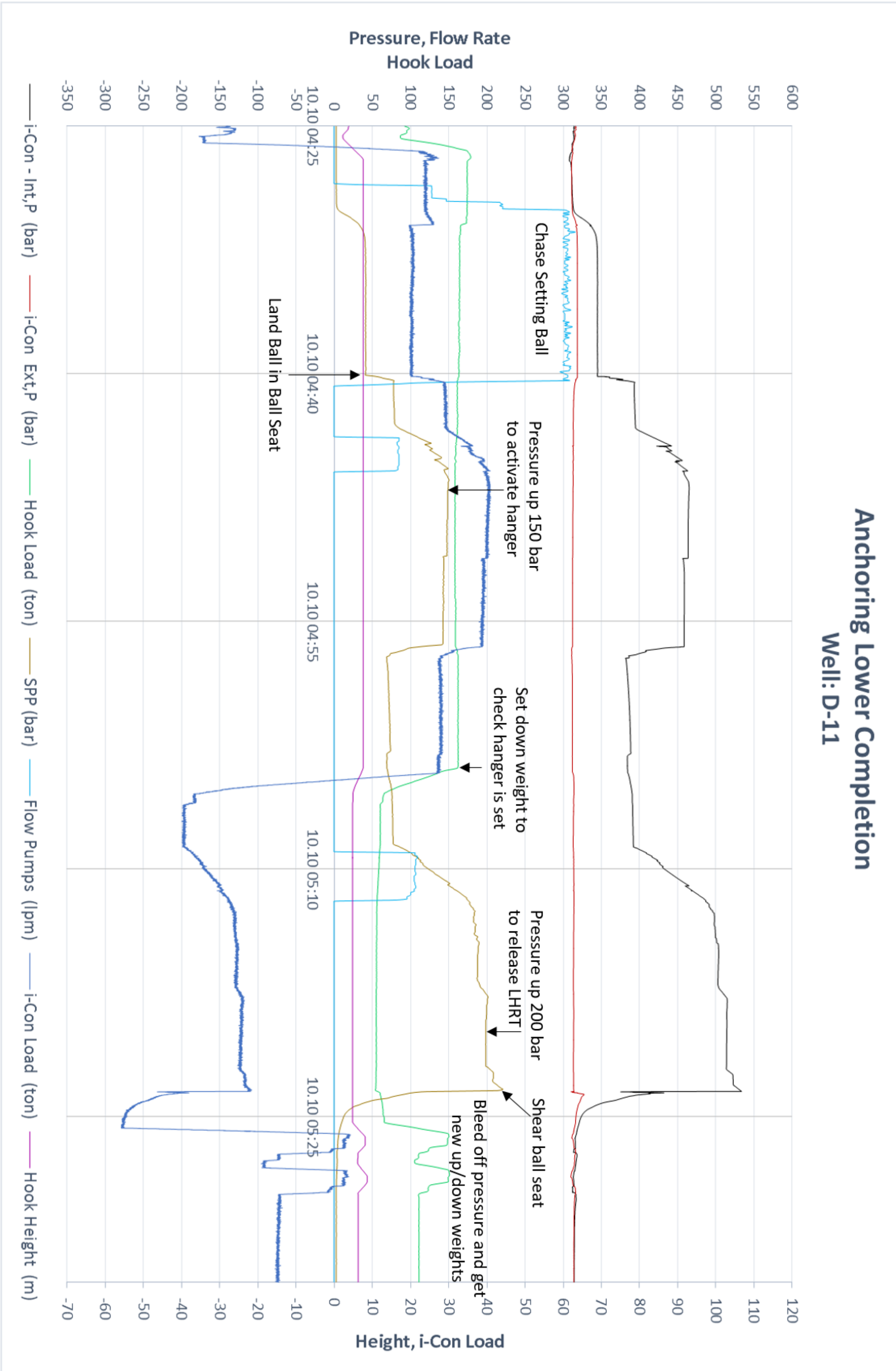

Figure 5-2: Description of Anchoring Operations

Once the lower completion is run in to the planned screen setting depth, or to the maximum possible setting depth, the liner hanger is to be activated so the lower completion becomes firmly anchored to the casing wall using slips[10]. This event is shown and labeled in Figure 5-2.

The **anchoring of the lower completion** is initiated when the setting ball is dropped. The ball falls freely at first, and is then pumped (chased) down the installation string until it lands in the ball seat located in the liner hanger. The installation string above the ball seat then becomes a closed volume. Once the ball is seated, the flow rate is reduced and the pressure inside the installation string (internal pressure) is increased to a predetermined pressure (150 bar in Figure 5-2) and held for approximately 5 minutes in order to activate the slips in the liner hanger, anchoring it to the casing wall. After the pressure is bled off, weight is set down on in order to verify whether the liner hanger has been properly anchored. If the liner hanger slides down, the internal pressure is increased again to attempt a new activation.

Once the liner hanger is correctly anchored, the installation string is pressured up to 200 bar in order to release the liner hanger running tool. At this point, the installation string can move freely without moving the liner hanger and lower completion. As soon as the running tool is released, the string is pressured up further until the ball seat is sheared. This causes the volume to become an open volume again, allowing circulation. The pressure is bled off once more, and the string is pulled up to gain new up and down weights.

[10]**Slips**: hardened metal grip with steel teeth which are pushed against the inside of the casing to hang off the liner hanger and lock the energized packer in place

5.2.3 3 – CIRCULATION THROUGH LOWER COMPLETION

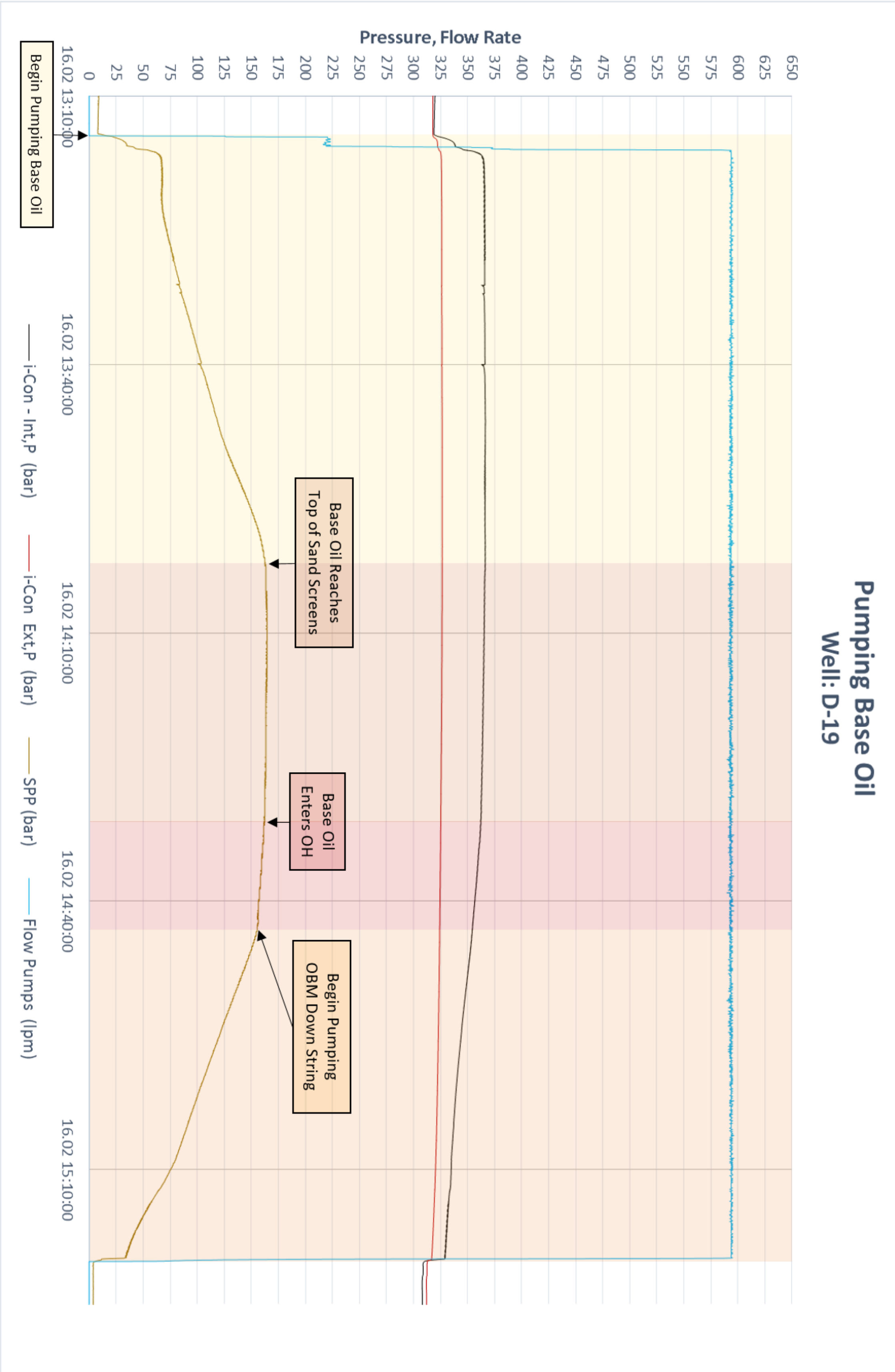

Figure 5-3: Illustration of Circulation Operations and corresponding SPP responses

After the lower completion is anchored in place, **circulation through the lower completion** is established as shown in Figure 5-3. This is due to the fact that a fluid called base oil must be pumped into the reservoir section prior to isolating the lower completion and commencing the other completion operations.

The base oil is pumped in order for the reservoir section with screens to be filled with a suitable fluid. The main objectives of the base oil is to dissolve the mud filter cake on the borehole walls as well as any plugging material in the screens. It is also designed to flow easily through the screens without blocking them. As the base oil is a low density fluid, it maximizes the underbalance in the well during the well clean-up and flow initiation prior to production. Therefore, the well clean-up becomes as quick and effective as possible. This fluid also causes the handling of initial flow from the well (which includes completion and reservoir fluid) to be as easy as possible because oil comes in returns directly. Finally, base oil minimizes the need for flaring on the rig during the clean-up.

The volume of base oil is calculated so that it only fills about 90% of the screen section of the well. Hence, the oil based mud (OBM) which is in the well needs to be displaced out and removed. This displacement is initiated once the pumping of base oil has begun. This can be seen in Figure 5-3 when the stand pipe pressure (SPP) suddenly increases at the same time the flow rate increases from zero. This initial pressure increase corresponds to the friction forces through the pumping system. As the base oil is lighter than the OBM filling the well, the u-tube effect[11] causes an increasing amount of pressure in order to displace the heavier oil based mud down the installation string. Once the base oil reaches the top of the sand screens in the well, the SPP levels out until the base oil enters the open hole. This causes a slight pressure decrease.

Once the total volume of base oil is pumped down the string, OBM is pumped to further displace the base oil. This can be recognized in Figure 5-3 as the point where there is a marked change in the SPP (it begins to decrease). The reason behind this pressure response is a reverse u-tube effect compared to what was seen before as the OBM is heavier than the base oil. Once the base oil is displaced to the top of the sand screens (Figure 5-5), pumping ceases.

[11]U-tube effect: in a u-tube manometer, the height of one leg of fluid is changed by altering the fluid density in the other leg. Hence, when the installation string is one leg and the annulus is the other, pumping a denser fluid into the installation string will cause fluid to flow into the annulus, and vice versa.

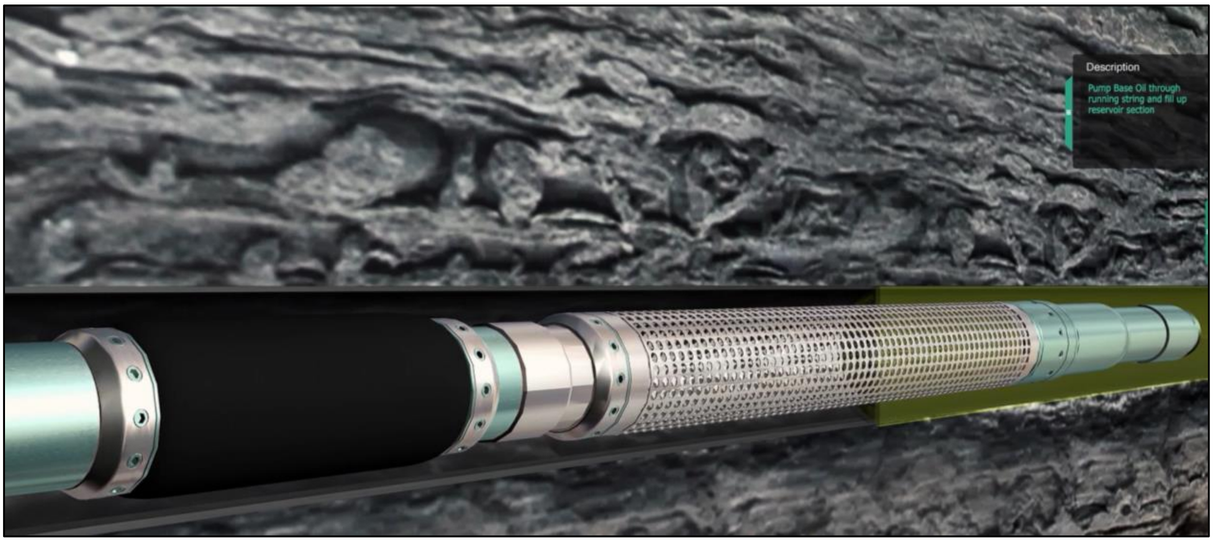

Figure 5-4: Snap Shot of Base Oil Entering Open Hole (Screenshot from Ridge AS Animation, 2016)

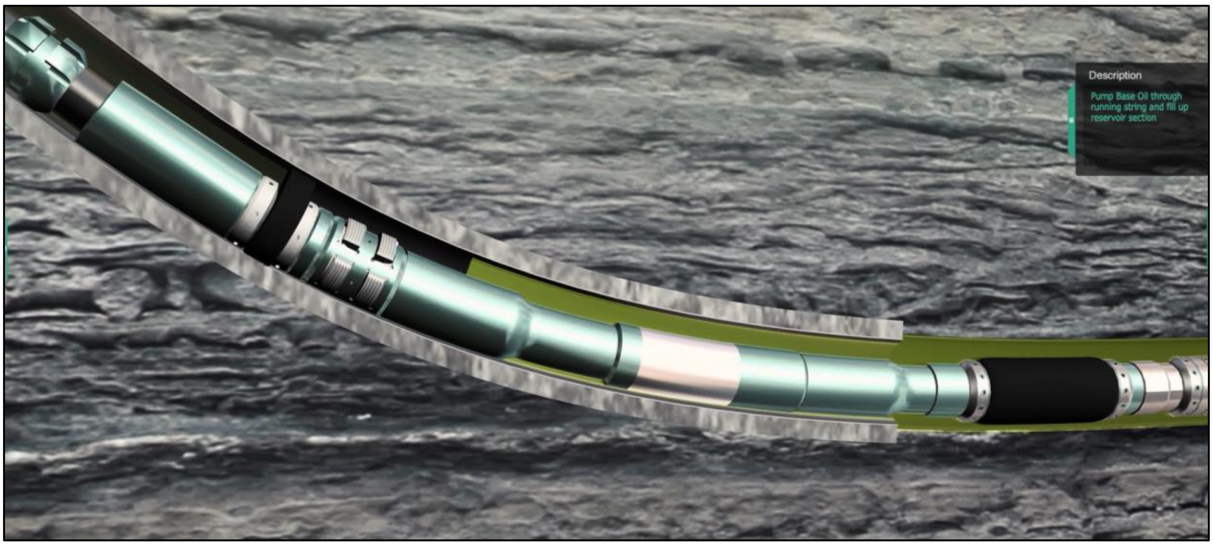

Figure 5-5: Snap Shot of Base Oil Reaching Top of Lower Completion (Screenshot from Ridge AS Animation, 2016)

5.2.4 4 – ISOLATING LOWER COMPLETION

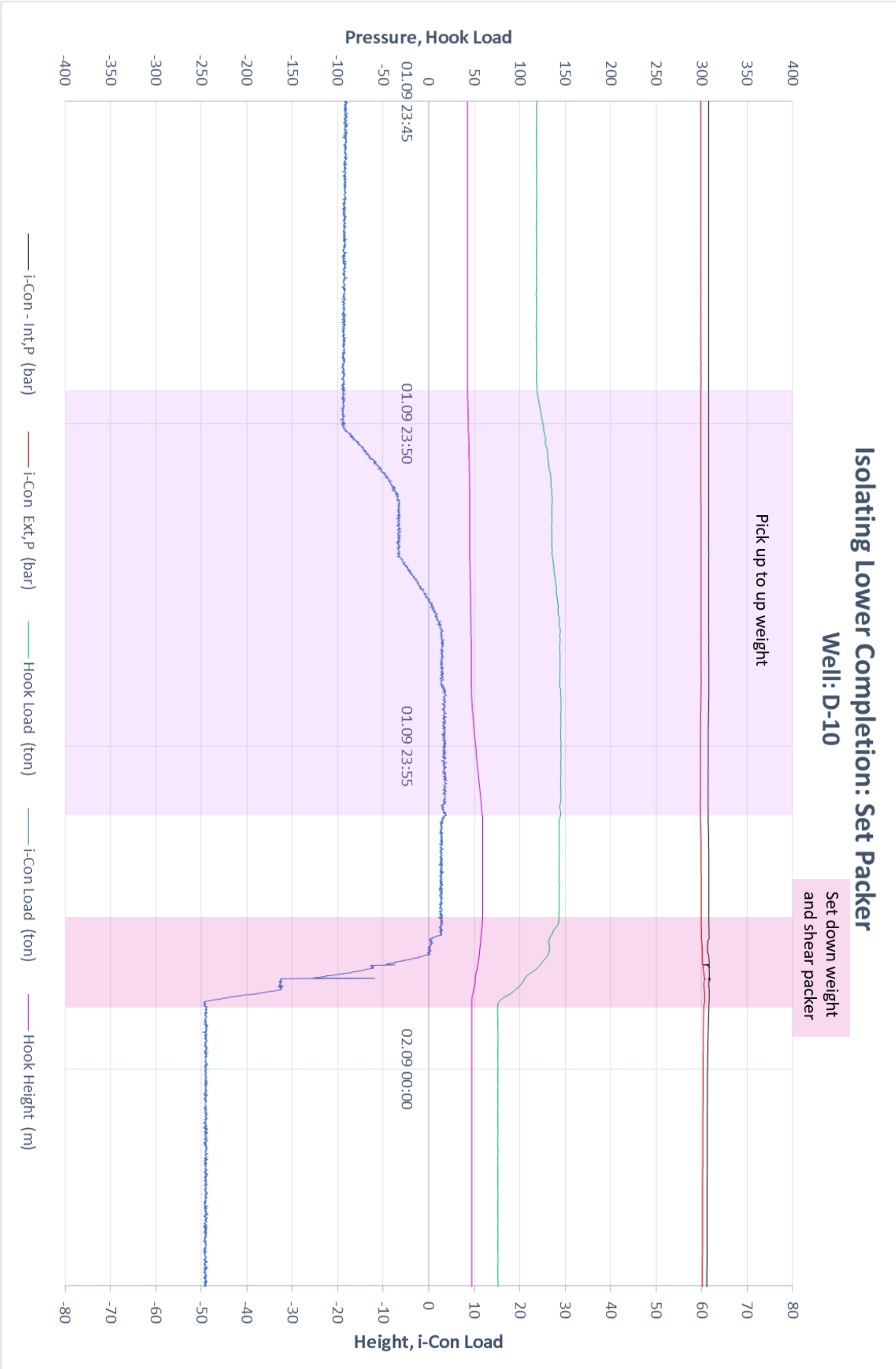

Figure 5-6: Illustration of Operations to Set Packer

Once the reservoir section of the well has been displaced to base oil, the lower completion is ready to be isolated. This is done in two different steps that occur at various times (see Figure 5-1). The first of these steps is to seal the annulus with the liner hanger packer (event 4a) and lock it in place, which corresponds to step 13 in Section 4.2.1.

This step commences directly after the displacement of base oil is complete and is displayed in Figure 5-6. The installation string, which is released from the lower completion, is first slowly picked up to a couple of meters past the recorded up-weight. This ensures that the setting dogs located on the liner hanger running tool are activated. The picking up of the string is evident when looking at the hook height in Figure 5-6.

The string is then lowered to set down weight on top of the PBR. This weight is maintained for at least five minutes to guarantee the packer has sheared and set. This implies that the packer is squeezed so that it expands and causes a seal between the liner hanger and the casing wall, and that the energized packer is locked in place to prevent later contraction.

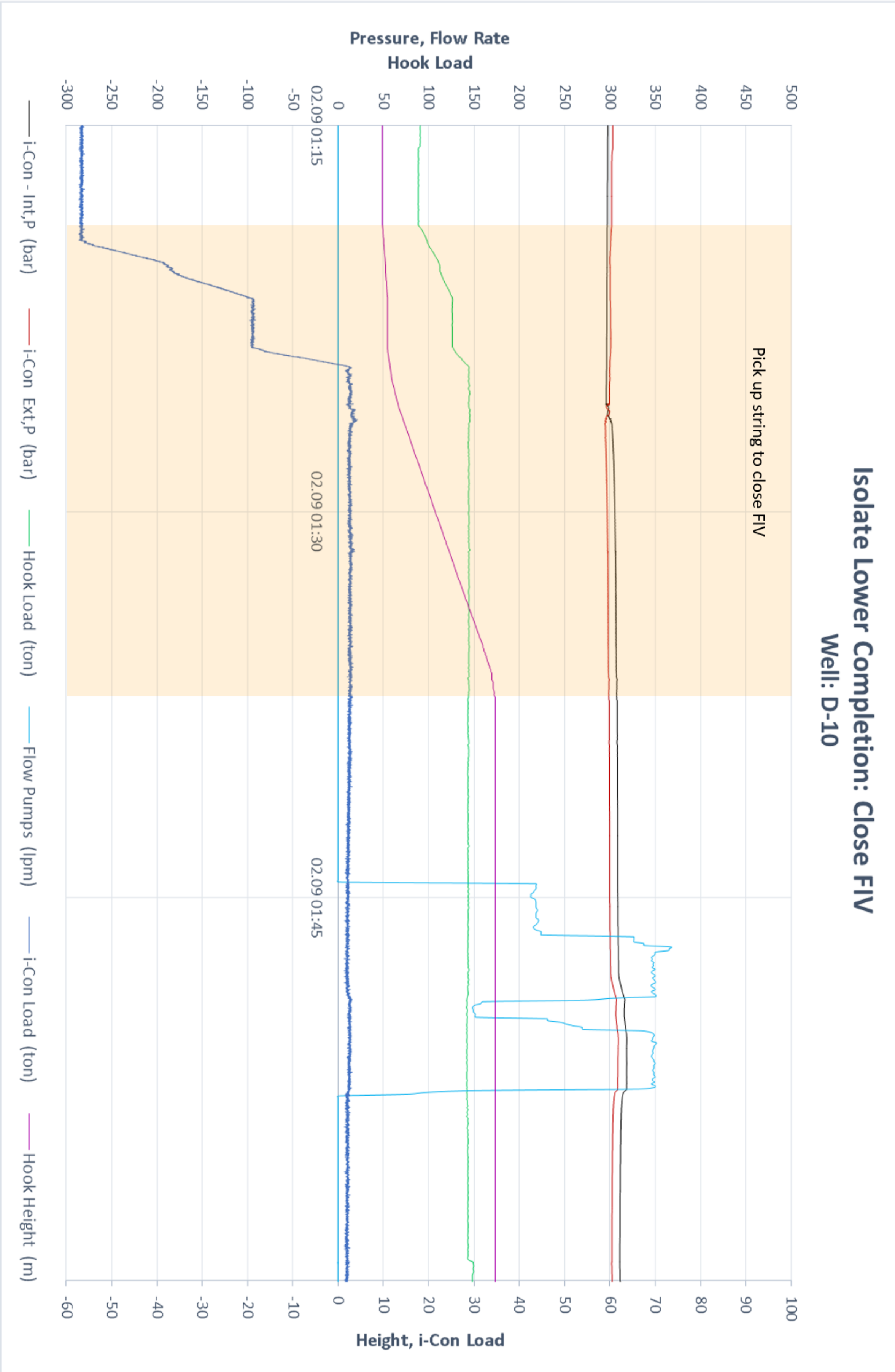

Figure 5-7: Illustration of Operations for Closing FIV

The second part of isolating the lower completion (see Figure 5-1) is to seal its inside using the FIV located below the liner hanger. This event (4b) is displayed in Figure 5-7 and corresponds to step 15 of the general installation sequence listed in Section 4.2.1.

Inside the installation string there is an inner string with a shifting tool located below the FIV (see step 5 in Section 4.2.1). When closing the FIV, the installation string is pulled out of the PBR so that the shifting tool is pulled past the FIV. This causes the valve to be mechanically closed. This step also includes pulling the seal located on the liner hanger running tool to be pulled out of the PBR in order to ensure that the installation string is completely free of the lower completion. When the seal is pulled out, there is no longer any division between the inside of the installation string from the annulus. Hence, from this point there is free communication between the inside and outside of the string.

The favorable method to close FIVs is to space out the installation string so that it can be pulled out approximately 25 m in one movement such as it was done in well D-10 (see Figure 5-1). When racking back one stand during the operation is required, the data becomes more undistinguishable and unclear.

5.2.5 5 – PRESSURE TEST LOWER COMPLETION

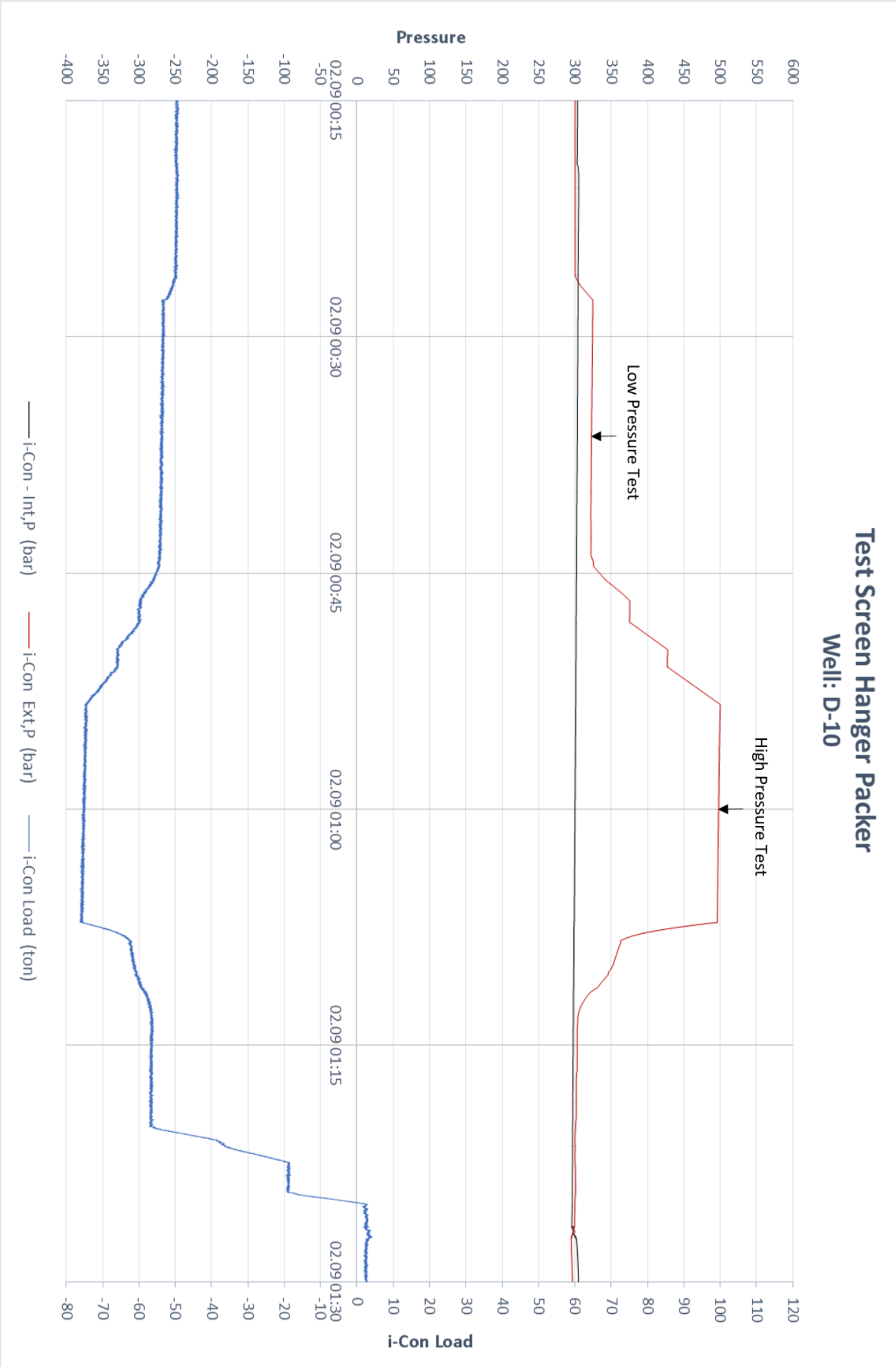

Figure 5-8: Description of Hanger Packer Pressure Test

After each step in the isolation of the lower completion, a pressure test is done in order to verify that the lower completion is properly isolated. As the isolation occurs in two steps, the **pressure testing of the lower completion** also occurs in two steps.

The first step (step 14 in section 4.2.1) is to pressure up the annulus to confirm that it is completely sealed. First the BOP is closed, then the cement pump is lined up to pressure up the annulus through the kill line. The pressure test often involves a low pressure test first (about 20 bar increase), followed by a high pressure test (approximately 200 bar increase). The pressured is then held for a specified amount of time. During the pressure test, there is not supposed to be any leaking of the pressure (pressure drop of the external pressure) as this might indicate a leak in the packer. If this occurs, the pressure test is considered unsuccessful.

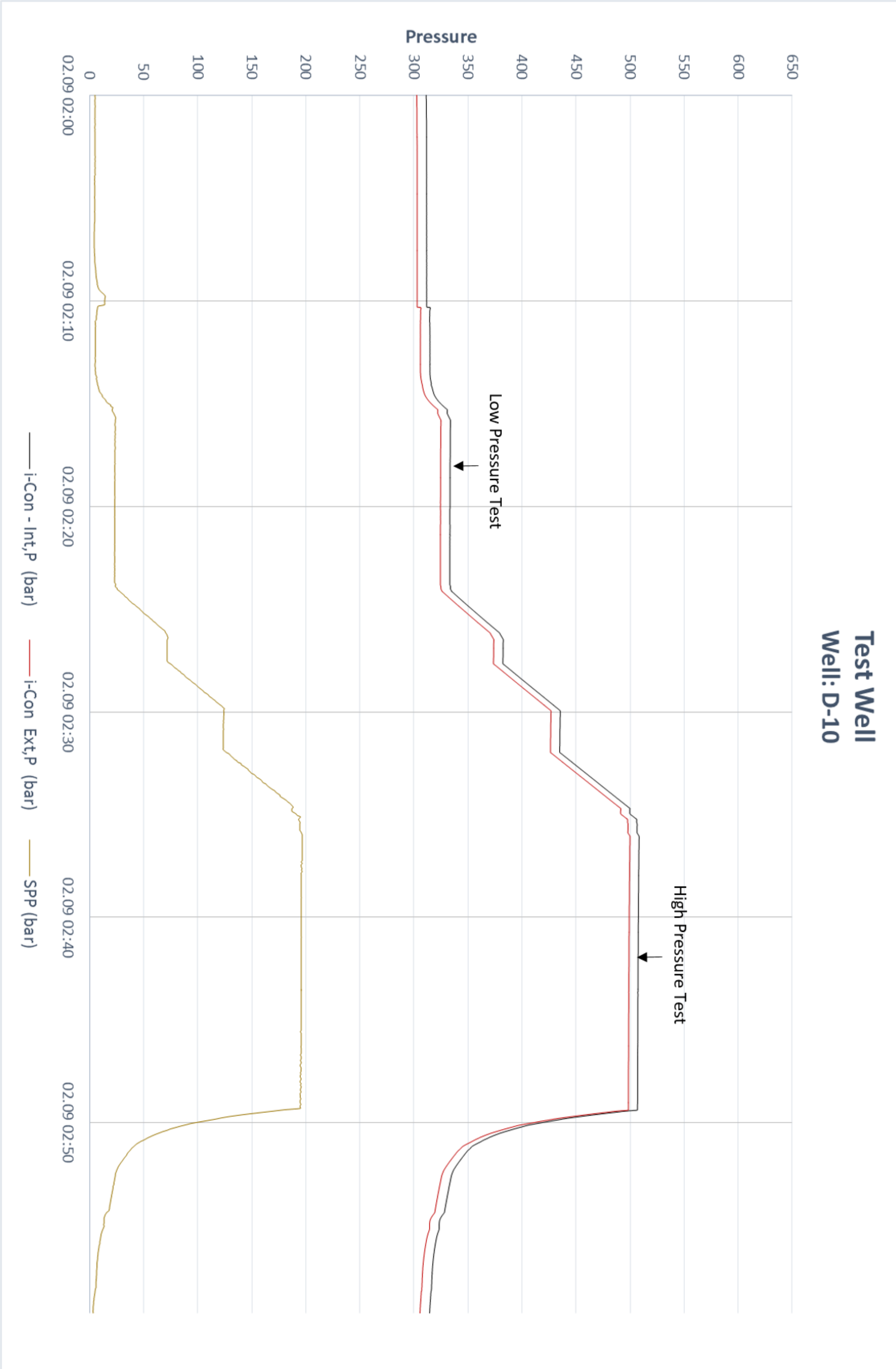

Figure 5-9: Illustration of Pressure Testing the Well

The second part of the pressure test occurs after the FIV has been closed (see Figure 5-1) and the liner hanger running tool has been pulled free of the PBR. The pressure test is designed to test both the FIV and the hanger packer.

This pressure test has been performed at Ivar Aasen by pressuring up with both the cement and mud pumps. The pressure test shown in Figure 5-9 involves pressuring up the well by pumping down the installation string and kill line simultaneously. In order for the test to be successful, the volume pumped to increase pressure must equal the volume bled off. There is to be no pressure drop in the well in order for the test to be successful.

Following the final pressure test, the well is circulated clean by several bottoms up volumes before the installation string is pulled out of hole.

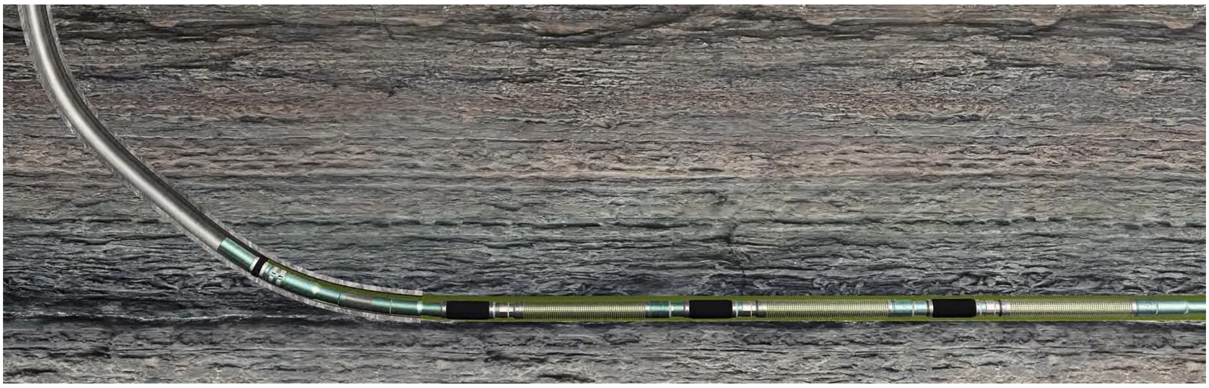

Figure 5-10: Snap Shot of Installed Lower Completion Downhole (Screenshot from Ridge AS Animation, 2016)

6 LOWER COMPLETION INSTALLATION SUMMARIES

The following chapter includes a summary of the lower completion installations that took place in the five oil producers at Ivar Aasen. General remarks on the operations are made, while the relevant downhole events and operational problems are highlighted. The plots showing the overview of each well installation can be found in Appendix C.

6.1 WELL 16/9-D-10

Though some losses were experienced while making up and running in hole with the screen section of the completion, the installation initially went rather smoothly. When reaching the casing shoe at 2746 m MD, there was a heavy backflow indicating that the float shoe was not holding causing an open ended displacement. There was a restriction at 4384 m MD, and the string was worked down from this depth to the setting depth at 4467 m MD by reciprocation (16/1-D-10 FWR Section B - Drilling and Completion, 2016). The TD of the OH section was 4664 m MD, causing a rat hole of 197 m.

Circulation was broken with 250 lpm and the screen hanger setting ball was dropped. The ball was in free fall for 30 minutes before it was chased with oil based mud (OBM) pumped at 250 lpm. The ball landed in the seat, and the hanger was anchored to the casing. The liner hanger running tool was released, and ball seat sheared.

The base oil was pumped into the reservoir section without significant losses. The liner hanger packer was then set and pressure tested. As the test was good, the pressure was bled off and the string was picked up to close the FIV. Circulation was broken with 350 lpm before the annular preventer was closed and the well was pressure tested. The circulation was broken again and 1.8 bottoms up was circulated at 2000 lpm. The well was flow checked on trip tank, and the string was pulled out of hole.

6.2 WELL 16/1-D-11

Dynamic losses were experienced when running in hole with the sand screens, and at 2101 m MD static losses also occurred. When running in hole from 2128 (i-Con tool picked up) to 2773 m MD backflow was observed indicating an open end displacement. Though the floats were attempted sealed, there was no success (Daily Drilling Reports Well 16/1-D-11, 2015). The OH section was reached at 3065 m MD.

When running in OH there was no observed backflow, and the returns were according to open ended displacement. Though there were no losses initially, minor losses were experienced from 3700 m MD. At 4866 m MD a restriction was met which could not be passed. The Turborunner Reamer Shoe was activated and several attempts were made to pass the restriction. Finally, it was decided that the lower completion was to be installed above the restriction, 224 m above the planned setting depth.

The installation string was spaced out, and the screen hanger setting ball was dropped and allowed to free fall for 15 minutes. It was then chased with OBM at 300 lpm. The ball was seated, and the hanger was activated. The liner hanger running tool was released and the ball seat was sheared.

Base oil was pumped with no significant losses, and the liner hanger packer was set. During the pressure test of the packer it was observed that the pressure was dropping off. Surface equipment was troubleshot to identify the leak, but nothing was found. Three more packer tests were performed with the same result as the first one. In spite of this, the FIV was closed. The final pressure test of the well (pressured up through kill line and string) showed that there were no leaks in the FIV or the packer. Circulation was established, and 2 bottoms up were circulated before the string was pulled out.

6.3 WELL 16/9-D-14 T3

The first 1600 m of running in hole with the lower completion, no losses were recorded although backflow was observed from 1000 m MD (Daily Drilling Reports Well 16/9-D-14 T3, 2015). The lower completion was run to the planned screen setting depth of 4535 m MD. Circulation was broken with 600 lpm prior to dropping the screen hanger setting ball. The ball was in free fall for 20 minutes.

The ball was chased and landed in the ball seat. The hanger was activated and verified set prior to releasing the liner hanger running tool and blowing the ball seat. The reservoir section was filled with base oil up to the formation isolation valve prior to setting the hanger packer. The packer was pressure tested and the pressure was found to be leaking off. The packer was reset, and the pressure test repeated twice with the same result. The FIV was closed, and circulation was broken with 200 lpm. The well was then pressure tested down both the kill line and string, and no significant pressure drop was observed. The well was flow checked after circulating 2 bottoms up, and the string was pulled out of hole.

6.4 WELL 16/1-D-16

The **first section of the lower completion** that was run was 841 m long. When running in hole there were many restrictions so the string was rotated and weight was set down in order to pass them. The entire string weight was set down at various times, and rotation was established up to 8 rpm. TD (6216m MD) was finally tagged. The scoop head was released and the screens were dropped so the scoop head was positioned at 5374 m MD. The installation string was pulled out of hole after circulating bottoms up.

The **second section of lower completion** run was 1530 m. In this run there were no significant restrictions or problems down to 5351 m MD. The topdrive was made up to the string and 5 m^3 was circulated to clear potential debris. When entering the scoop head of the first section of sand screens, the string stopped 6 m shallower than planned. Maximum weight was set down (45 ton hook load) and expected pressure increase was observed when string landed in connection.

The setting ball was dropped and allowed to free fall for 10 minutes before it was chased with 300 lpm. 30 tons were set off on the scoop head. The ball was observed landed in ball seat, and hanger was activated and verified set, followed by the release of the running tool and shearing of the ball seat. Weight was set down on the liner hanger, and base oil was pumped until the entire screen section was filled. During this operation, losses were experienced with an increasing rate from 5 m^3/hr to 11 m^3/hr. The total loss after the circulation was 305 m^3. 46 bar was observed trapped on stand pipe along with return flow in flowline after pumps were shut down. The well was monitored with closed BOP for four hours.

The liner hanger packer was set and pressure tested. As the test was considered successful, the FIV was closed. 2.5 bottoms up were circulated, and the string was pulled out (Daily Drilling Reports Well 16/1-D-16, 2016).

6.5 WELL 16/1-D-19

After picking up and making up i-Con to the installation string, damage was found on surface equipment which took about 4.5 hours to repair in total. When running in open hole, minor losses occurred (total of $3m^3$) and the hole was in good condition. As the lower part of the reservoir section only contains shale, it was decided to set the screens 354 m above the TD of the reservoir section.

The ball was dropped once the screens were positioned at the desired setting depth. After free falling for 15 minutes, the ball was chased with 300 lpm. The ball was observed landed, and so the string was pressured up to set the hanger. When setting down weight to verify that the hanger was set, it was observed that the liner hanger slid down. The hanger was repositioned in the well and the hanger was set again. The second time it was verified set. The running tool was then released and the ball seat sheared.

The base oil was pumped and displaced into the OH section. The liner hanger packer was then set, and it was attempted pressure tested. However, the pressure was dropping off. The FIV was closed, and the entire well was pressure tested. This test was successful. Circulated bottoms up with 1900 lpm, and pulled out of hole (Daily Drilling Reports Well 16/1-D-19, 2016).

7 RESULTS

The following sections will present the final results and findings from the data analysis that was performed on the oil producers at Ivar Aasen. The results are presented in such a way that all the findings from each downhole event is gathered in one section. These five downhole events are as follows:

7.1 - Installation of Lower Completion
7.2 - Anchoring of Lower Completion
7.3 - Circulation Through Lower Completion
7.4 - Isolating Lower Completion
    a. Setting Liner Hanger Packer
    b. Closing Formation Isolation Valve
7.5 - Pressure Testing Lower Completion
    a. Pressure Testing Liner Hanger Packer
    b. Pressure Testing Well

7.1 INSTALLATION OF LOWER COMPLETION

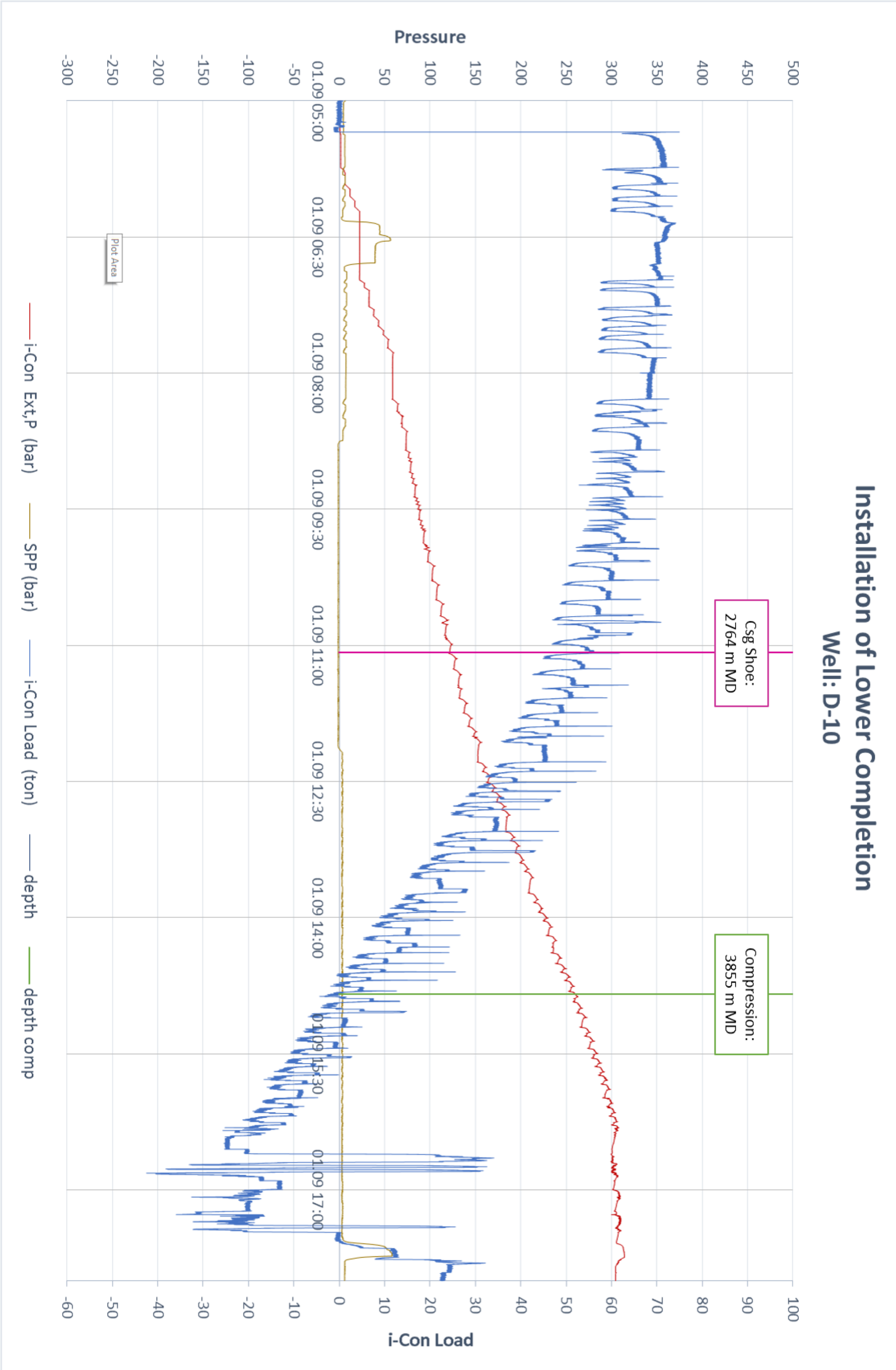

Figure 7-1: Installation of Lower Completion in Well D-10

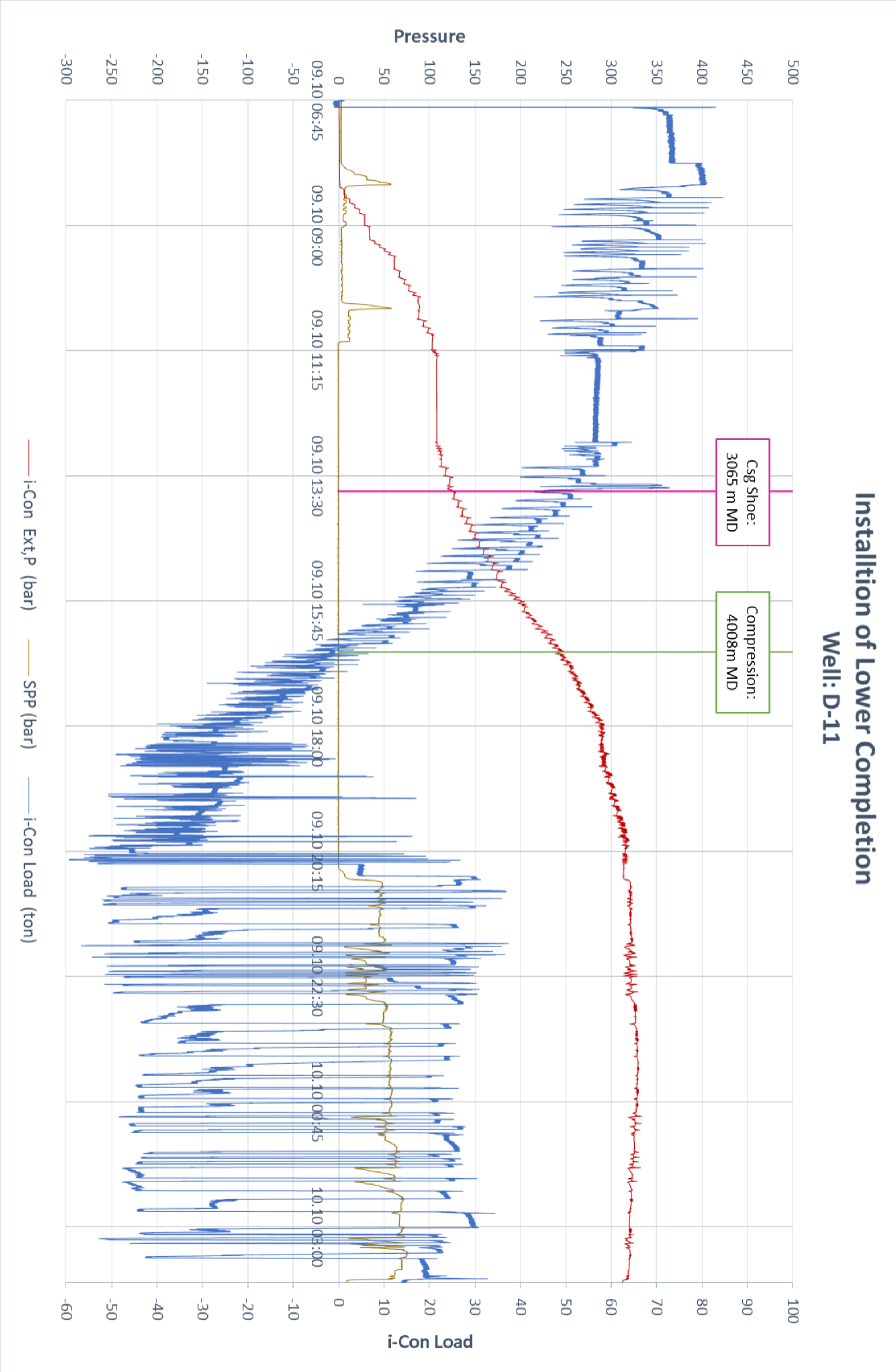

Figure 7-2: Installation of Lower Completion in Well D-11

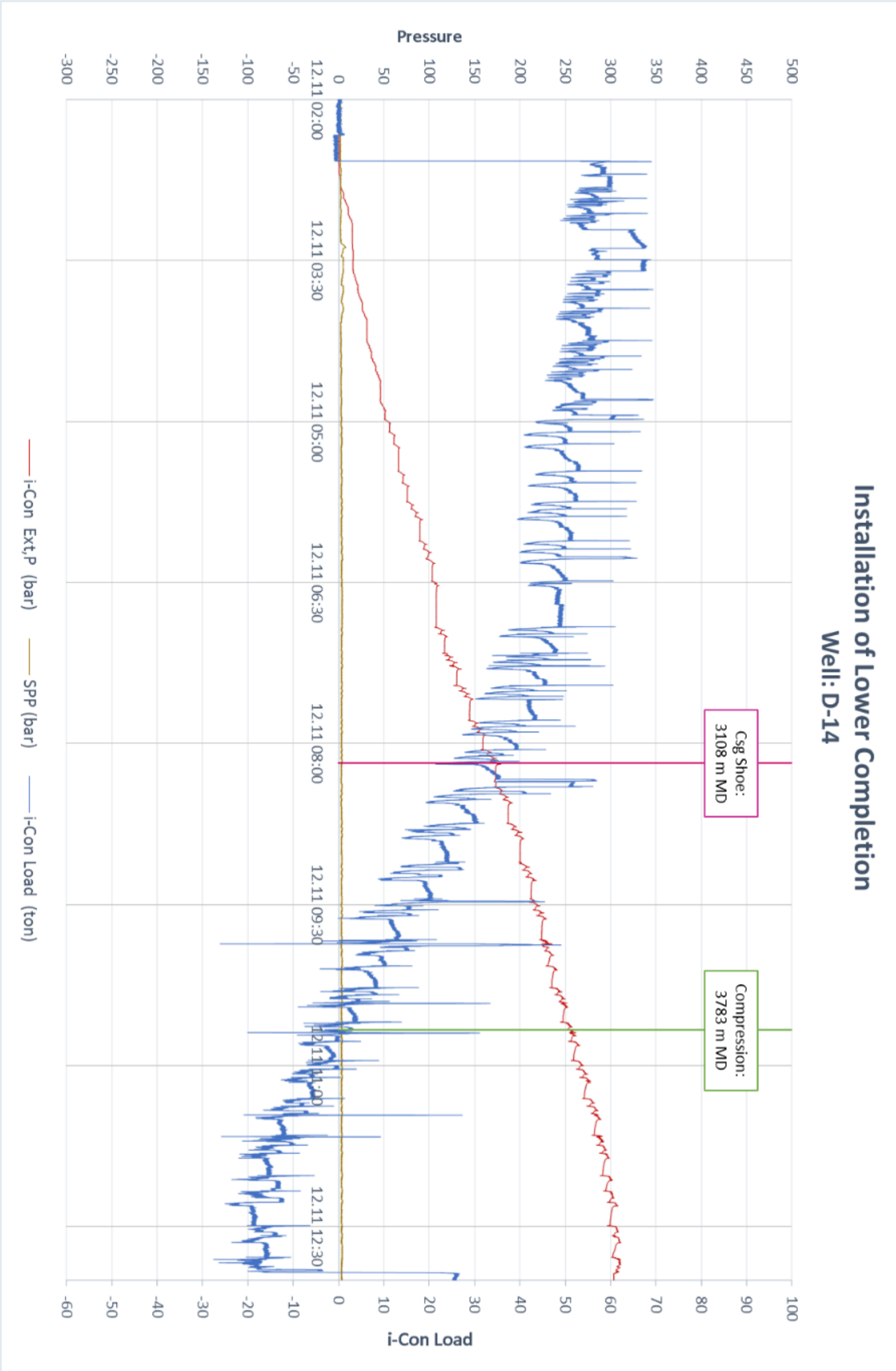

Figure 7-3: Installation of Lower Completion in Well D-14 T3

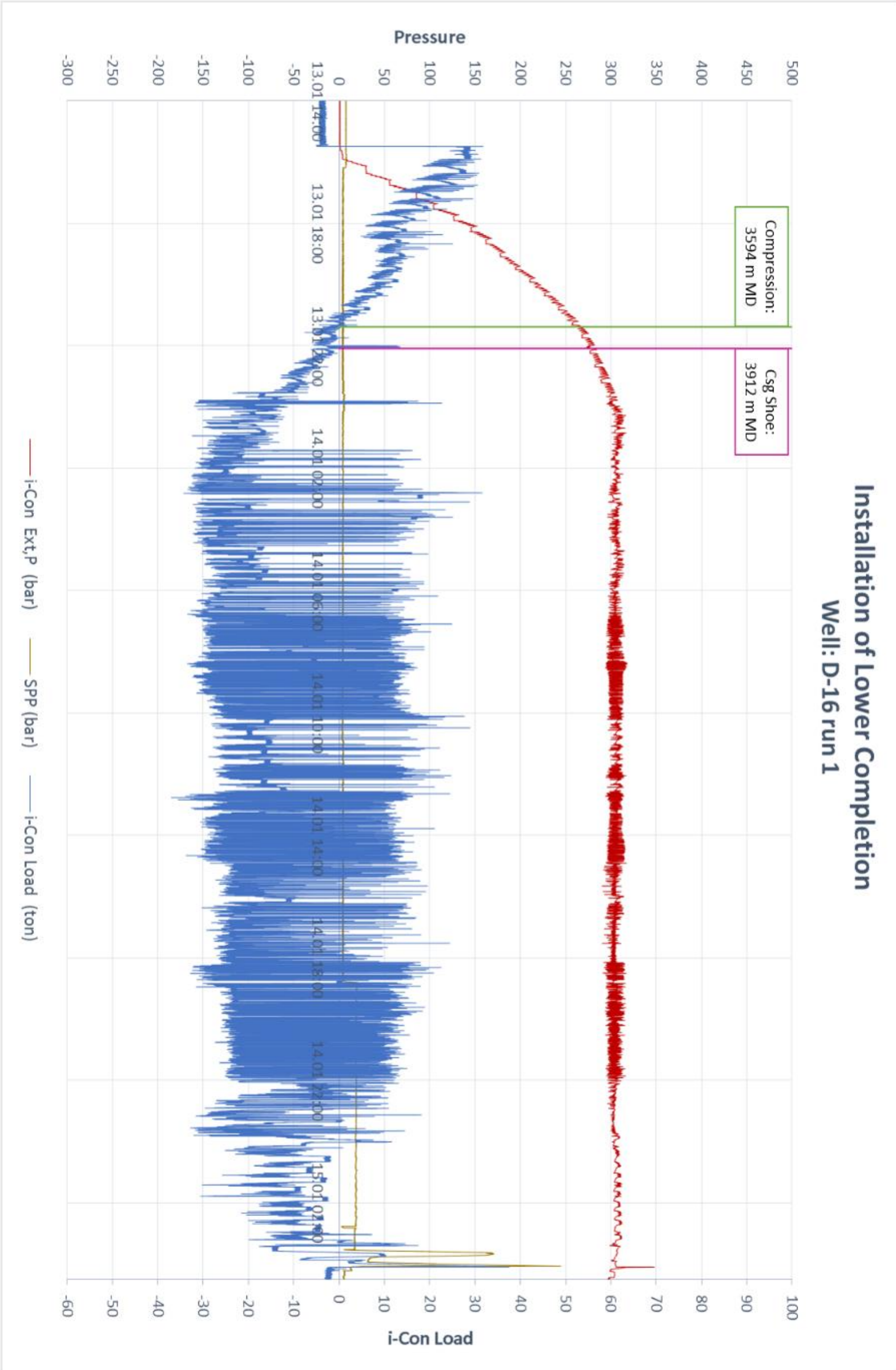

Figure 7-4: Installation of First Part of Lower Completion in Well D-16

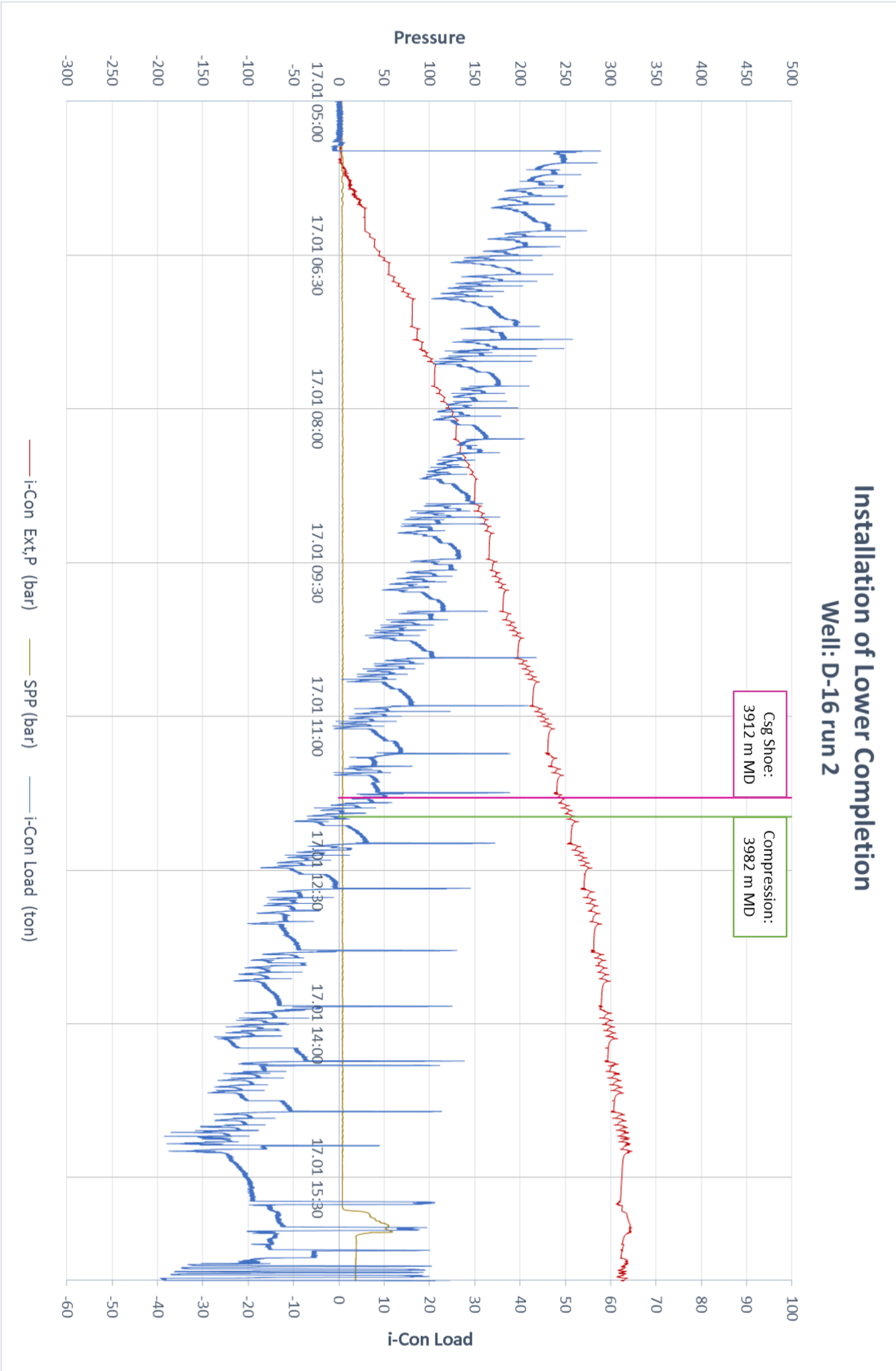

Figure 7-5: Installation of Second Part of Lower Completion in Well D-16

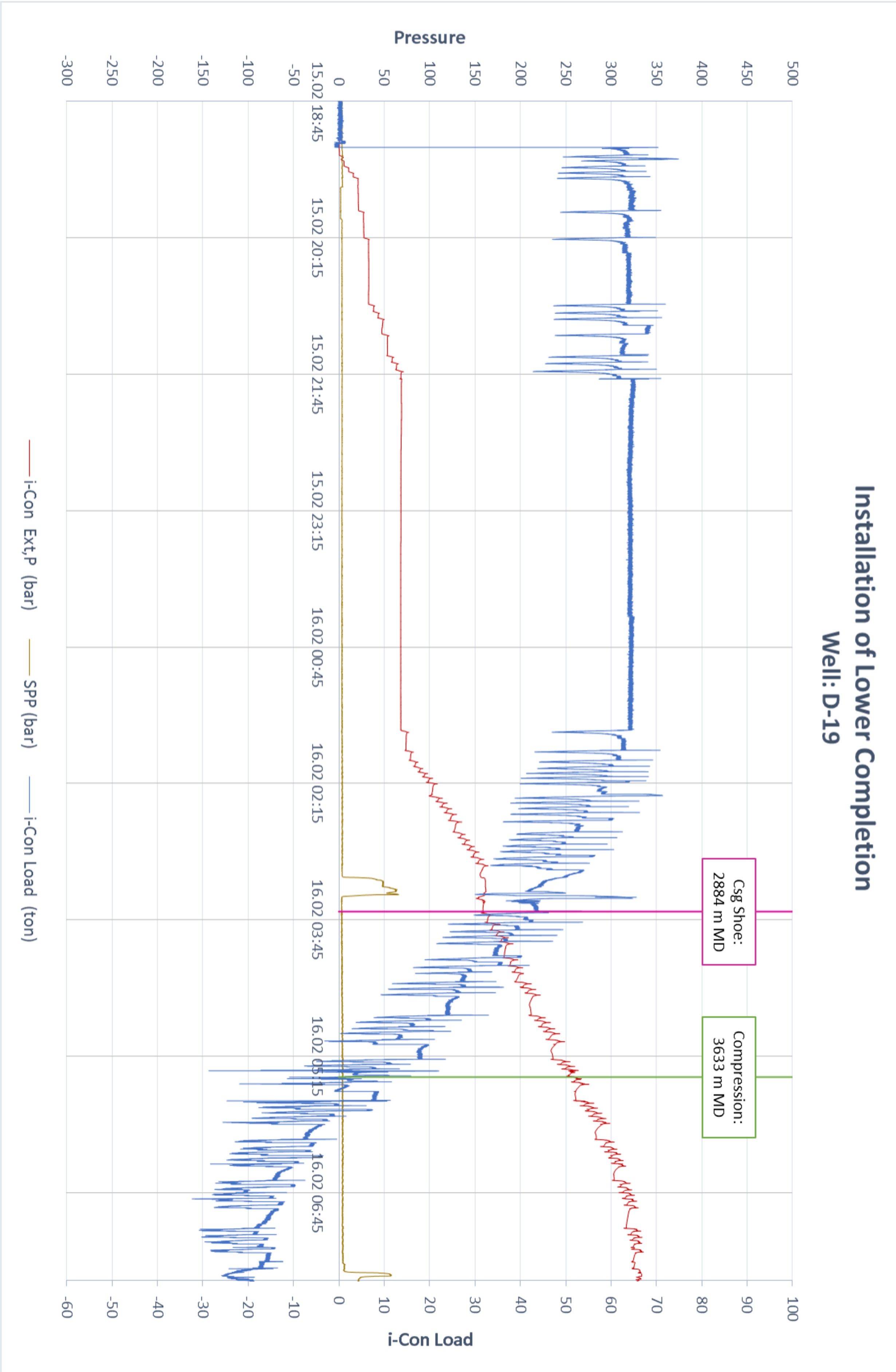

Figure 7-6: Installation of Lower Completion in Well D-19

Figure 7-1 through Figure 7-6 display data regarding the installation of the lower completion in each well. The figures also display the time when the 9 5/8" casing shoe was reached and its depth (pink marker), and the time and depth the installation string became compressed (green marker).

The included data is the axial load and external pressure measured by the tool, in addition to the SPP. The i-Con load is included as it provides information on what loads the liner hanger is subjected to downhole. As negative values represent compression, the tool load provides detailed information on how much the string is compressed. The maximum compressions are listed in Table 7-2.

The external pressure is included as it provides a pressure gradient when running in hole with the lower completion. Finally, the SPP is included as it is related to the flow rate and therefore provides a clear indication on when flow was used to activate the reamer shoe and wash down the lower completion.

Table 7-1 and Table 7-2 provide various data regarding the well and lower completion. The total depths of the 8 ½" OH reservoir section, casing shoe depths, and lower completion shoe depths are listed in Table 7-1 along with the calculated length of the lower completion, linerlap, and the length of lower completion positioned in the open hole. These calculations are based on the data provided in the tables of Chapter 4.

	TD of OH Section	Casing Shoe Depth	Lower Completion Shoe Depth	Length of Lower Completion	Linerlap	Length of Completion in OH
D-10	4664 m	2764 m	4467 m	1798 m	95 m	1703 m
D-11	5090 m	3065 m	4862 m	2115 m	318 m	1797 m
D-14 T3	4619 m	3108 m[12]	4535 m	1674 m	247 m	1427 m
D-16	6217 m	3912 m	6216 m	2371 m	67 m	2304 m
D-19	4861 m	2884 m	4507 m	1692 m	69 m	1623 m

Table 7-1: Relevant Depths and Lengths for the Completions in the Five Oil Producers

[12]As the well was sidetracked, this is the kick off point from well D-14 T2

Table 7-2 shows data related to the compression of the string. This information was gained from lower completion tallies, Final Completion Programs, and Final Well Reports.

	Casing Shoe Depth	Angle at Casing Shoe	∑HWDP in Installation String	Compression Depth[13]	Compression Depth from Csg Shoe	Max Compression
D-10	2 764 m	76° inc	579.2 m	3 855 m	1091 m	42 ton
D-11	3 065 m	78° inc	569.7 m	4 008 m	943 m	59 ton
D-14 T3	3 108 m	78° inc	1 025.6 m	3 783 m	675 m	27.5 ton
D-16 run 1	3 912 m	78° inc	970 m	3 594 m	- 318 m	37 ton
D-16 run 2			970 m	3 982 m	70 m	39 ton
D-19	2 884 m	80° inc	1 440.2 m	3 633 m	749 m	32 ton

Table 7-2: Relevant Well and String Compression Information in the Five Oil Producers

Figure 7-7 is a well comparison plot of the experienced i-Con Load versus the measured depth for each well. The data is aligned so that the zero point for the depths at each well is the 9 5/8” casing shoe depth. The load is on the y-axis meaning that once the values cross the x-axis the installation string is in compression. The compression depth compared to the casing shoe depth is easily recognized in the plot.

[13]Compression depth: bit depth when i-Con tool experiences that string is in compression

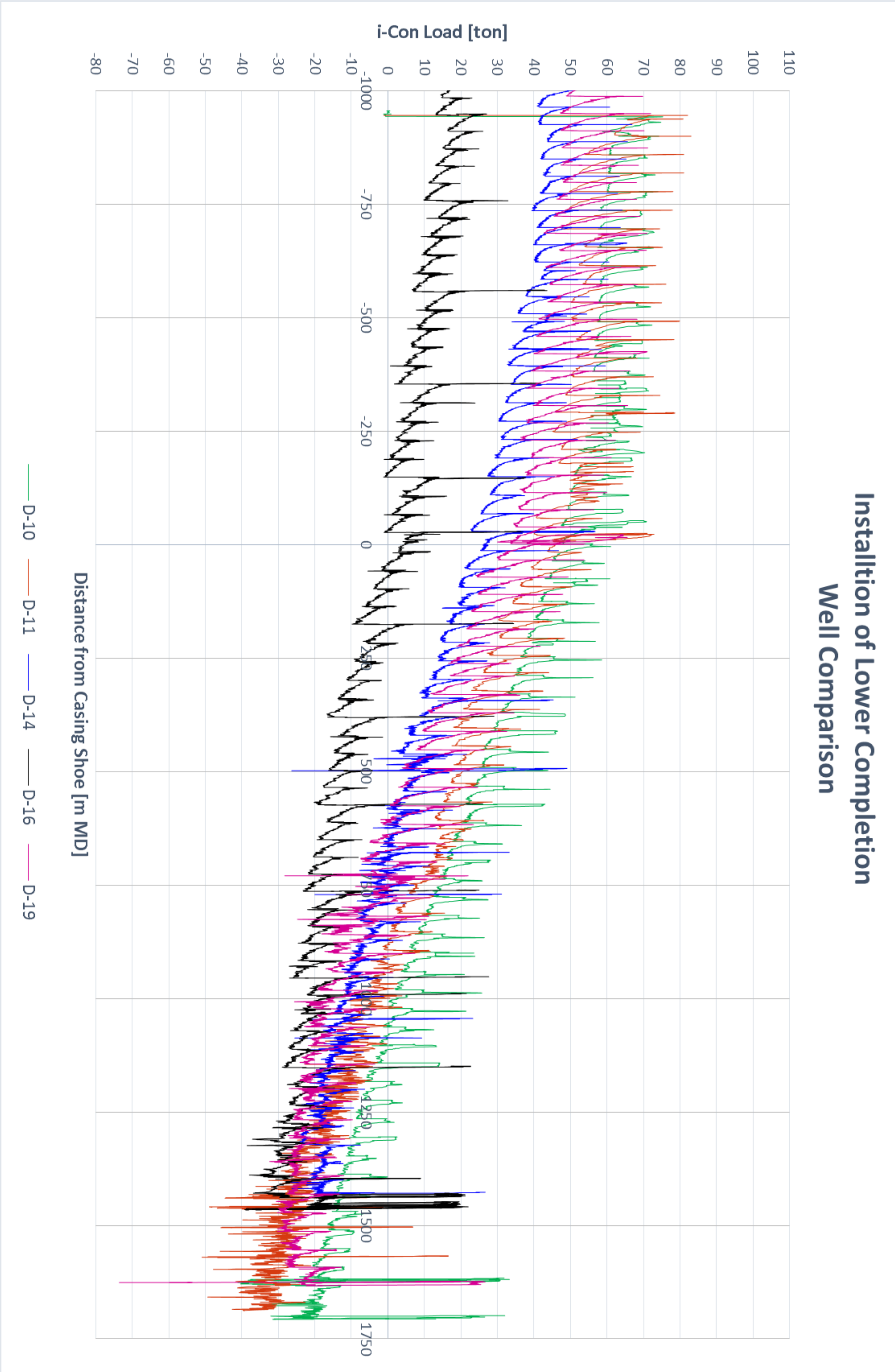

Figure 7-7: Well Comparison of Lower Completion Installation

7.2 ANCHORING THE LOWER COMPLETION

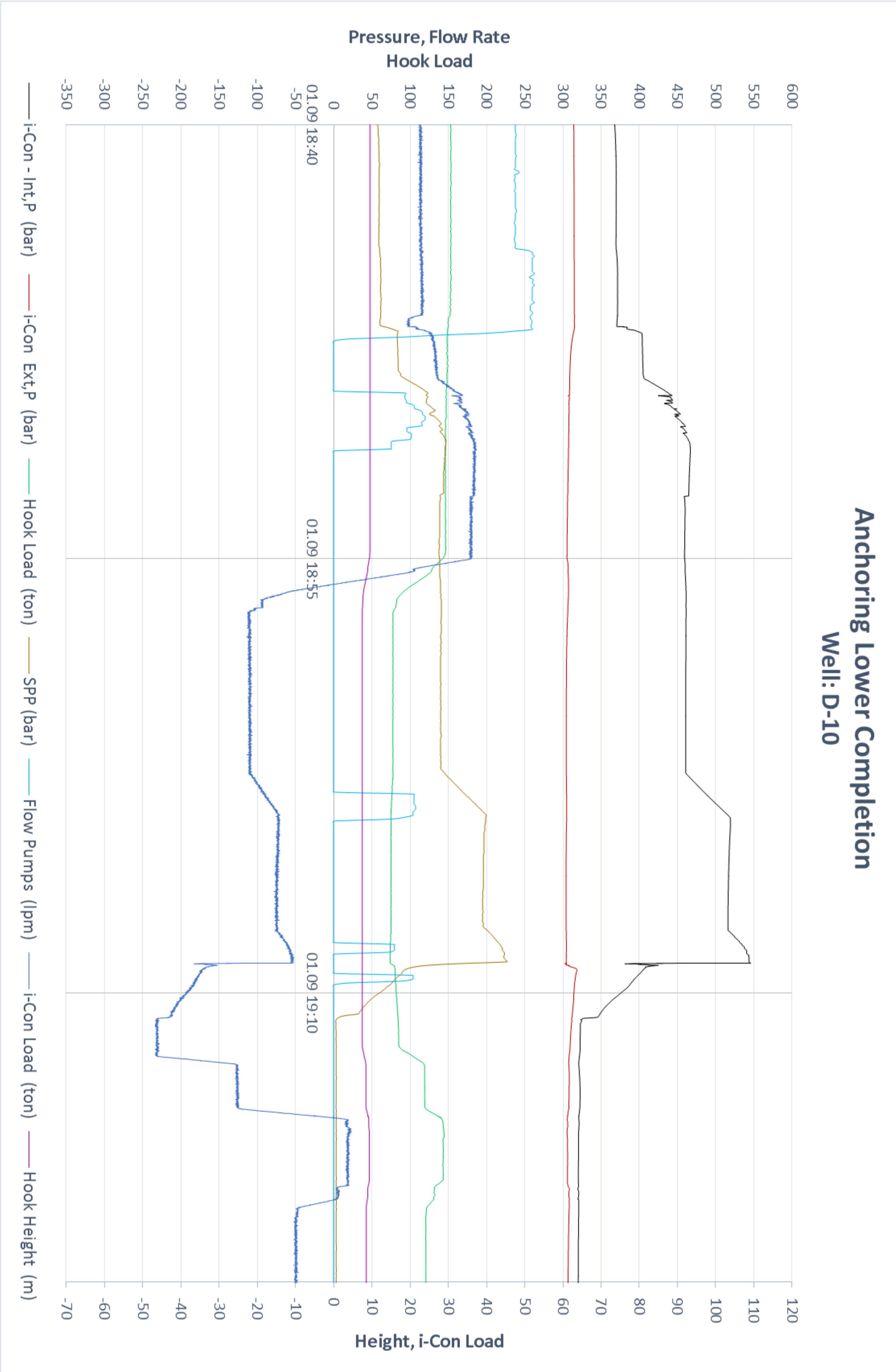

Figure 7-8: Operations for Anchoring the Lower Completion in Well D-10

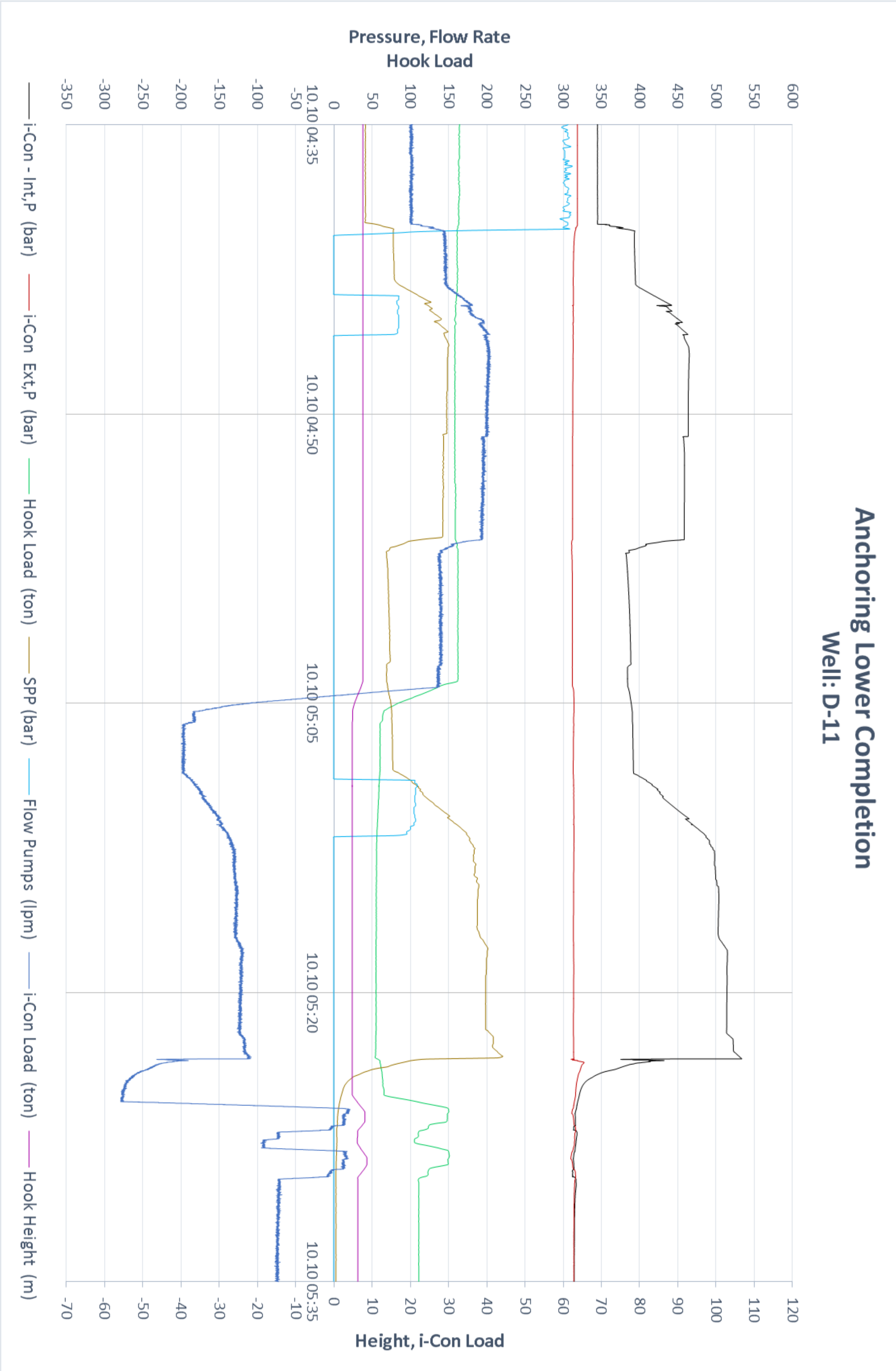

Figure 7-9: Operations for Anchoring the Lower Completion in Well D-11

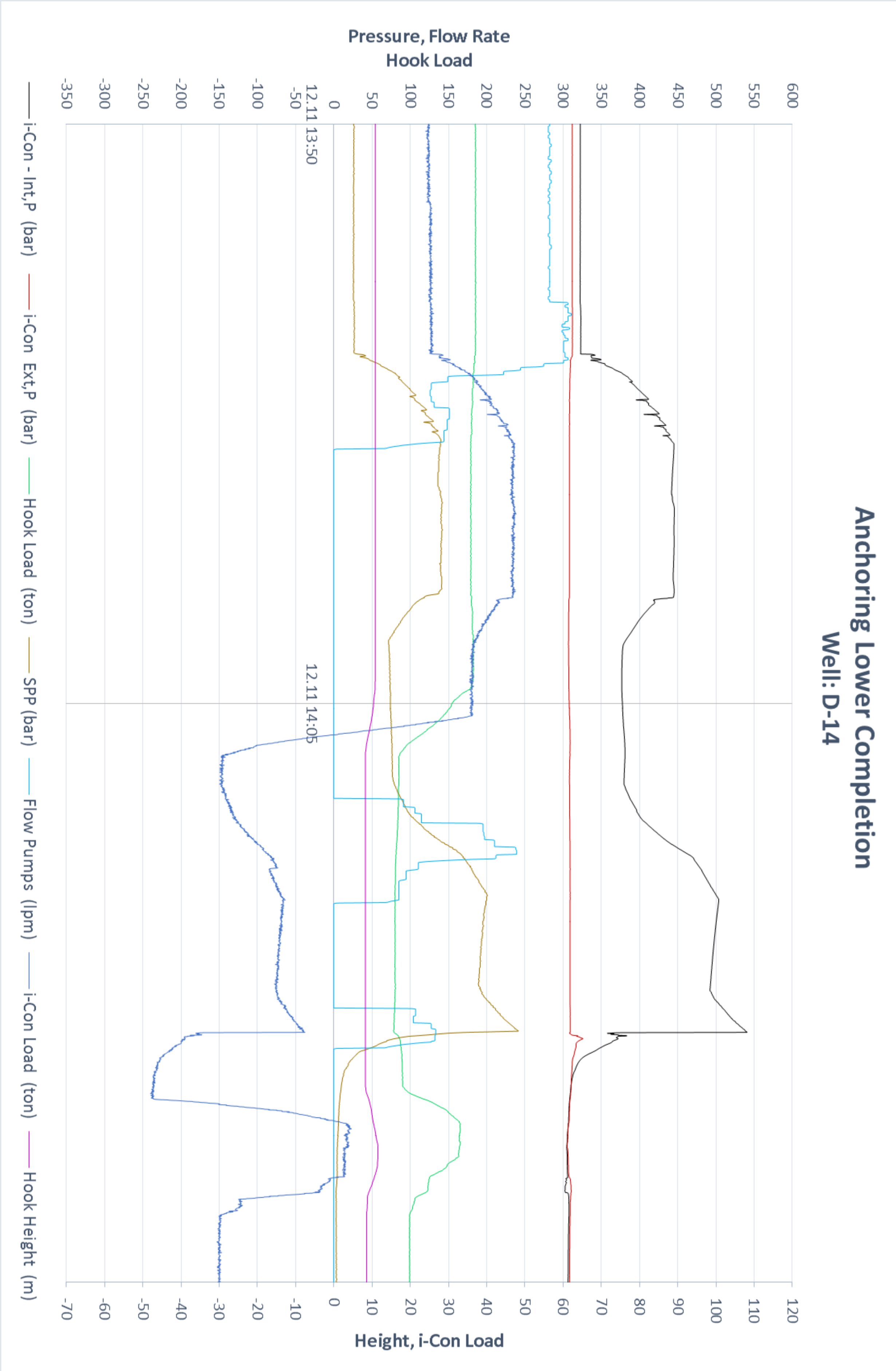

Figure 7-10: Operations for Anchoring the Lower Completion in Well D-14 T3

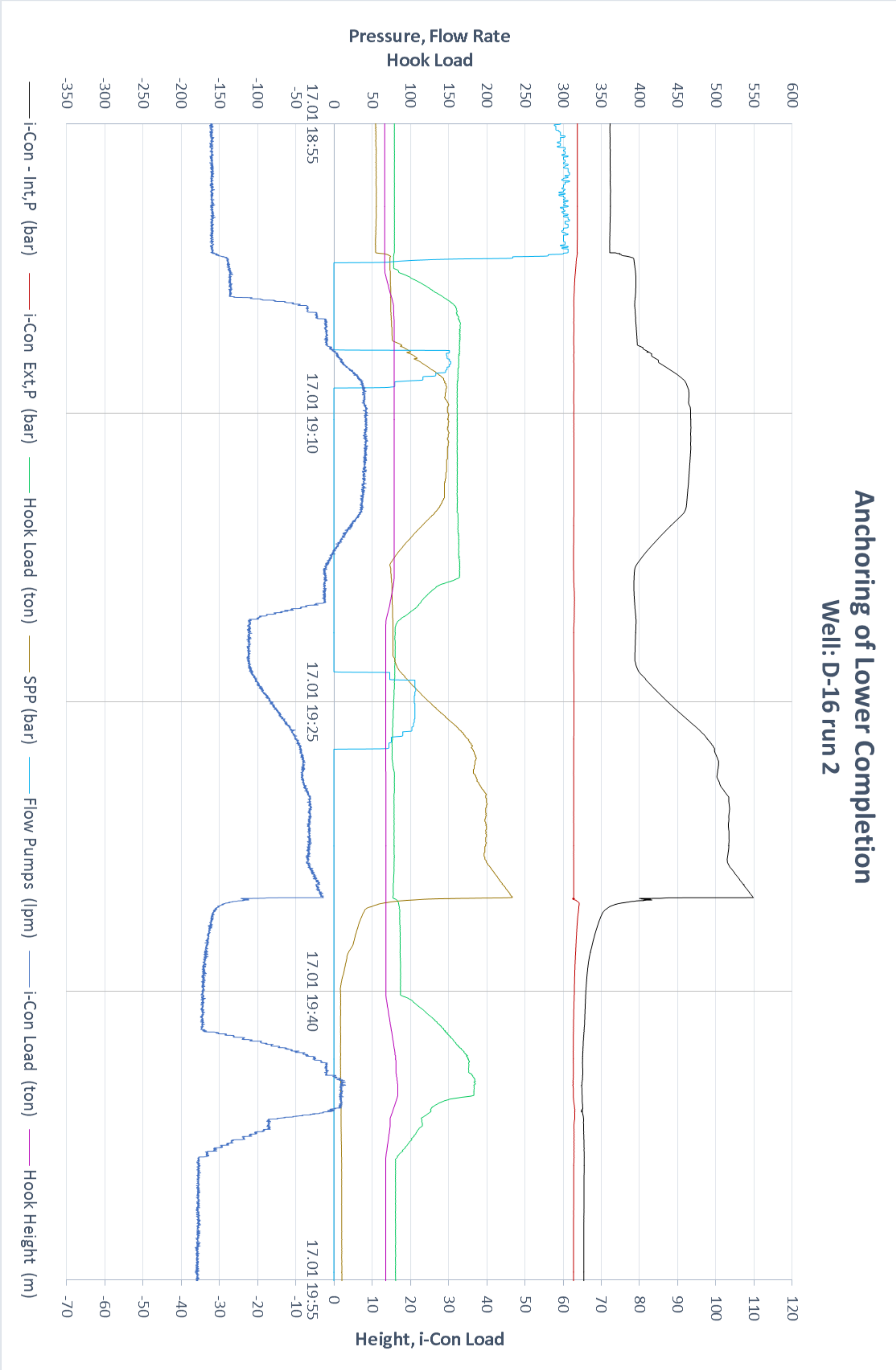

Figure 7-11: Operations for Anchoring the Lower Completion in Well D-16

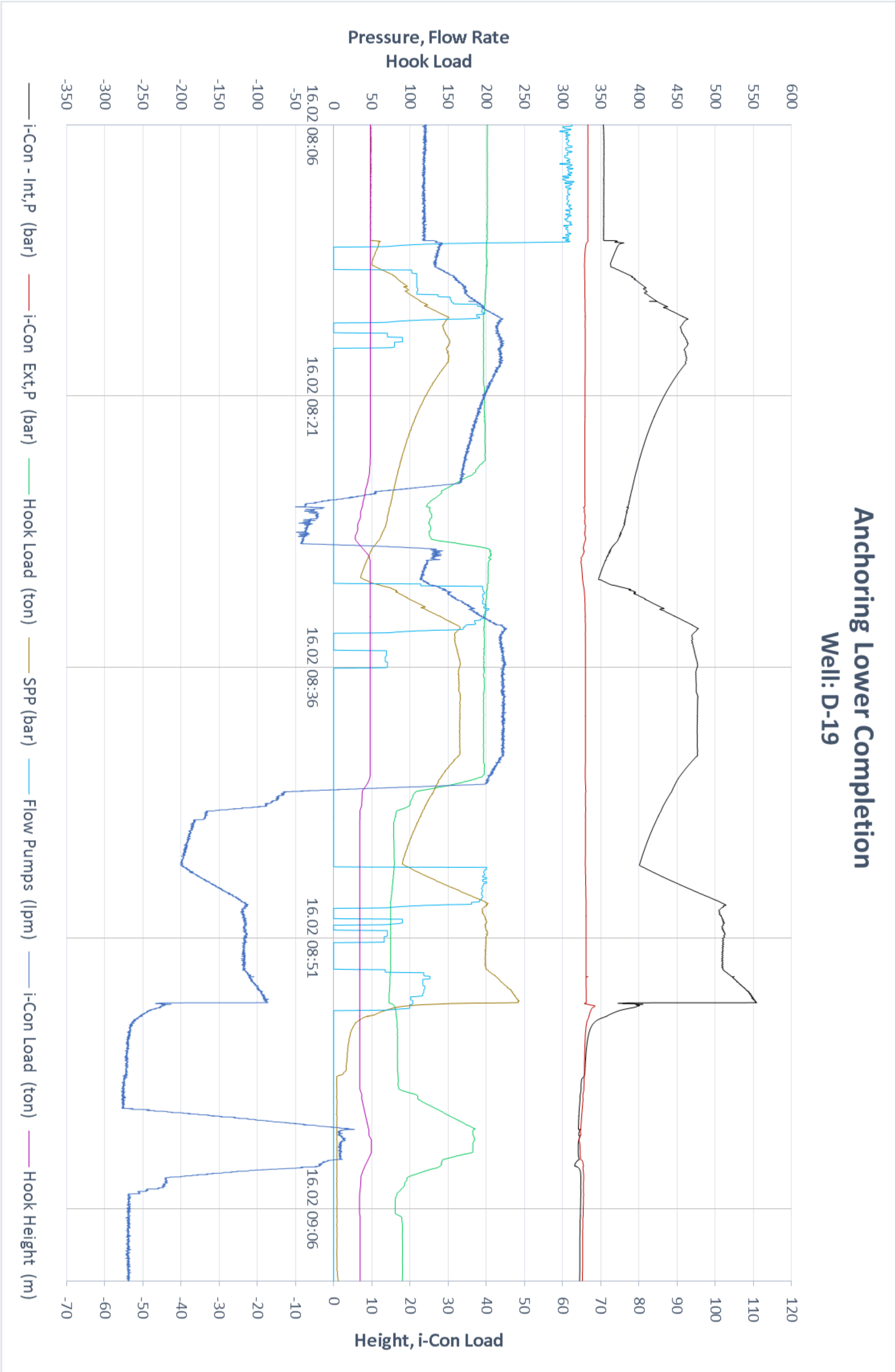

Figure 7-12: Operations for Anchoring the Lower Completion in Well D-19

Figure 7-8 through Figure 7-12 display the entire anchoring sequence of the lower completion that occurred in each oil producer. The plots display both surface data and downhole data from the liner hanger setting ball was chased, until the operation is complete and up/down weights are recorded.

The relevant variables to include during this downhole event are hook height, hook load, i-Con load, flow rate, SPP, and internal and external pressures. The hook moves up and down during the anchoring of the lower completion as weight is put down on the hanger to verify if it has set. This affects the hook load and the i-Con load. The pumps are used to pressure up the string to set the hanger, and the SPP and the internal pressure are affect by this. The external pressure is included to gain a greater understanding of the downhole incidents.

The plots display the chasing of the setting ball with a pump rate of about 300 lpm, followed by the landing of the ball. This can be seen by the sudden pressure increase of the SPP and the internal pressure, which also occur approximately at the same time as the pumps are stopped. The pressure inside the string is then increased with about 150 bar and held for roughly 10 minutes. Subsequently, weight is set down to verify if the liner hanger has been set.

The installation string is then pressured up to approximately 200 bar and held for around 4 minutes to release the liner hanger running tool. Finally, the string is pressured up further until the ball seat is sheared. This pressure corresponds to the pressure spike seen in the SPP and internal pressure. The SPPs when the ball seat was sheared are listed in Table 7-3 along with the duration of the downhole event from the time the ball lands in the ball seat until after the ball seat is sheared.

	Event Duration	Ball Seat Shear Pressure
Well D-10	33 min	241 bar
Well D-11	54 min	220 bar
Well D-14 T3	28 min	231 bar
Well D-16	45 min	235 bar
Well D-19	53 min	224 bar

Table 7-3: Duration of Anchoring of Lower Completion and Ball Seat Shear Pressure (SPP)

Figure 7-12 displays a hanger activation attempt in well D-19. The ball was chased with 300 lpm, and the ball landed in the ball seat (about time 08:11). The installation string was pressured up about 150 bar, but the pressure leaked off. Weight is set down (about time 08:25 to 08:30) resulting in an uneven trend in the hook load and hook height as well as the axial tool load. The installation string is pressured up to about 160 bar and held for approximately 8 minutes. Weight is then set down and hanger is verified to be set.

Figure 7-13 is a well comparison where the differential pressure response for all the wells are plotted in a single graph. The zero point for all wells was chosen to be the time at which the ball seat was sheared. Figure 7-14 provides a comparison of the i-Con load in all the wells when setting the liner hanger. The zero point was set to be the same as in Figure 7-13. The time scale for both plots is 300 seconds, which corresponds to five minutes.

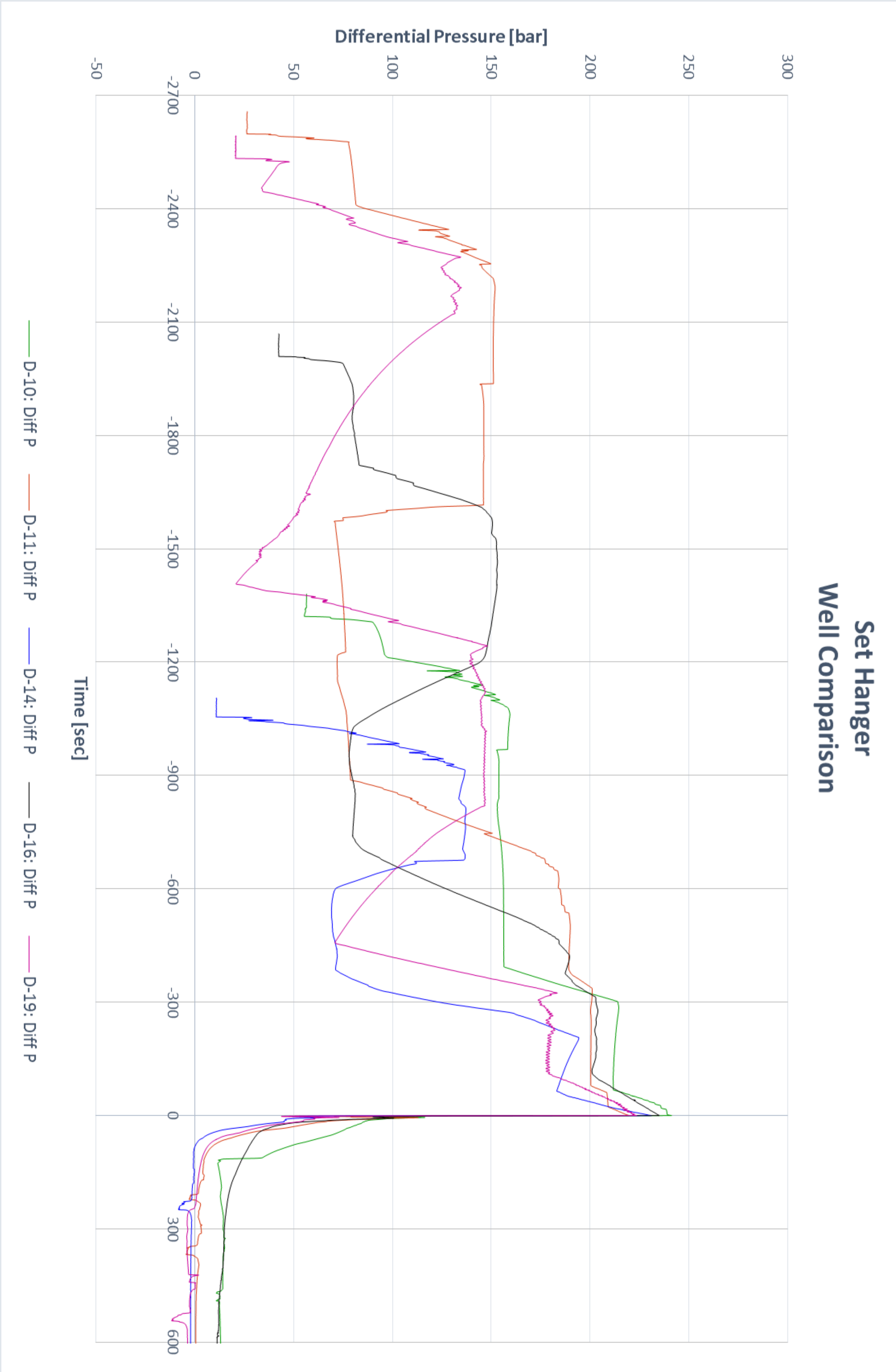

Figure 7-13: Well Comparison of Differential Pressure Response when Setting Liner Hanger

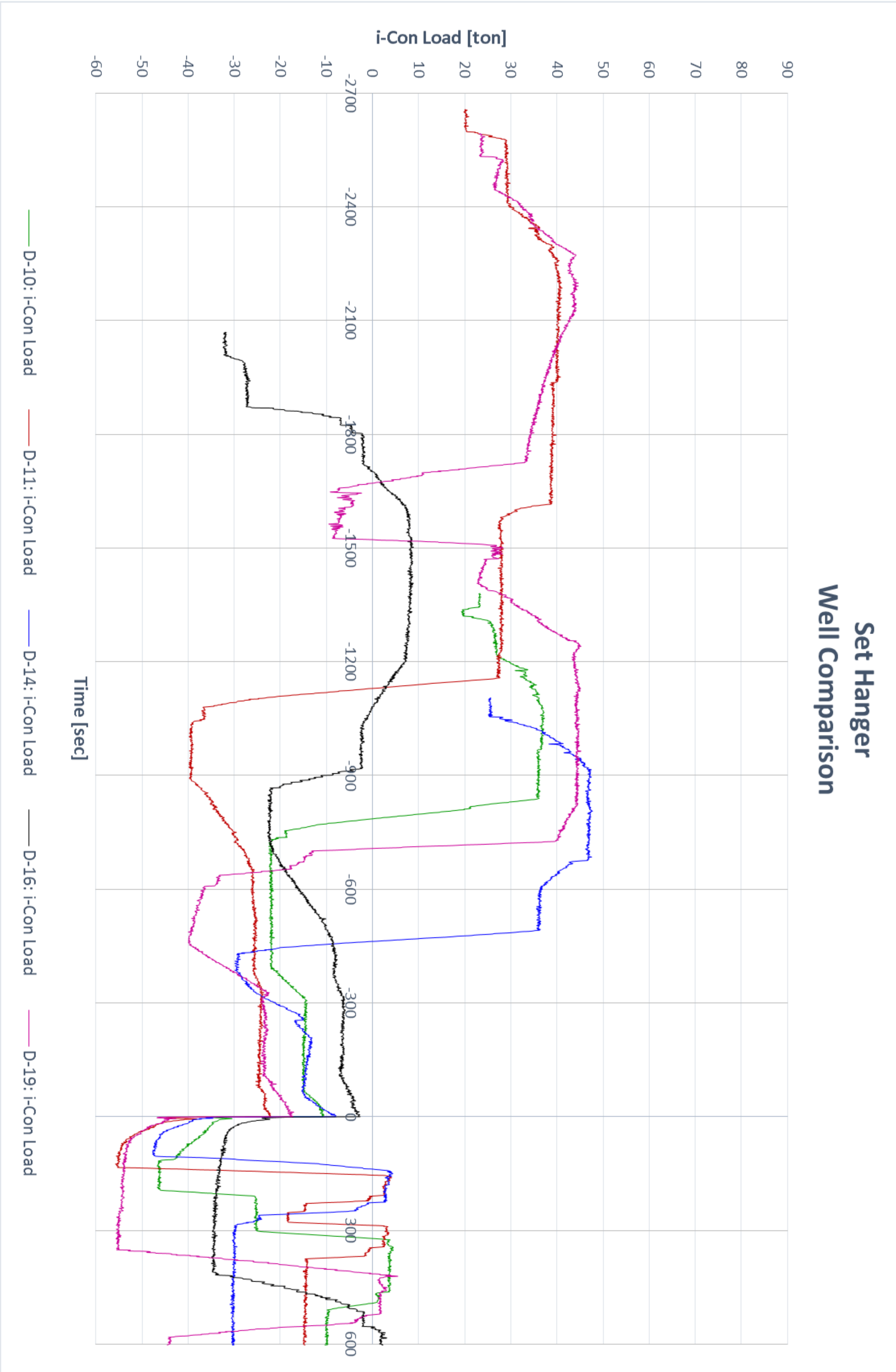

Figure 7-14: Well Comparison of Experienced i-Con Tool Load when Setting Liner Hanger

7.3 CIRCULATION THROUGH LOWER COMPLETION

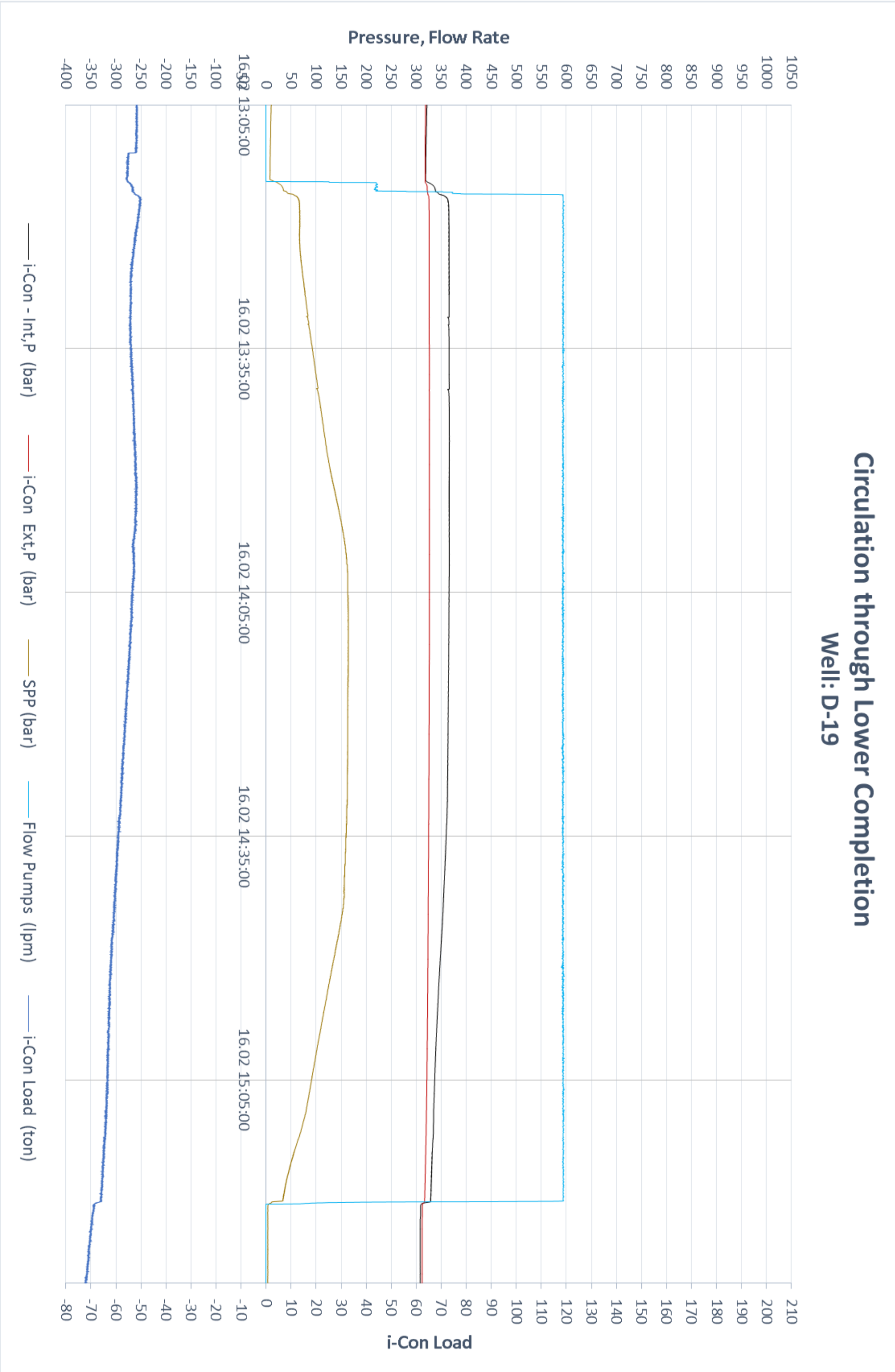

Figure 7-15: Circulation through Lower Completion in Well D-19

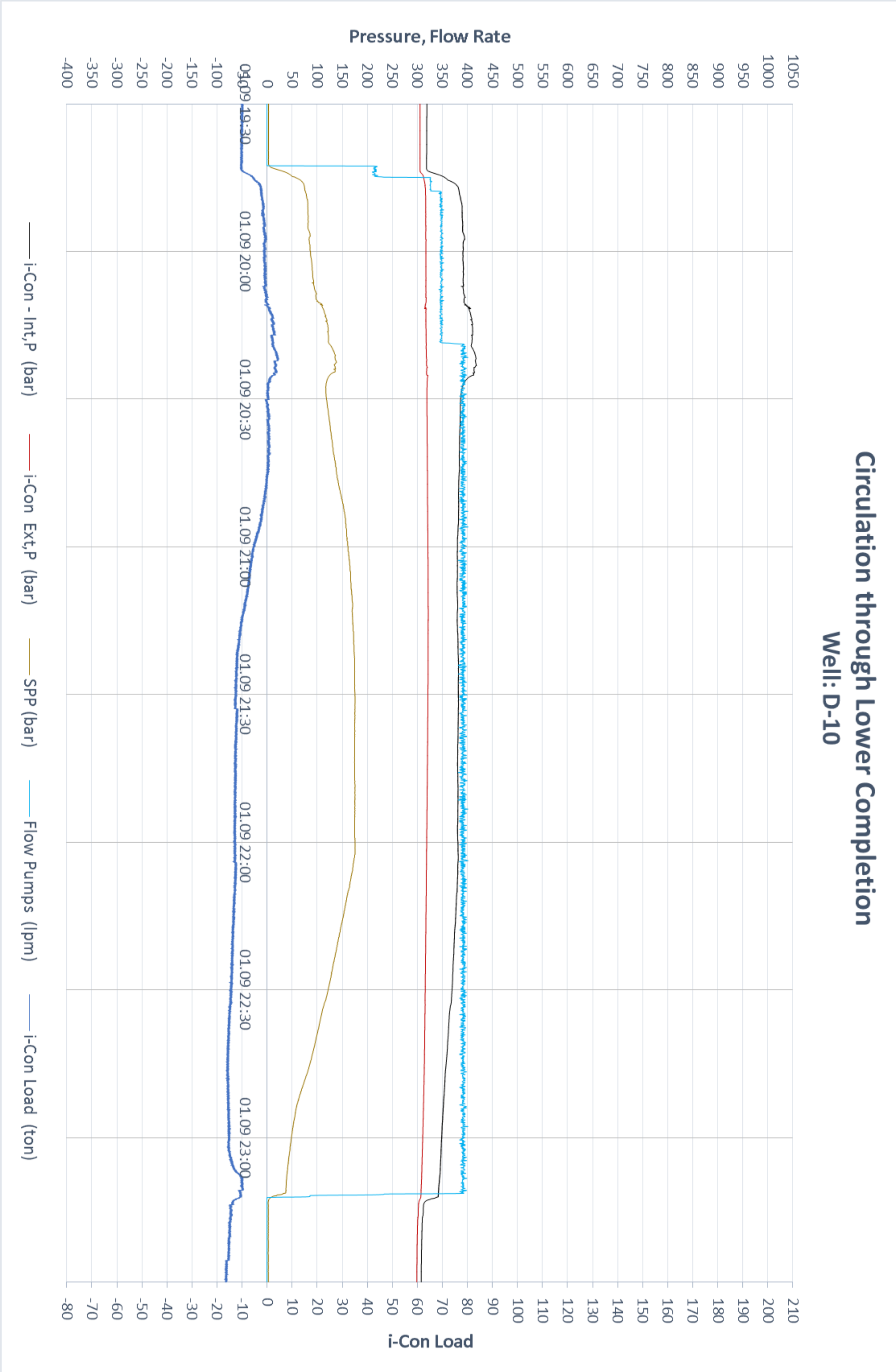

Figure 7-16: Circulation through Lower Completion in Well D-10

The circulation through the lower completion at well D-19 and D-10 shown in Figure 7-15 and Figure 7-16 respectively. In Appendix D, the corresponding plots for the other three wells are displayed. From the surface data, the flow rate and SPP is represented while the internal pressure, external pressure and tool load is included from the downhole data. These variables (except for the load) are also used in the following five plots.

	Minimum i-Con Load [ton]	Maximum i-Con Load [ton]	Maximum Flow Rate [lpm]
Well D-10	5 tension	12 compression	401
Well D-11	10 compression	25 compression	808
Well D-14 T3	18 compression	49 compression	1017
Well D-16	23 compression	37 compression	617
Well D-19	51 compression	66 compression	598

Table 7-4: Maximum and Minimum i-Con Loads Experienced During Circulation for all Wells

Table 7-4 has listed the maximum and minimum loads experienced by the tool during the circulation through lower completion, as well as the maximum flow rate used. During the circulation in all the wells, the string stays compressed at all times except for in D-10, which can be seen in Figure 7-16.

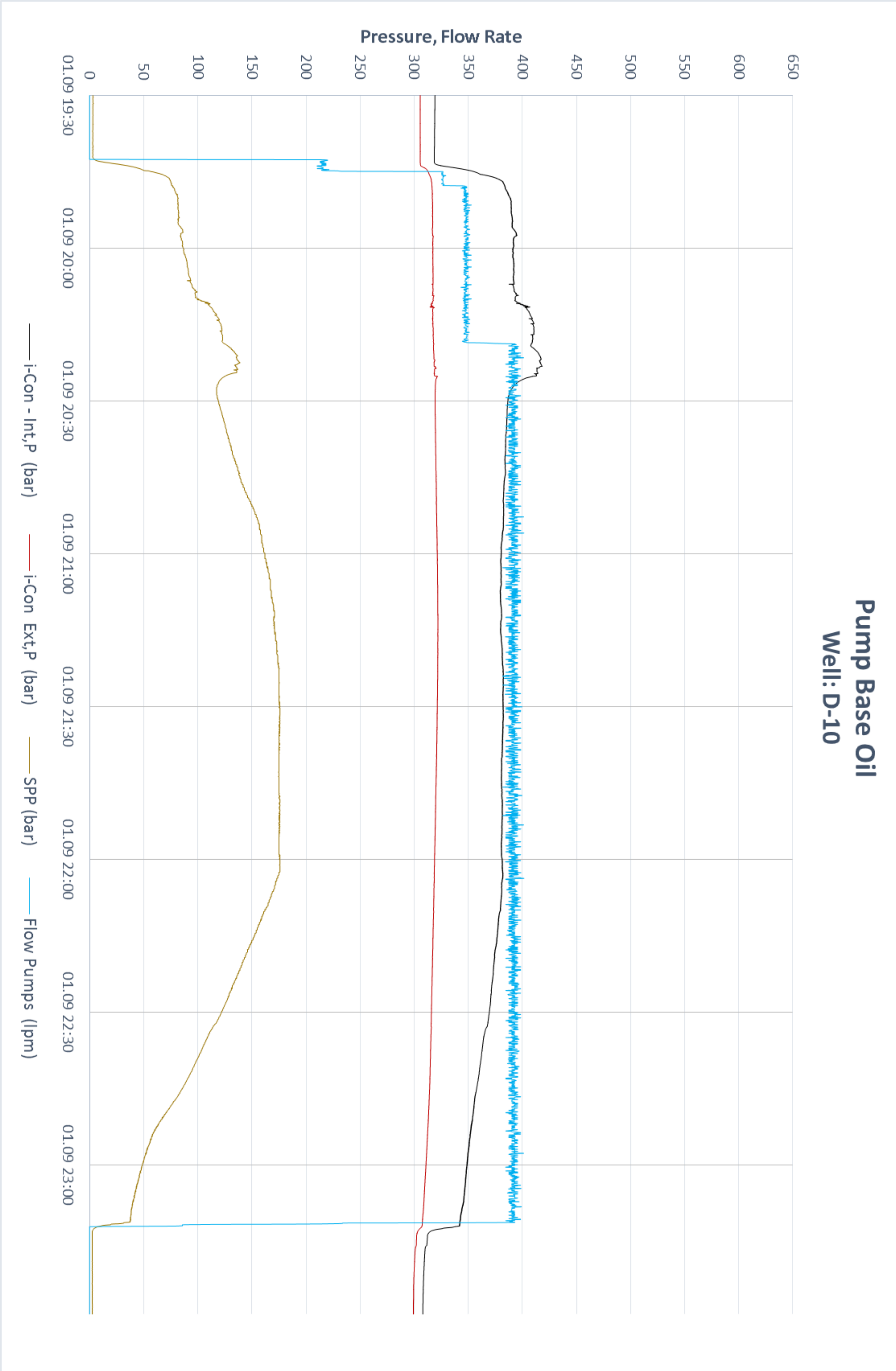

Figure 7-17: Pressure Responses and Flow Rate when Pumping Base Oil in Well D-10

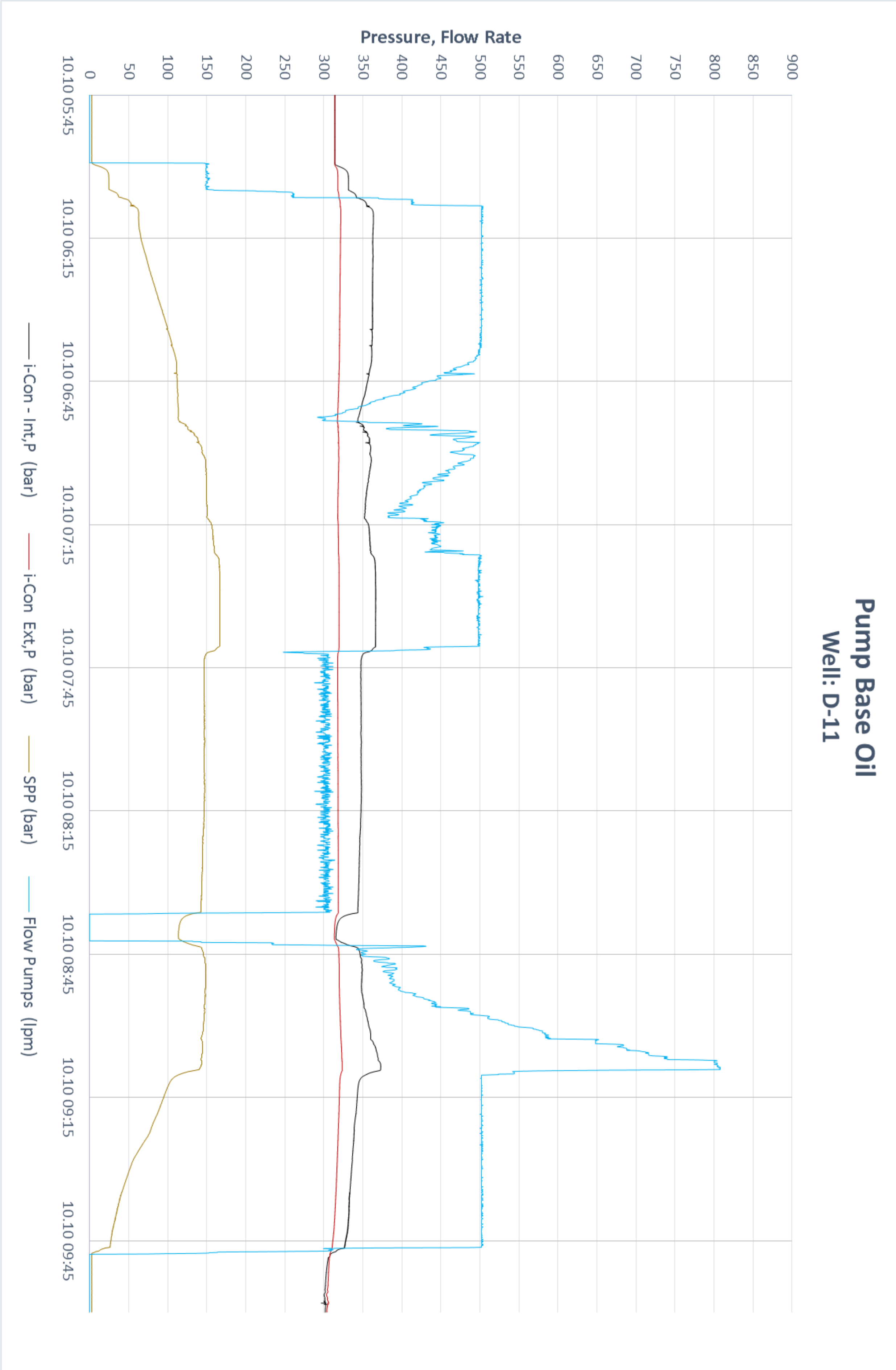

Figure 7-18: Pressure Responses and Flow Rate when Pumping Base Oil in Well D-11

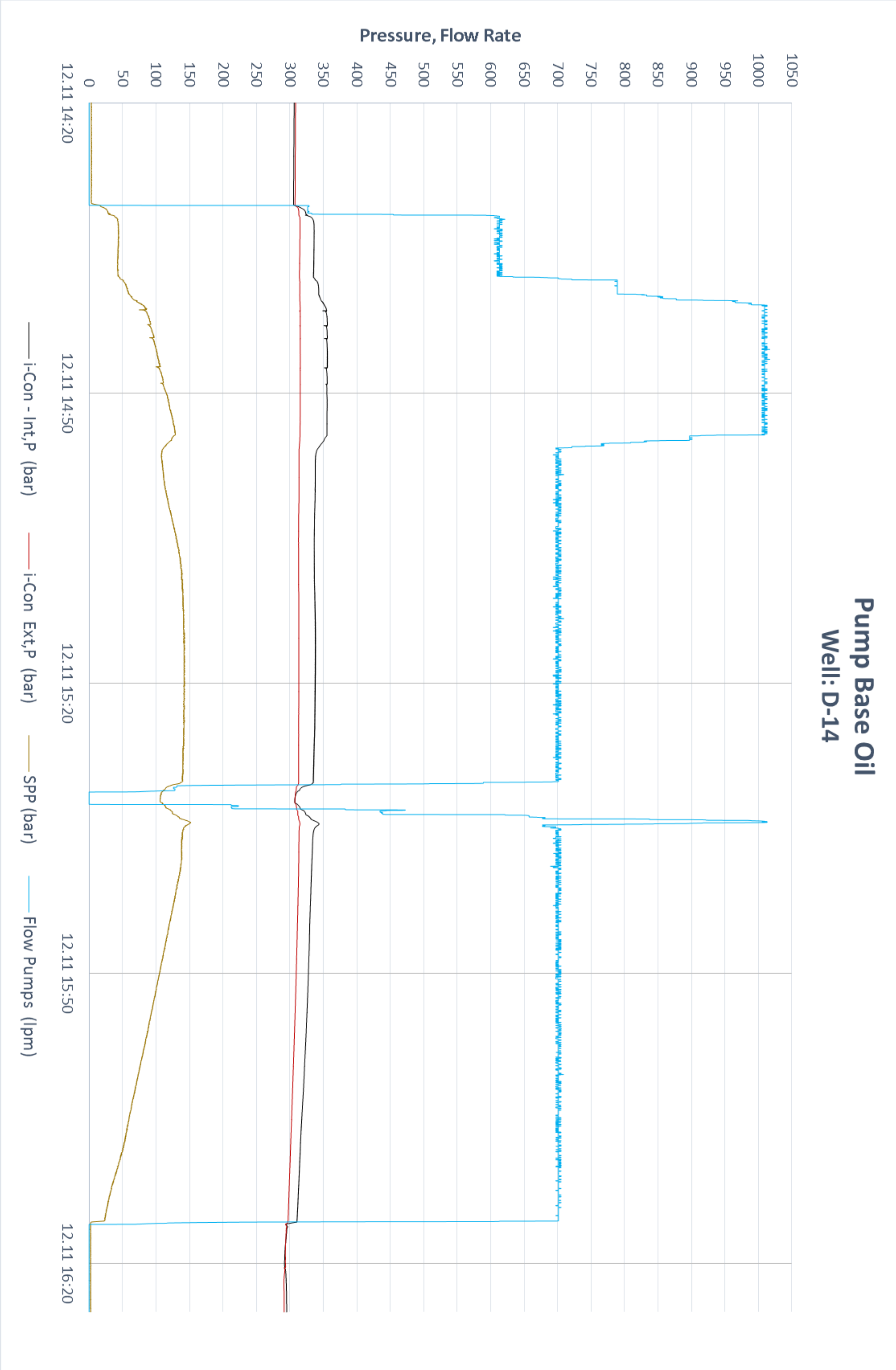

Figure 7-19: Pressure Responses and Flow Rate when Pumping Base Oil in Well D-14 T3

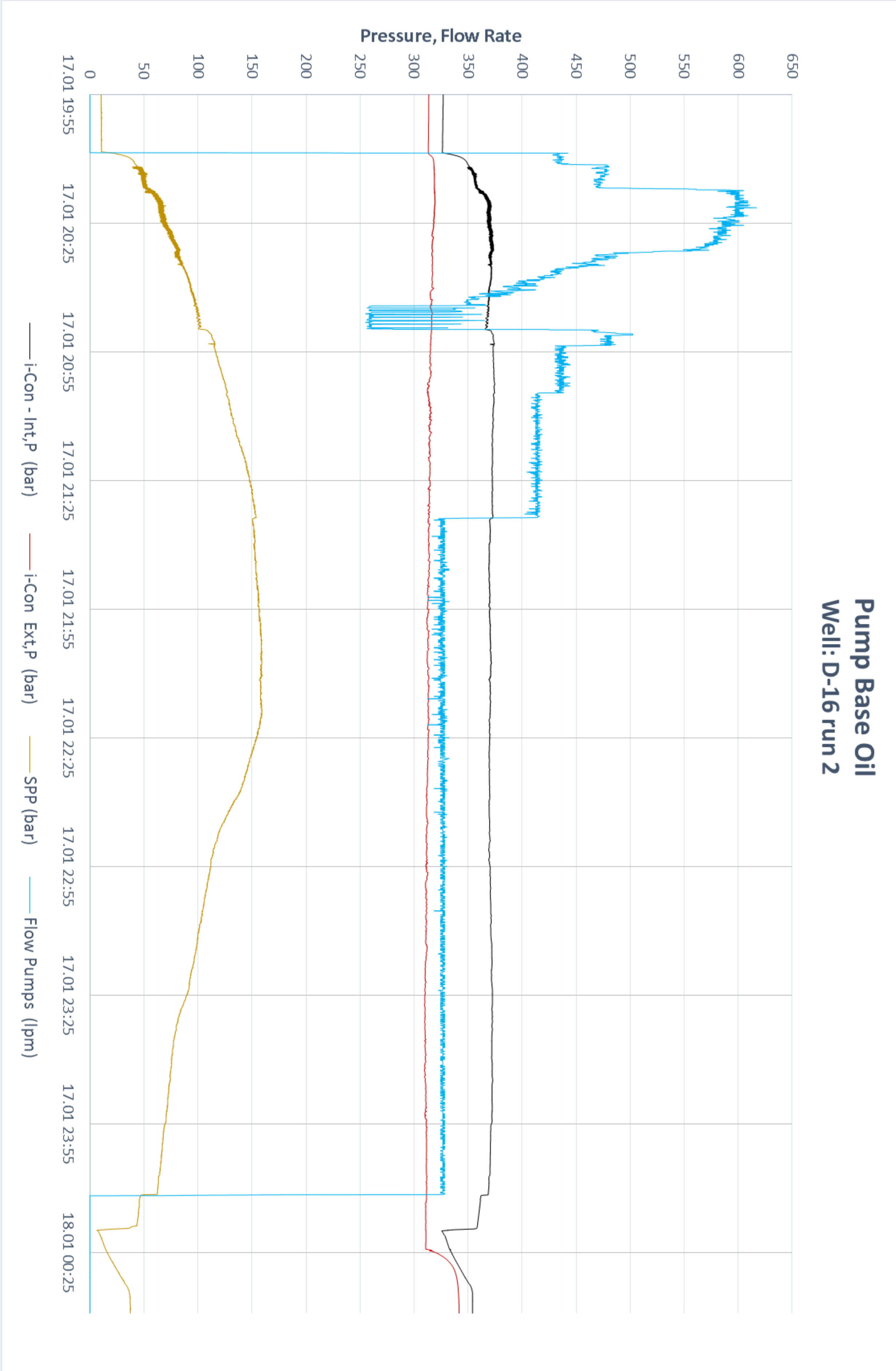

Figure 7-20: Pressure Responses and Flow Rate when Pumping Base Oil in Well D-16

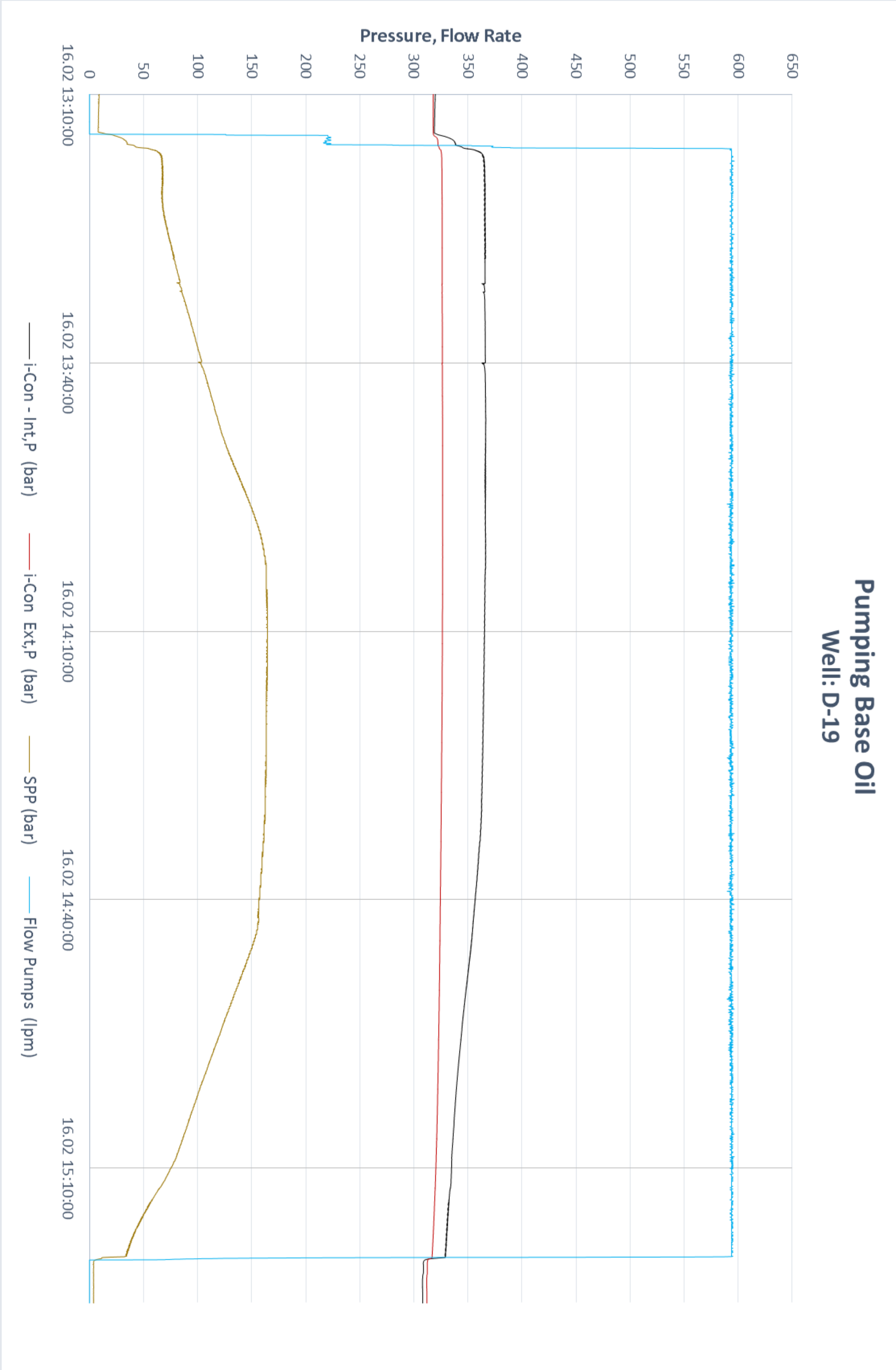

Figure 7-21: Pressure Responses and Flow Rate when Pumping Base Oil in Well D-19

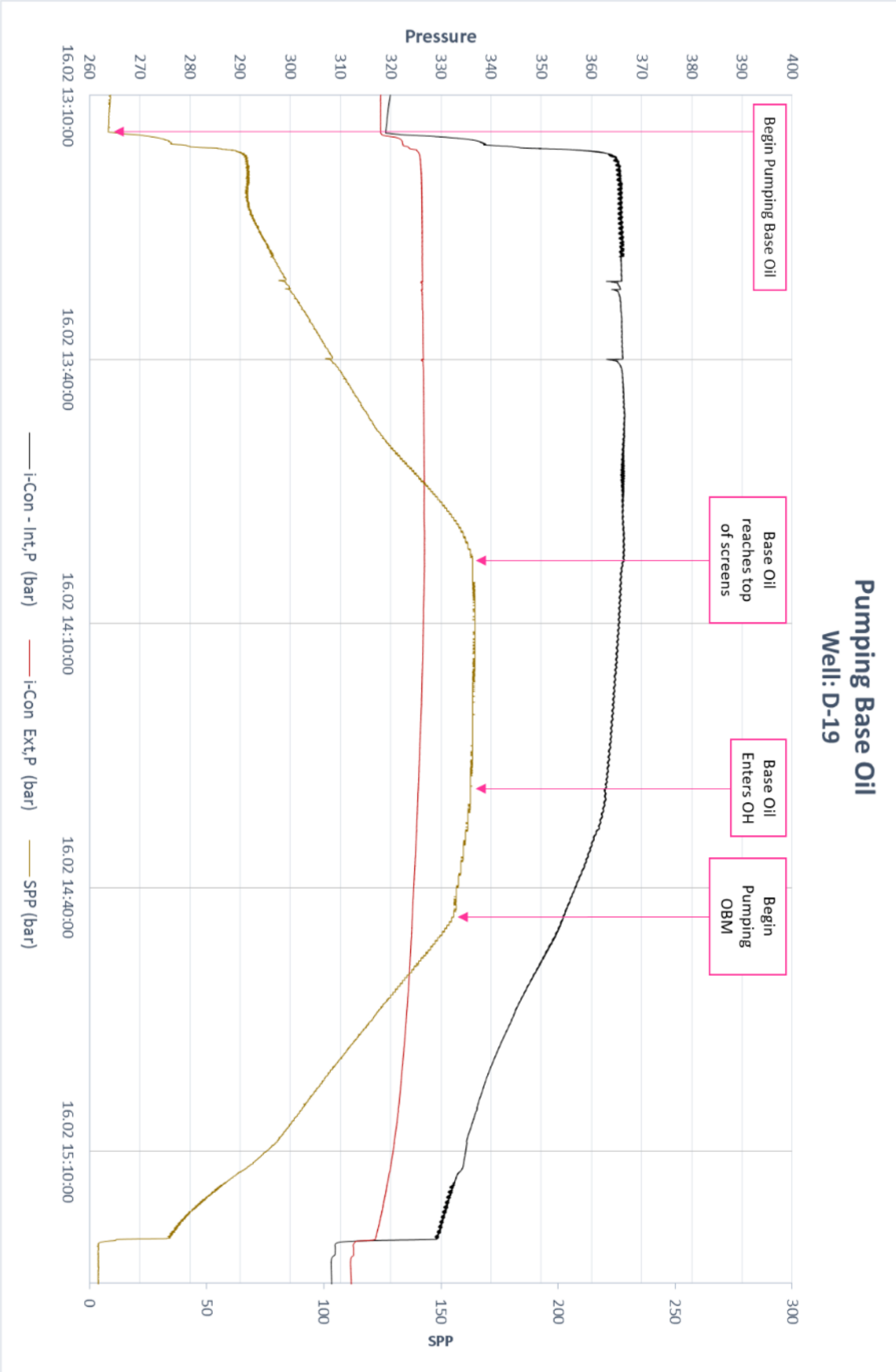

Figure 7-22: Pressure Response Zoom when Pumping Base Oil in Well D-19

Figure 7-17 to Figure 7-21 show the same operation as Figure 7-15 and 7-16 minus the tool load, and with altered ranges on the y-axis. Figure 7-22 shows the internal and external pressure responses, and the SPP variation in well D-19.

It can be seen that the pump rate in wells D-10 and D-19 was kept relatively constant. In D-11, on the other hand, the pump rate was erratic and unstable. This was also the case for the first hour and a half at D-16, though the pump rate became stable after this time. At D-14, the flow rate increased in steps to 1000 lpm but was decreased to 700 lpm after about 15 minutes. The pumps were also shut down once the total volume of base oil had been pumped before they were resumed to displace the base oil with OBM.

The flow rate variations for all the oil producers are plotted together in Figure 7-23, where one can see how the they compare to each other. A similar plot with the SPP variation with time is shown in Figure 7-24. In both these plots, the operations are aligned so that the time where the flow rate increases from zero overlaps for each well. Hence, the duration of the operation in the various wells can be seen. The time interval is set to be 600 seconds, which corresponds to 10 minutes.

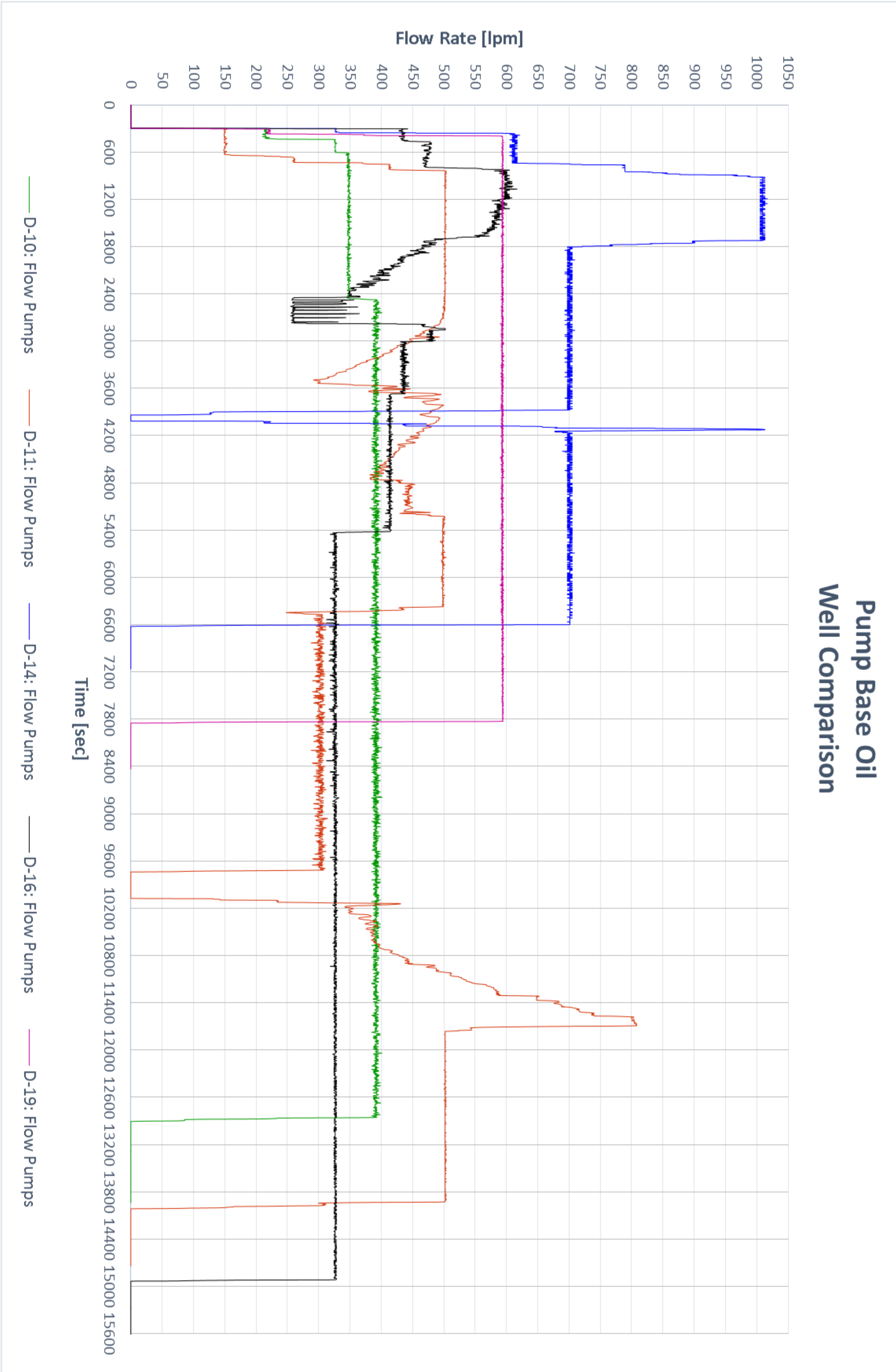

Figure 7-23: Well Comparison of Flow Rate when Pumping Base Oil

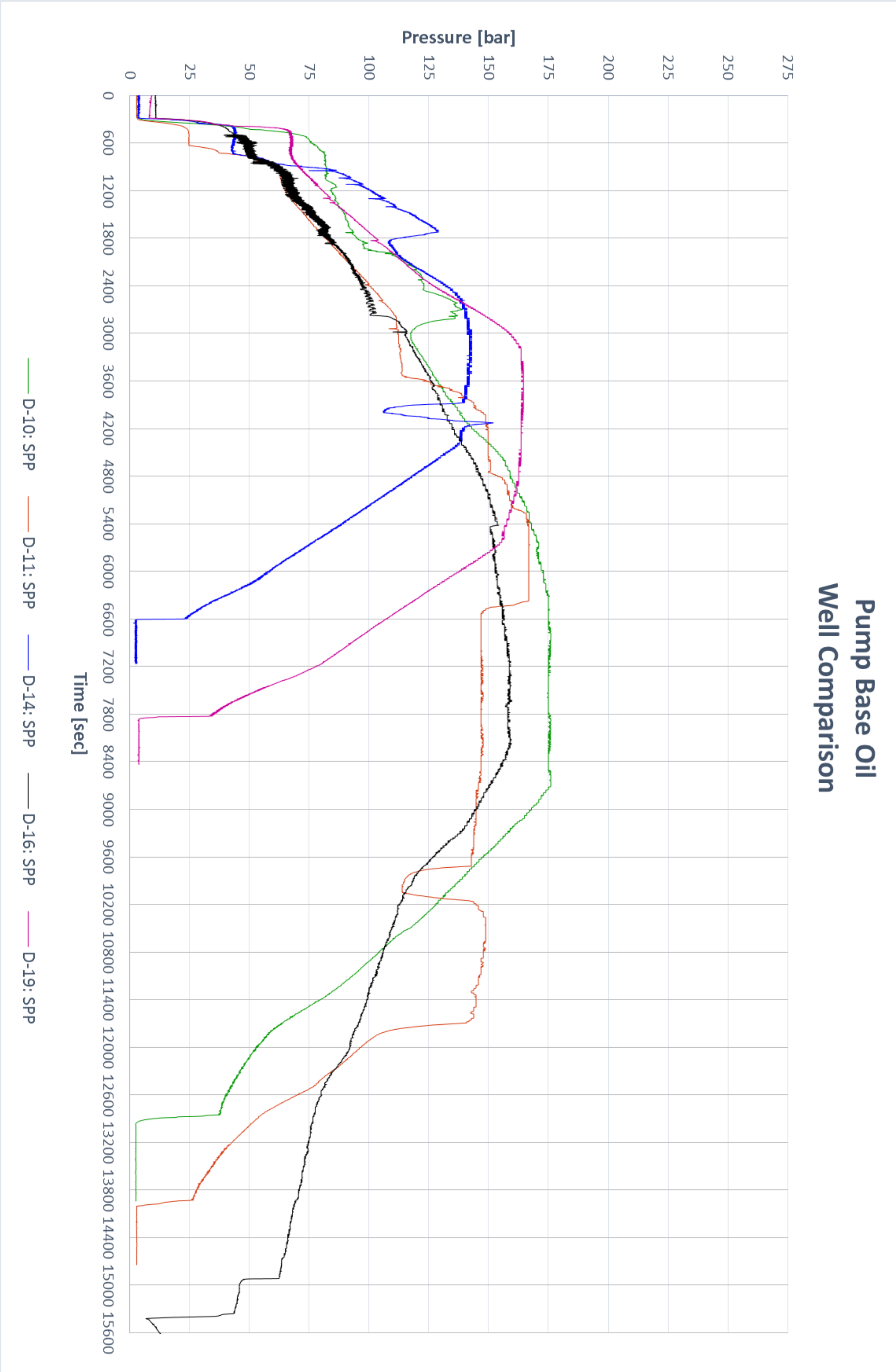

Figure 7-24: Well Comparison of Stand Pipe Pressure when Pumping Base Oil

7.4 ISOLATE THE LOWER COMPLETION

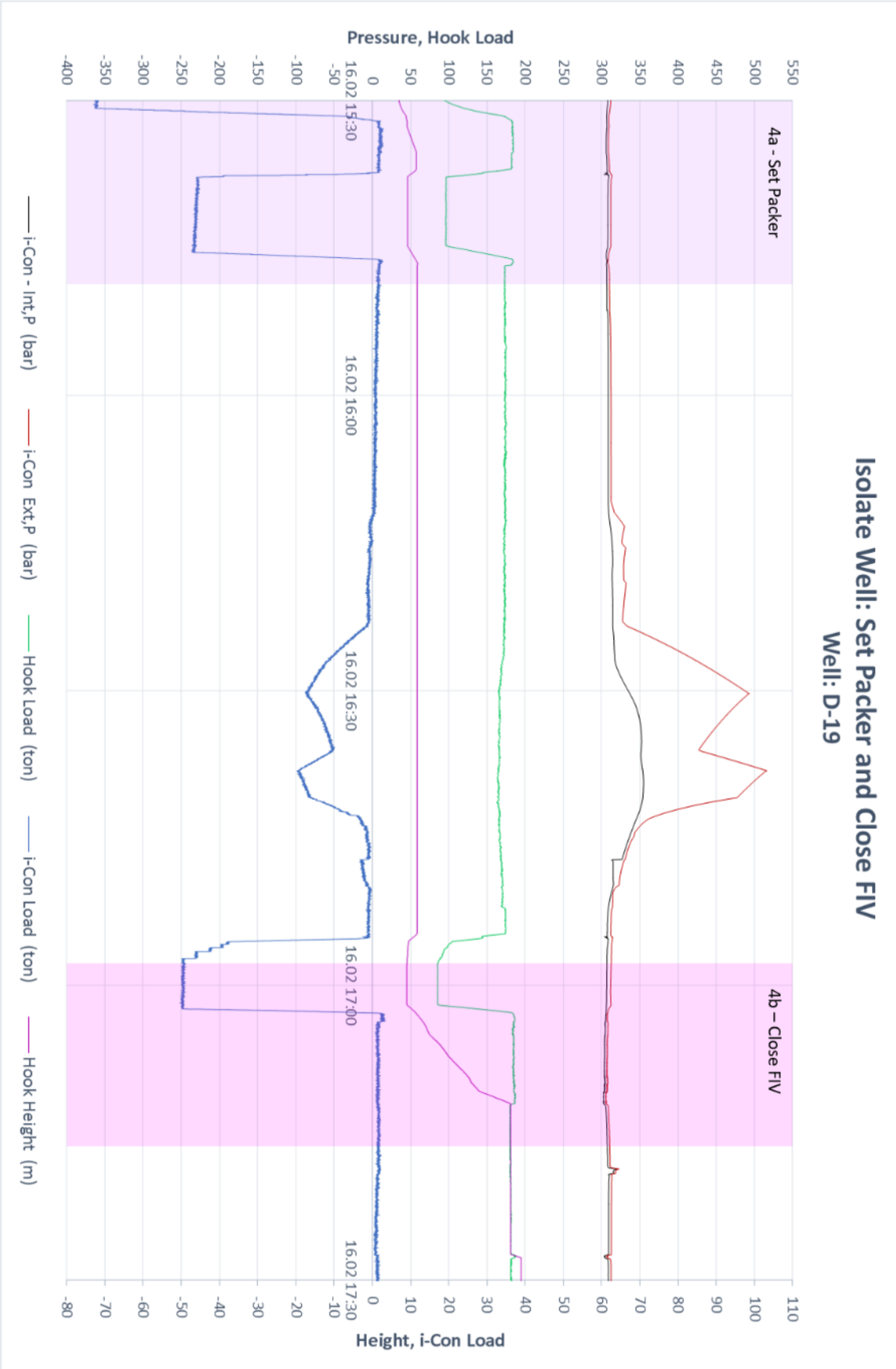

Figure 7-25: Plot Showing Downhole Events 4a and 4b Highlighted

7.4.A SET LINER HANGER PACKER

Figure 7-26: The Setting of the Liner Hanger Packer in Well D-10

Figure 7-26 shows the entire operation of setting the packer in well D-10 from about five minutes before the string was picked up until about 5 minutes after weight was set down on the PBR. The other plots showing the relevant data acquired for setting the liner hanger packer in the other oil producers at Ivar Aasen are displayed in Appendix E.

The included variables from the surface data are the hook height and hook load, while the i-Con load, internal and external pressures represent the downhole data. These variables are also seen in five of the six following figures. The following plots are zoomed in on a particular section of the entire operations shown in the figures mentioned above.

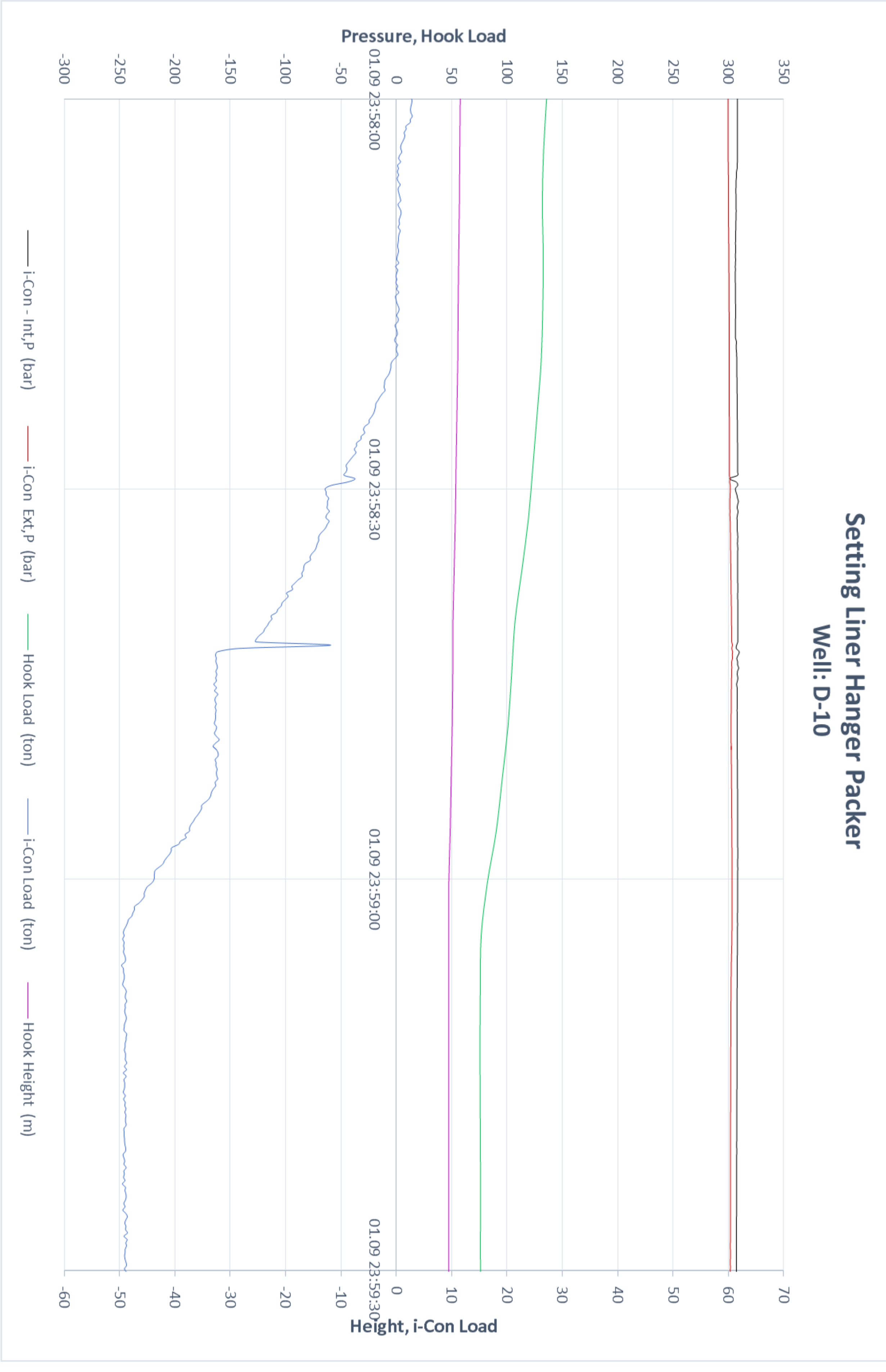

Figure 7-27: Shearing of Liner Hanger Packer during Setting in Well D-10

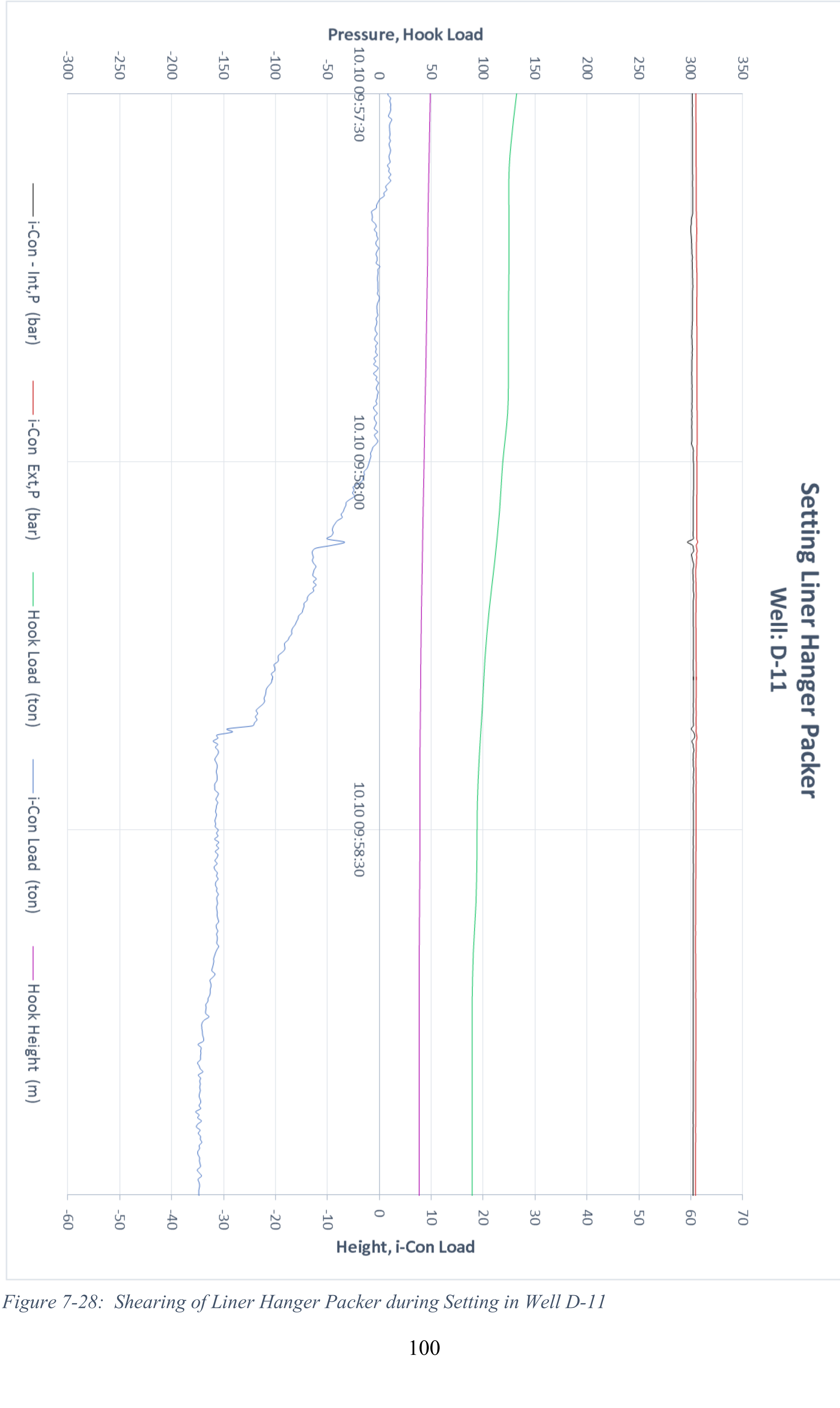

Figure 7-28: Shearing of Liner Hanger Packer during Setting in Well D-11

Figure 7-29: Shearing of Liner Hanger Packer during Setting in Well D-14 T3

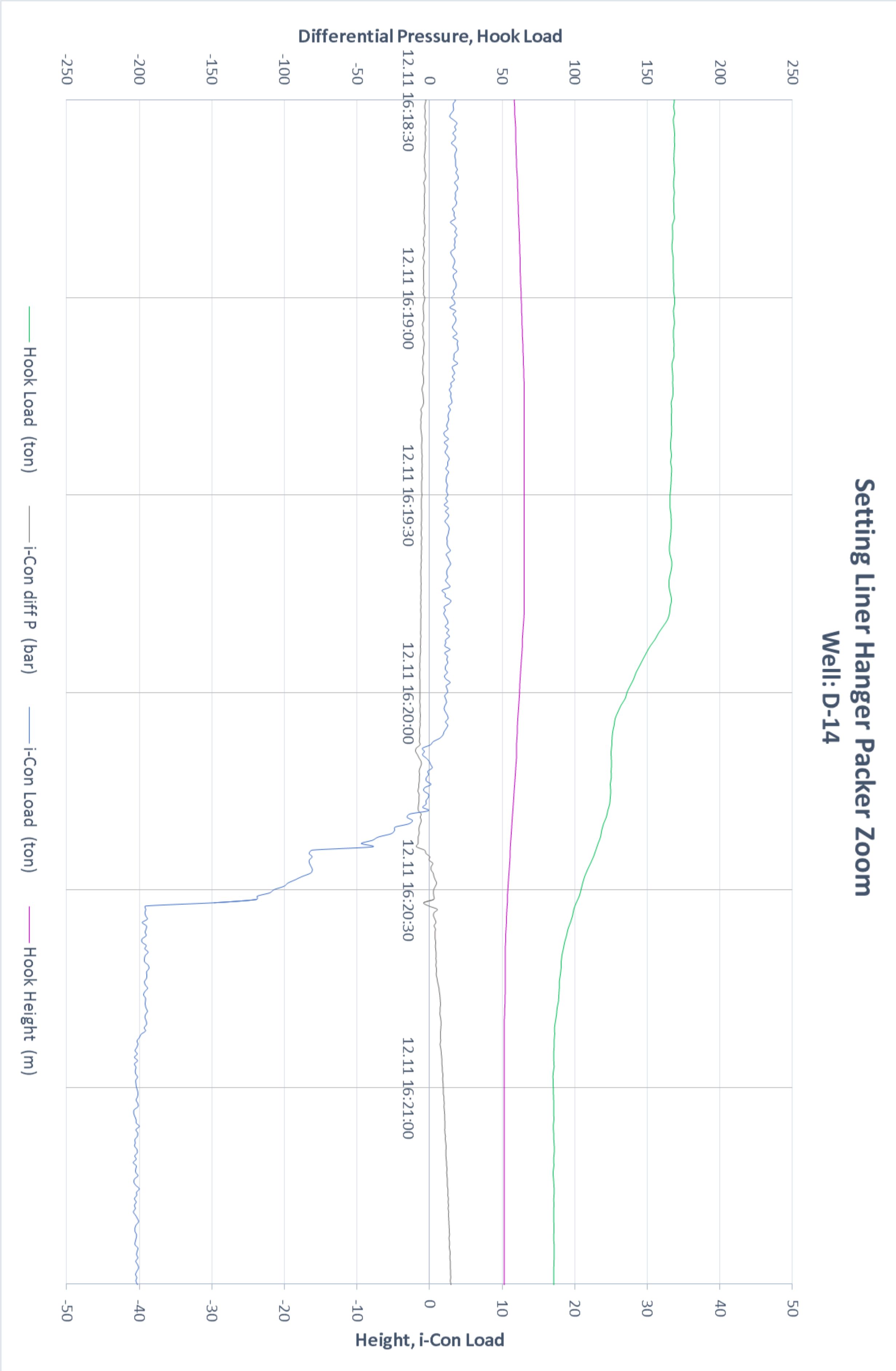

Figure 7-30: Zoom in of Liner Hanger Packer Setting in Well D-14 T3

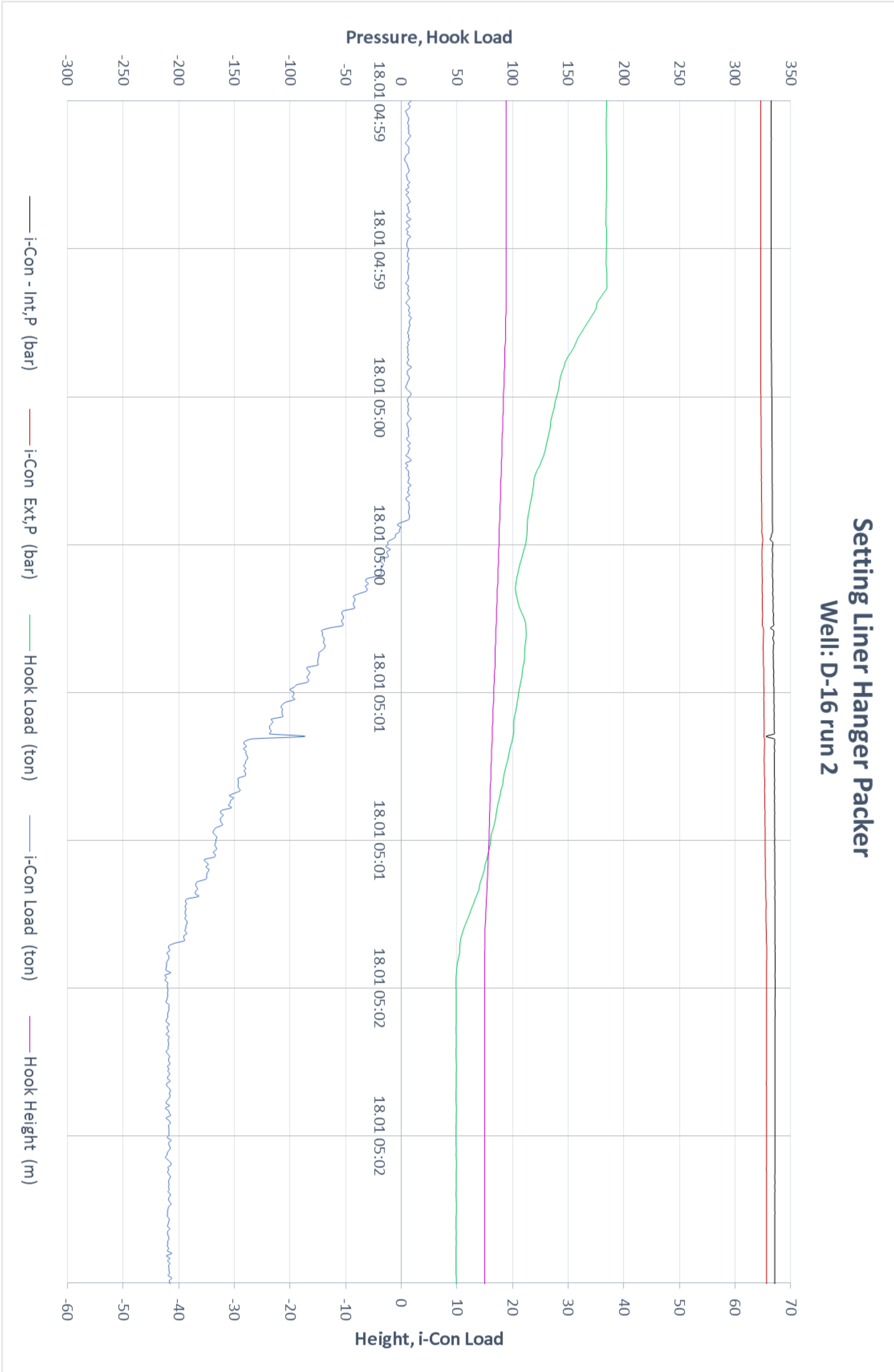

Figure 7-31: Shearing of Liner Hanger Packer during Setting in Well D-16

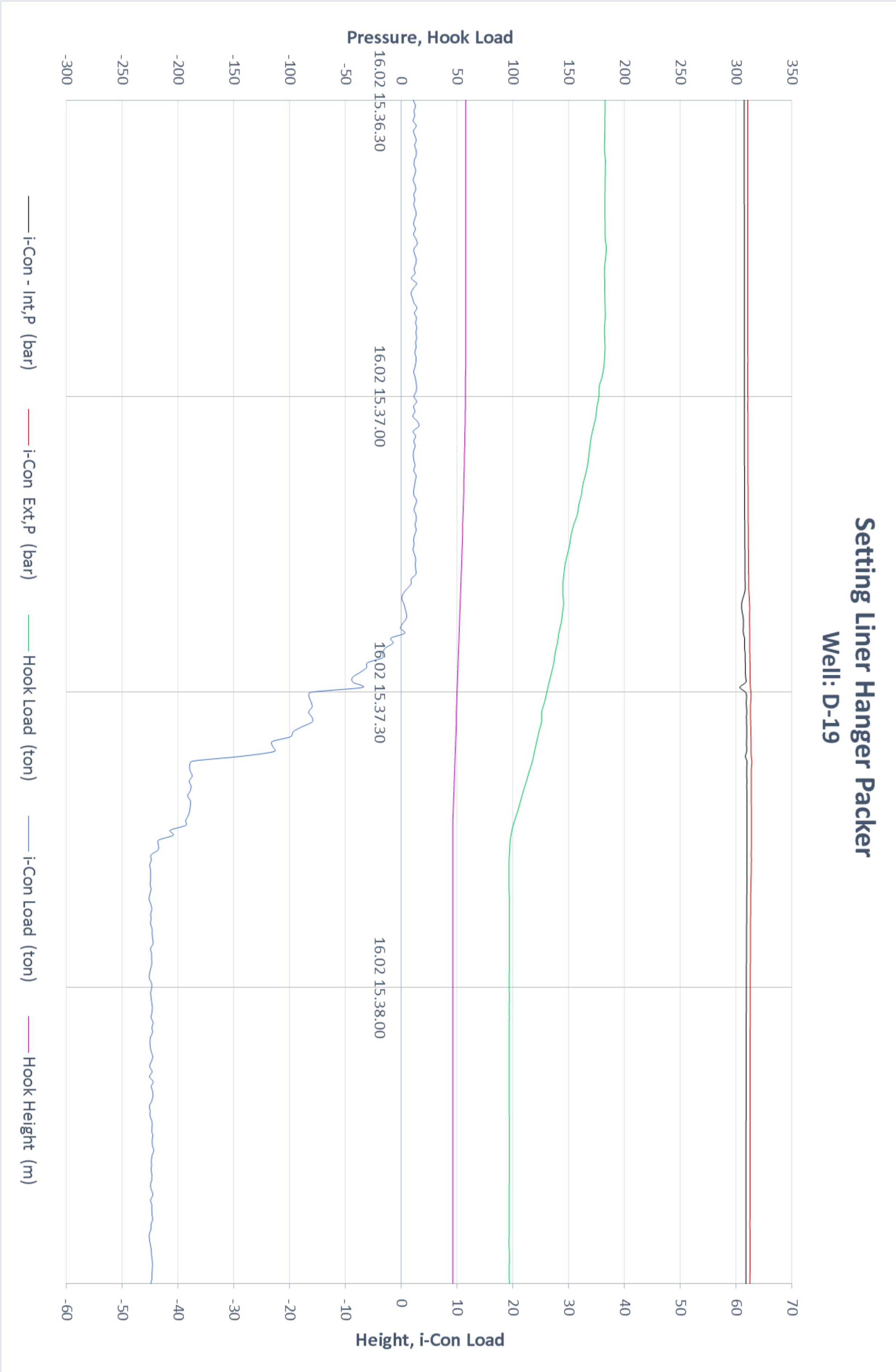

Figure 7-32: Shearing of Liner Hanger Packer during Setting in Well D-19

All the plots from Figure 7-27 to Figure 7-32 show the setting and shearing of the liner hanger packer in each well. There is a clear indication of shearing when looking at the i-Con load in each plot, and the values where these occur are presented in Table 7-5. There are also irregularities in the internal pressures occurring simultaneously as the shearing.

	1st Shear on i-Con Load [ton]	2nd Shear on i-Con Load [ton]
Well D-10	9.4	25.3
Well D-11	9.2	24
Well D-14 T3	9.4	23.8
Well D-16	10.7	23.7
Well D-19	9.7	25
Average	**9.68**	**24.36**

Table 7-5: Shearing Loads of Packers in the Five Wells

Figure 7-30 does not have the same variables as the other plots. Instead of the internal and external pressures, it shows the differential pressure. This is done in order to clarify the pressure irregularities that occur in this well, as this was not as evident in Figure 7-29.

The i-Con loads experienced in the separate wells are plotted in the same graph in Figure 7-33. The time intervals on the x-axis are 60 seconds (1 minute), and the zero point is set for each well as the time the string is picked up. This time range and starting point are also used in Figure 7-34. However, the second figure shows the internal pressure variations for each well during the setting of the packer.

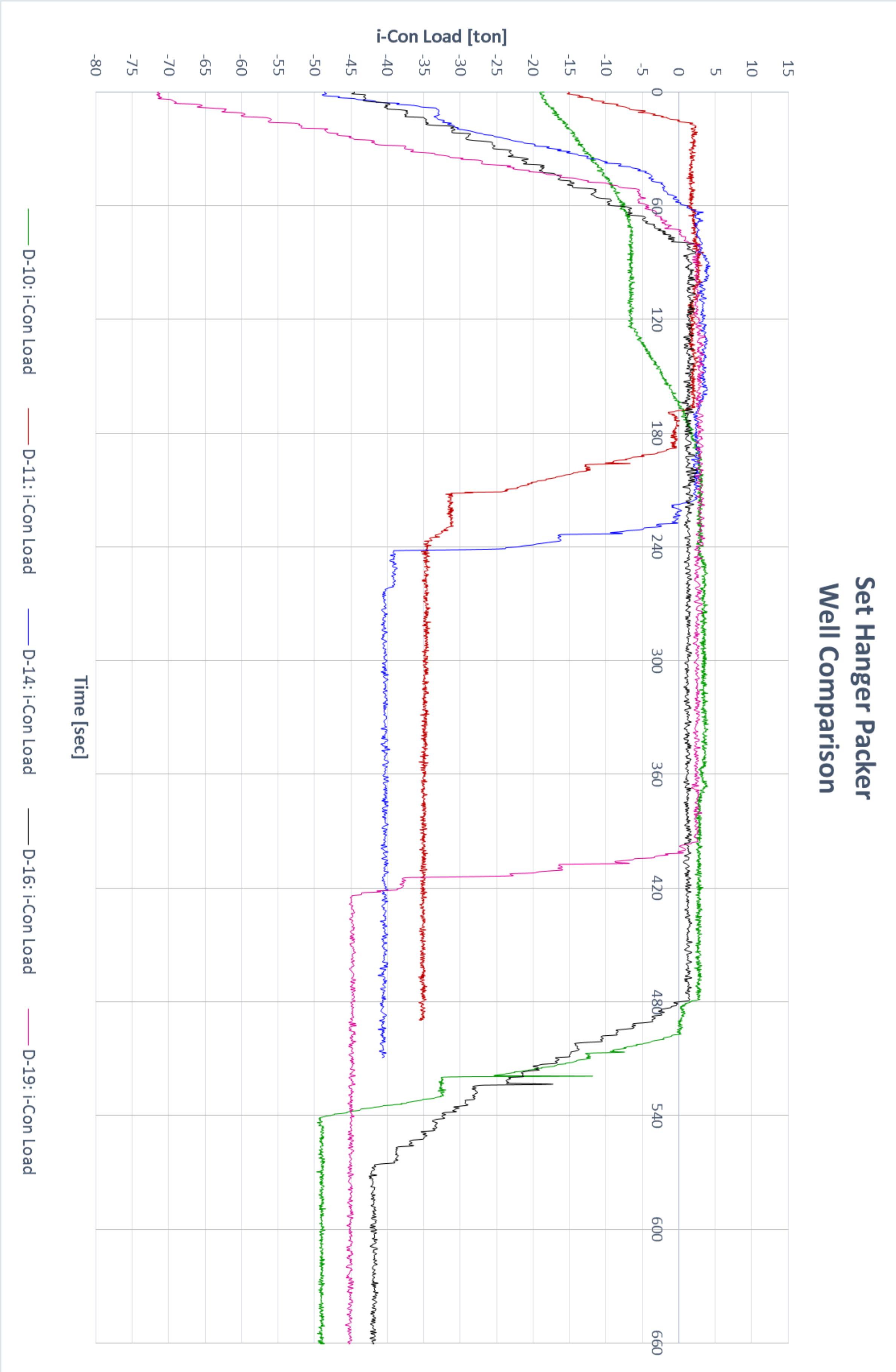

Figure 7-33: Well Comparison of Experienced i-Con Load when Setting Hanger Packer

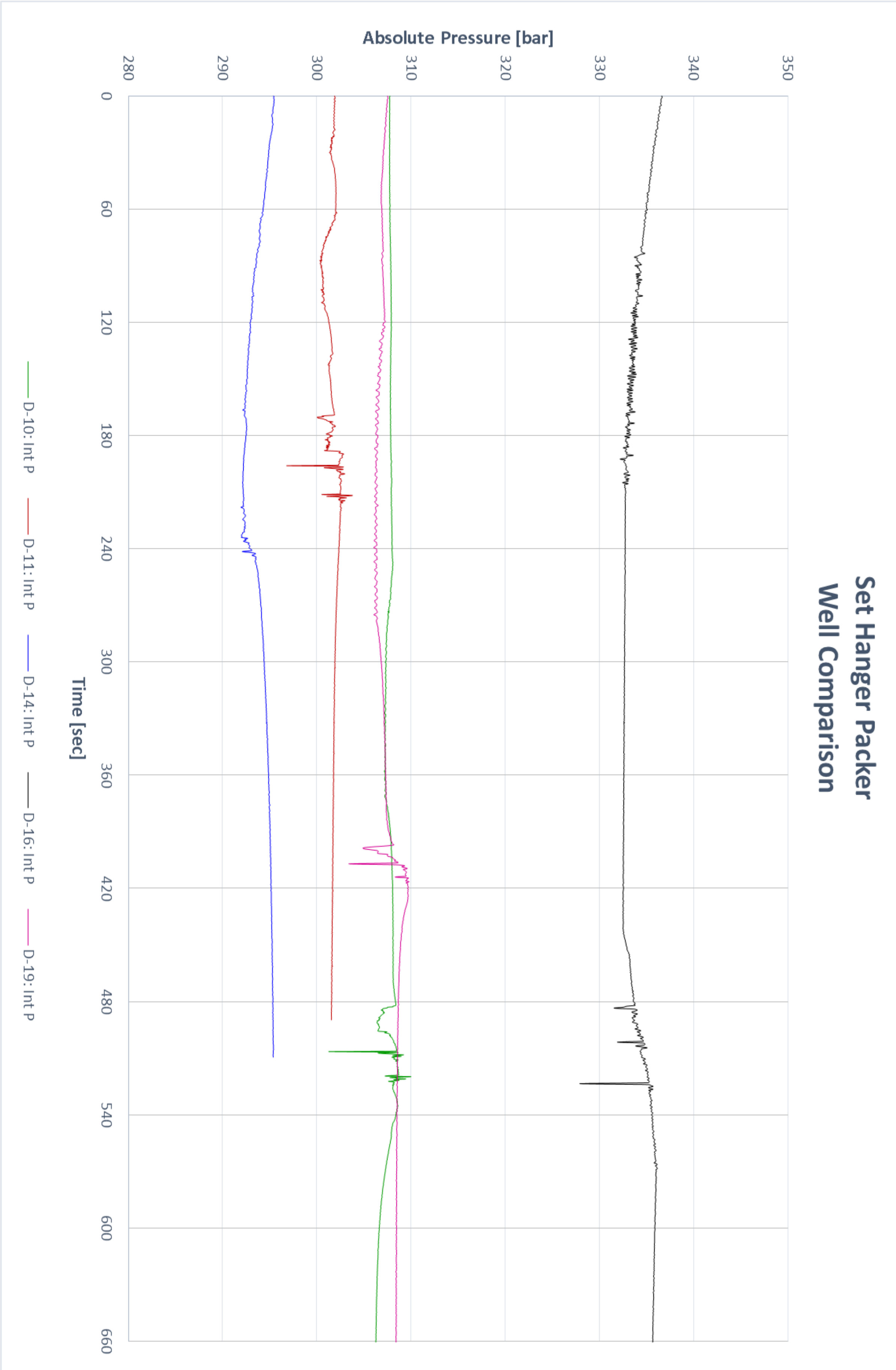

Figure 7-34: Well Comparison of Internal Pressure Response when Setting Hanger Packer

7.4.B CLOSE FORMATION ISOLATION VALVE

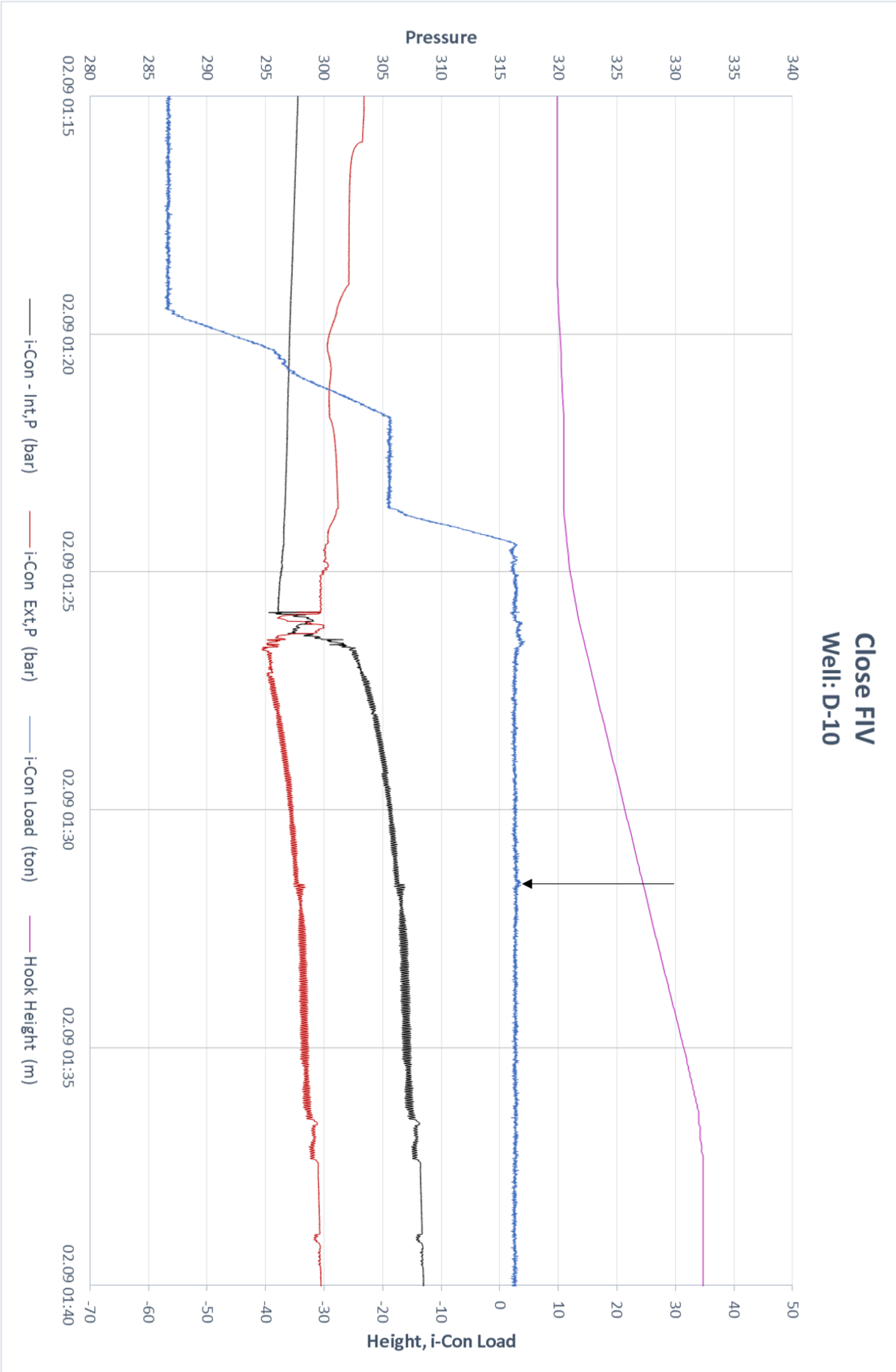

Figure 7-35: Closing of Formation Isolation Valve in Well D-10

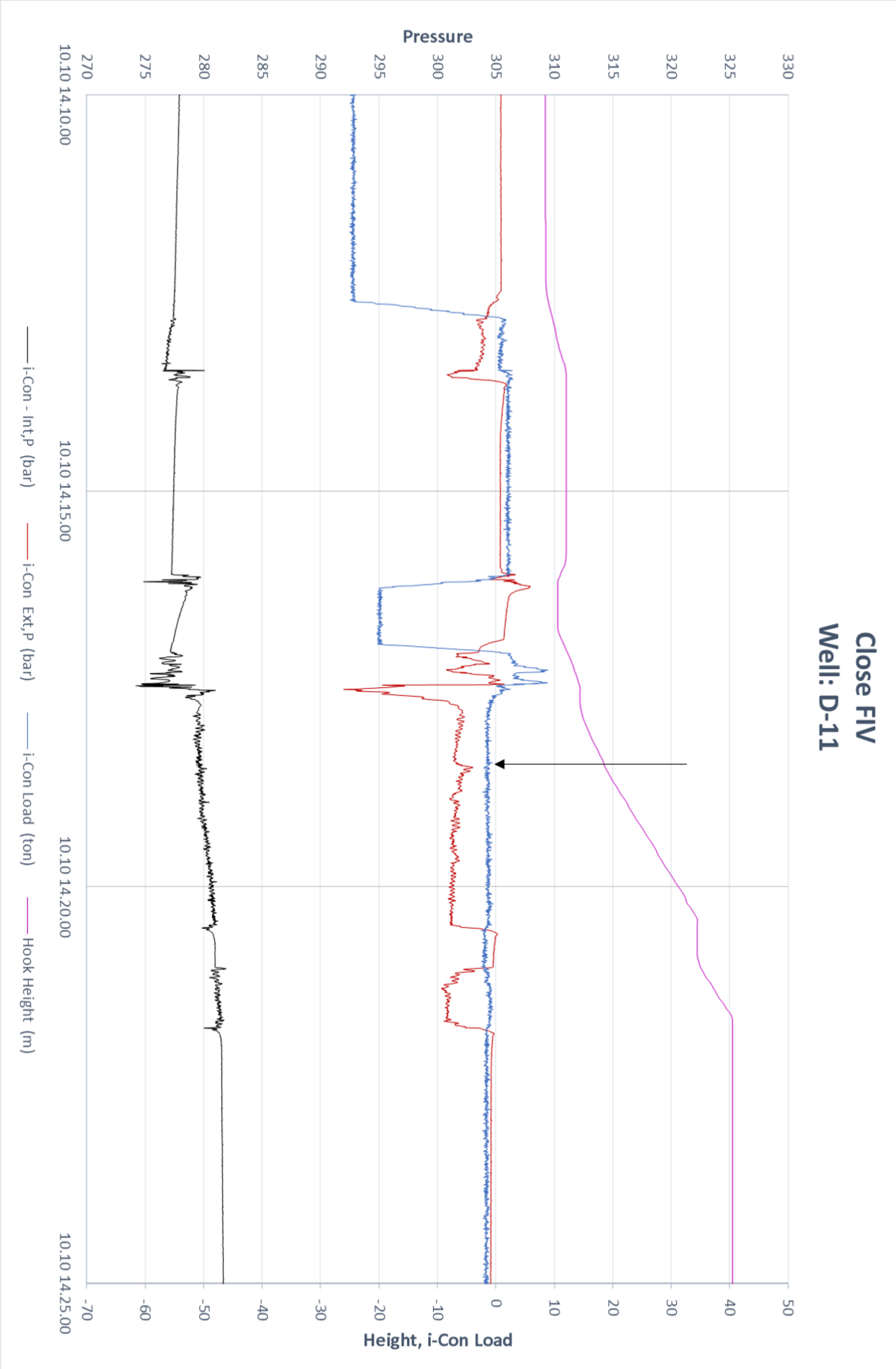

Figure 7-36: Closing of Formation Isolation Valve in Well D-11

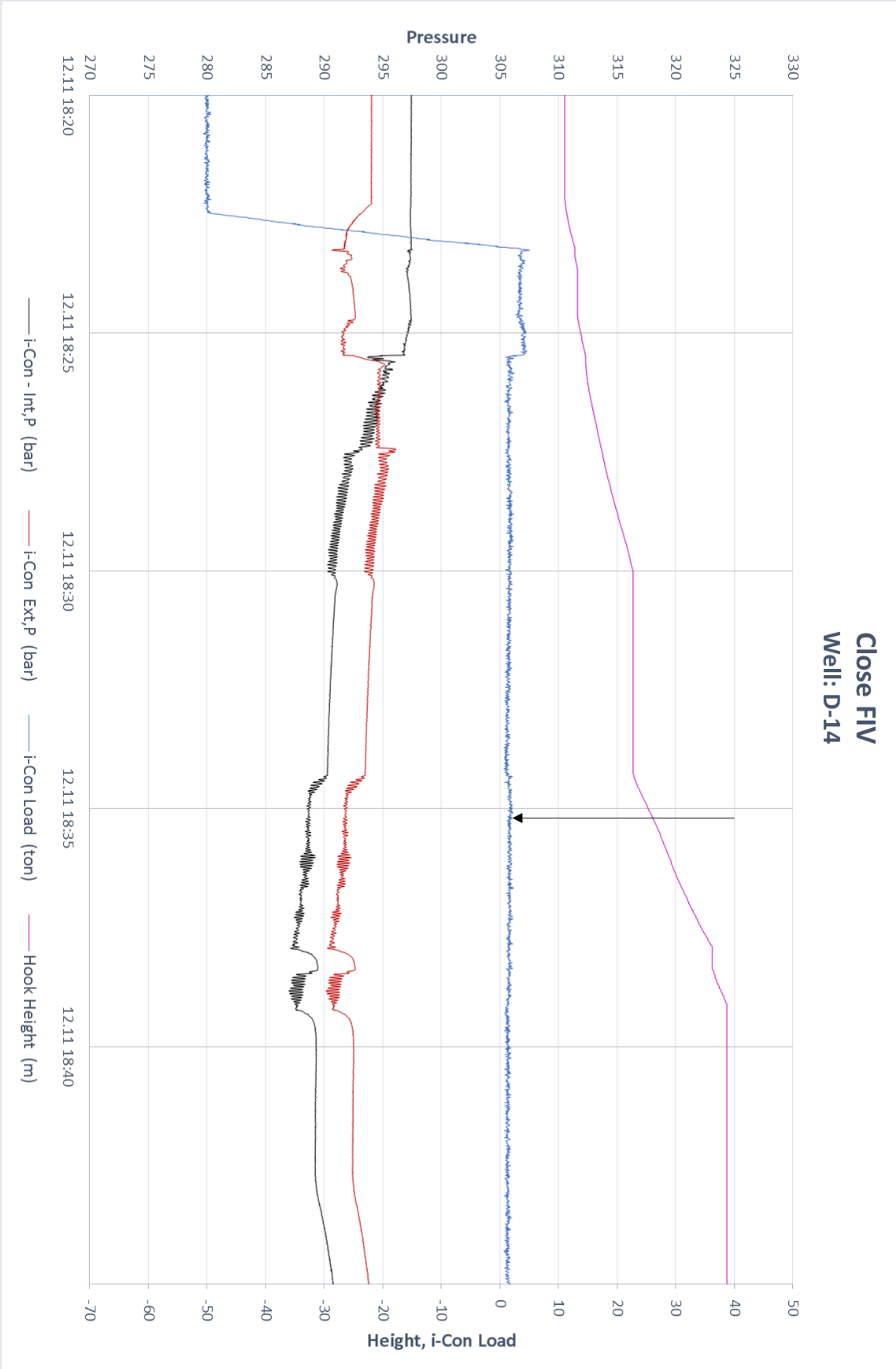

Figure 7-37: Closing of Formation Isolation Valve in Well D-14 T3

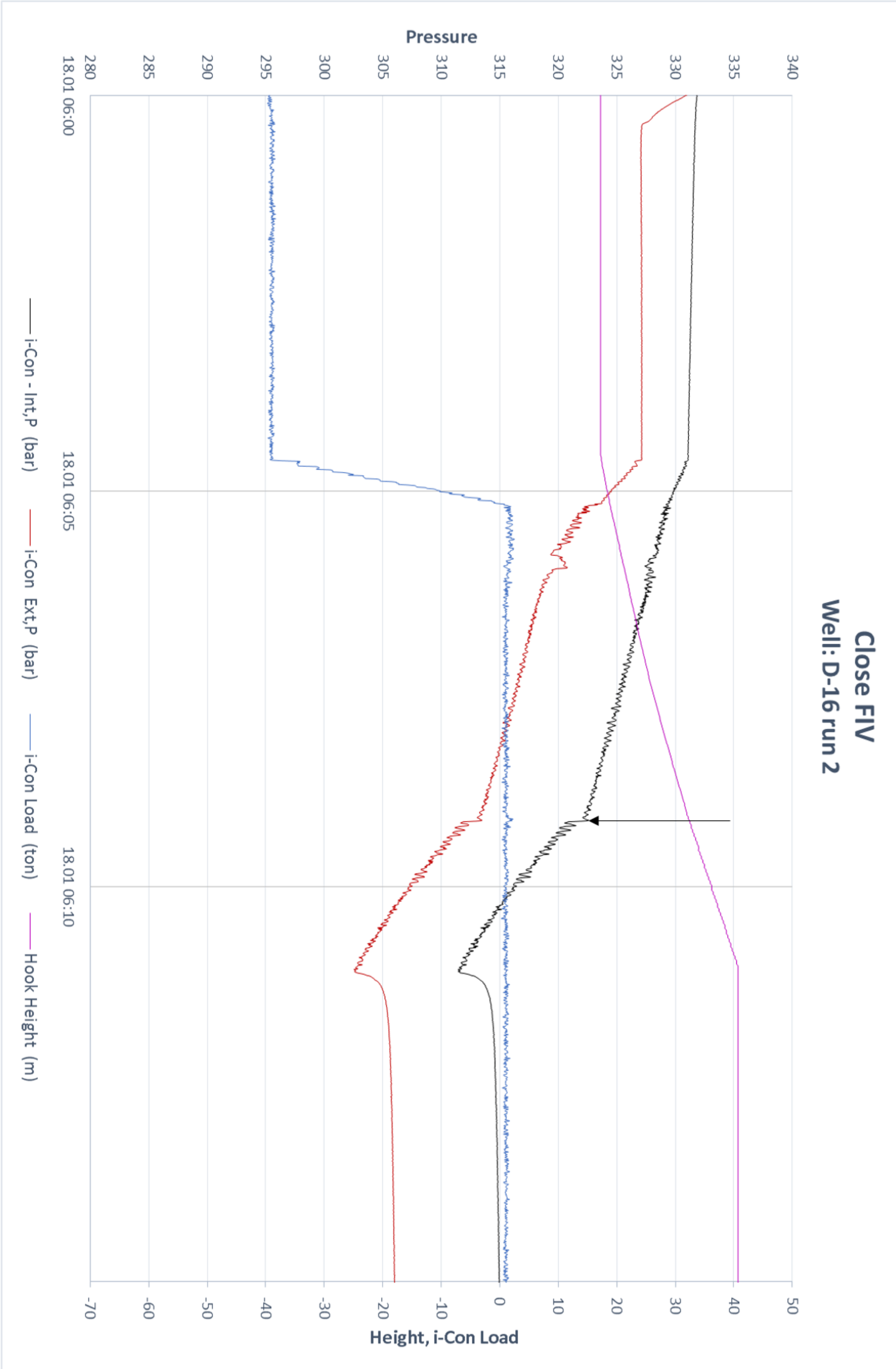

Figure 7-38: Closing of Formation Isolation Valve in Well D-16

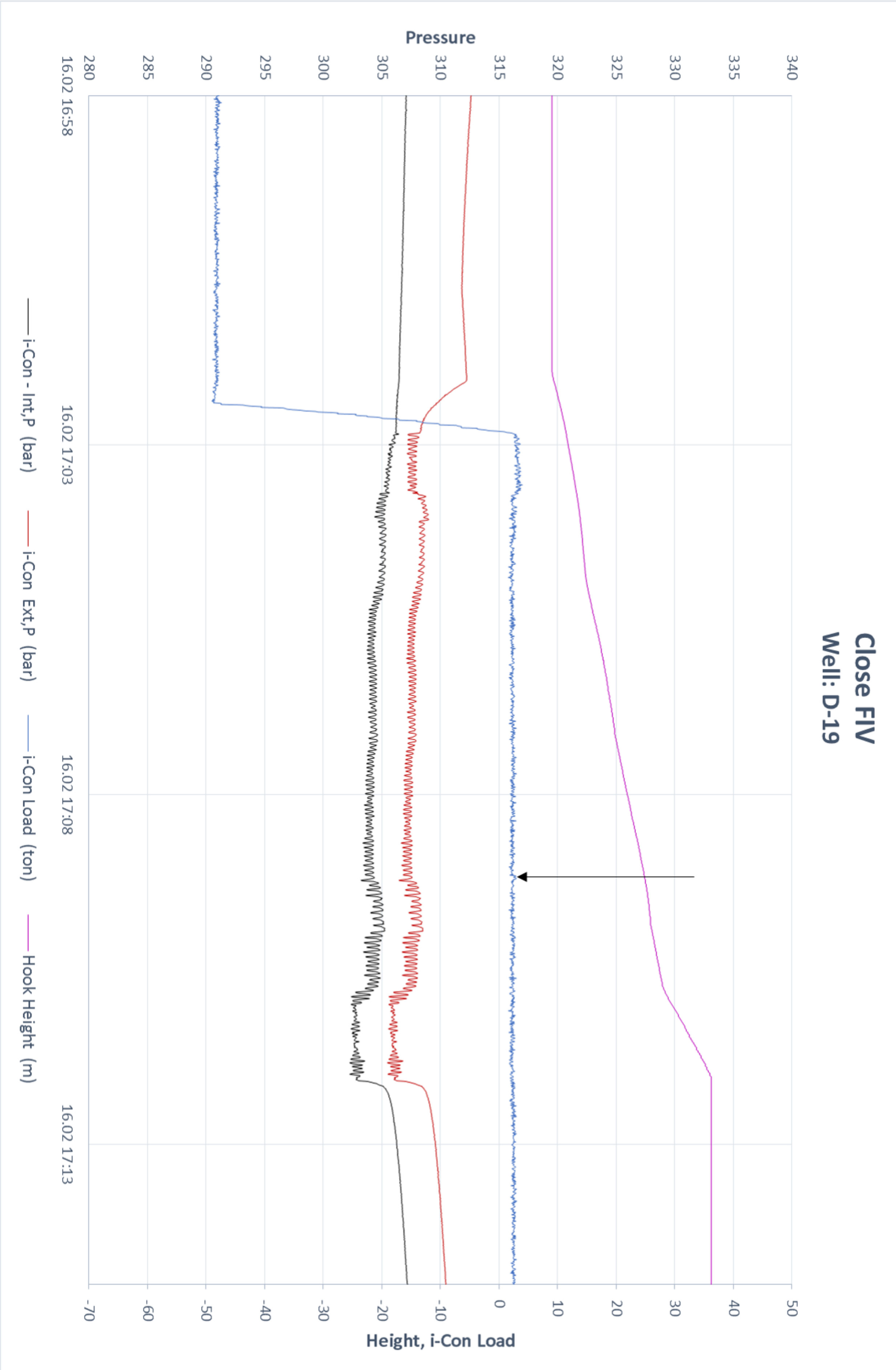

Figure 7-39: Closing of Formation Isolation Valve in Well D-19

Figure 7-35 through Figure 7-39 display the relevant data when studying the closing of the formation isolation valve. The hook height is considered the only relevant variable from the surface data as it allows one to see how much and in what way the string is being pulled up. The relevant downhole data are the i-Con load, internal pressure and external pressure.

In Figure 7-35, Figure 7-38 and Figure 7-39 it can be seen that the hook is continuously lifted during the closing of the FIV. In the other two plots, the hook is seen to be standing still at times. This is because a stand was racked back in order to lift the string the required distance. The arrow in the plots point to the i-Con load at the time the FIV is closed according to the tallies.

The table below displays the distance the hook was lifted before the FIV was closed as estimated by the string tallies. This distance is denoted as ΔHeight. The data was found after considering a study performed by Trican and Det norske concerning when the FIV was closed in the wells at Ivar Aasen.

	Closing ΔHeight tallies
Well D-10	13.0 m
Well D-11	8.8 m
Well D-14 T3	15.0 m
Well D-16	13.5 m
Well D-19	13.5 m

Table 7-6: Distances Tool String was Lifted when FIV was Closed Estimated by Tallies

7.5 PRESSURE TEST LOWER COMPLETION ISOLATION

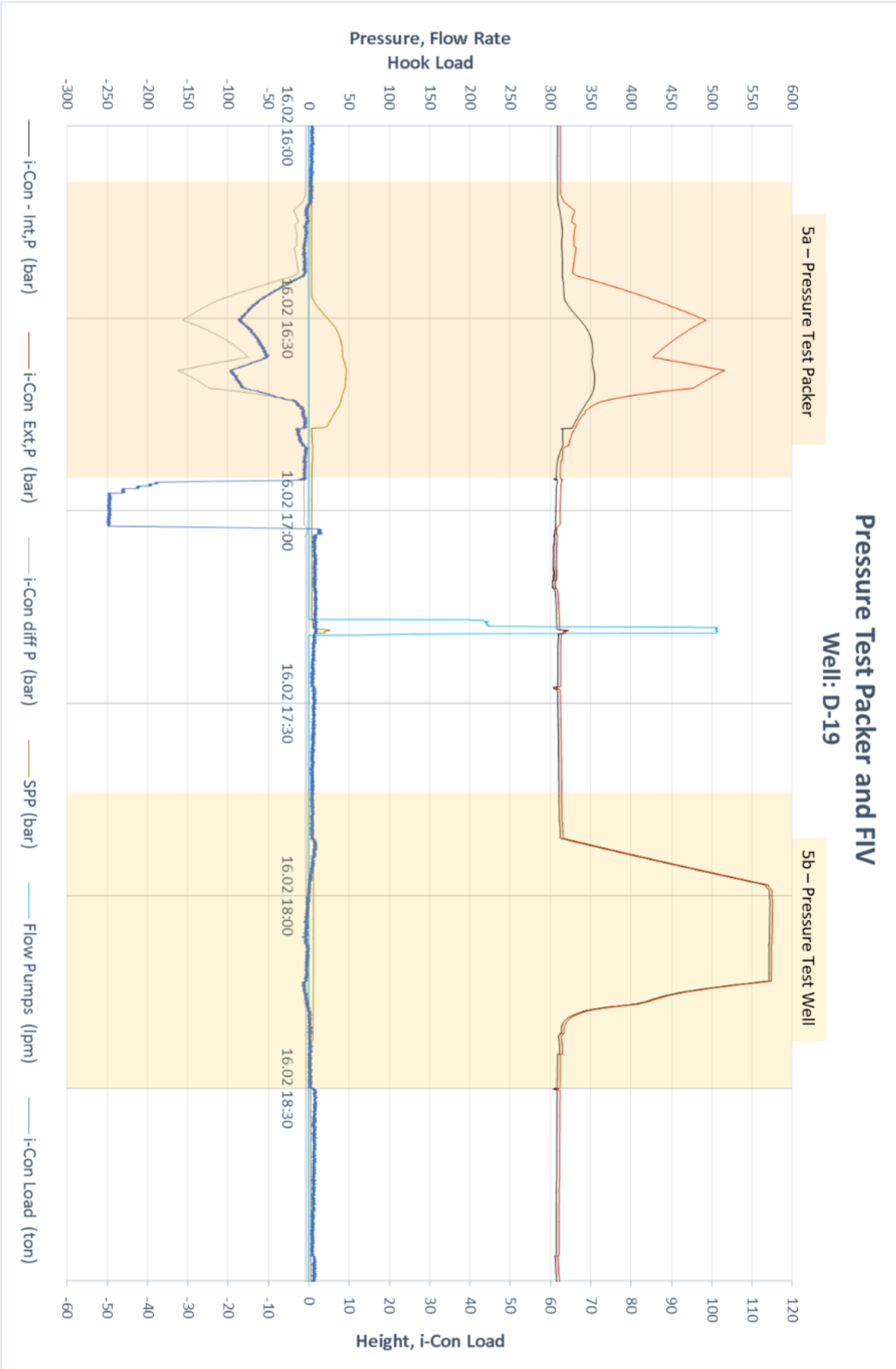

Figure 7-40: Pressure Test of Screen Hanger Packer and of FIV in Well D-19

7.5.A PRESSURE TEST LINER HANGER PACKER

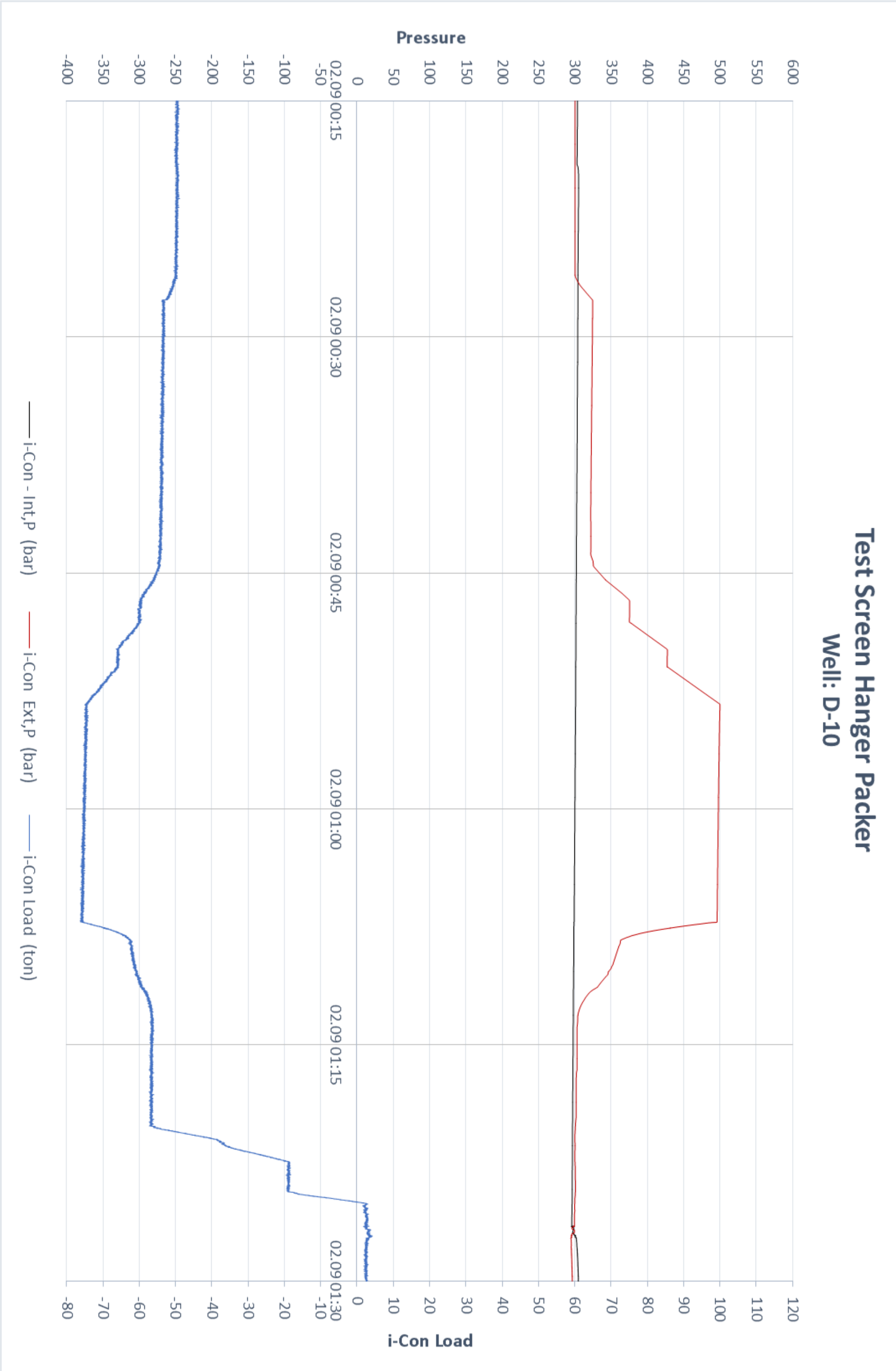

Figure 7-41: Pressure Test of Screen Hanger Packer in Well D-10

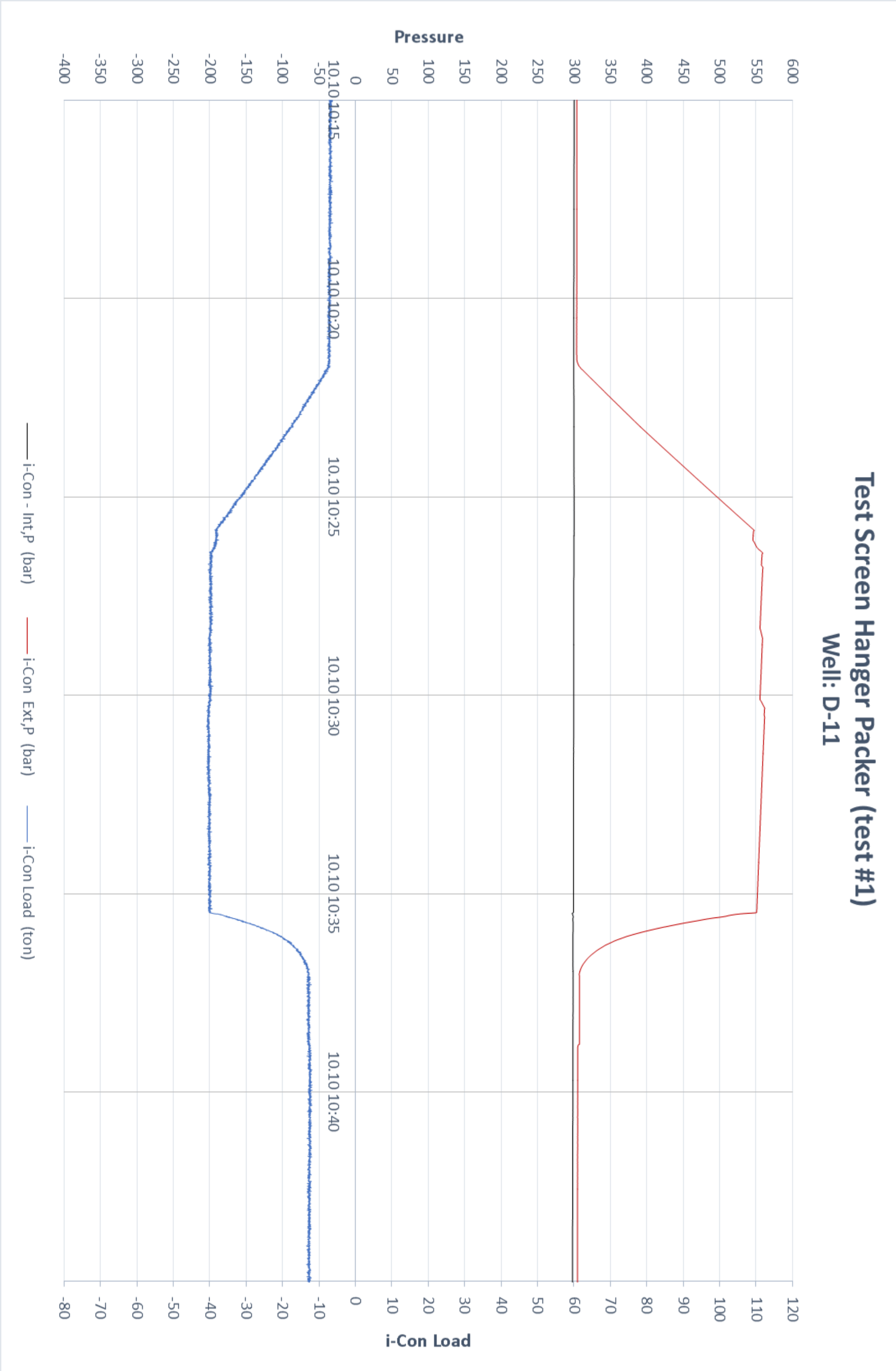

Figure 7-42: Pressure Test of Screen Hanger Packer in Well D-11

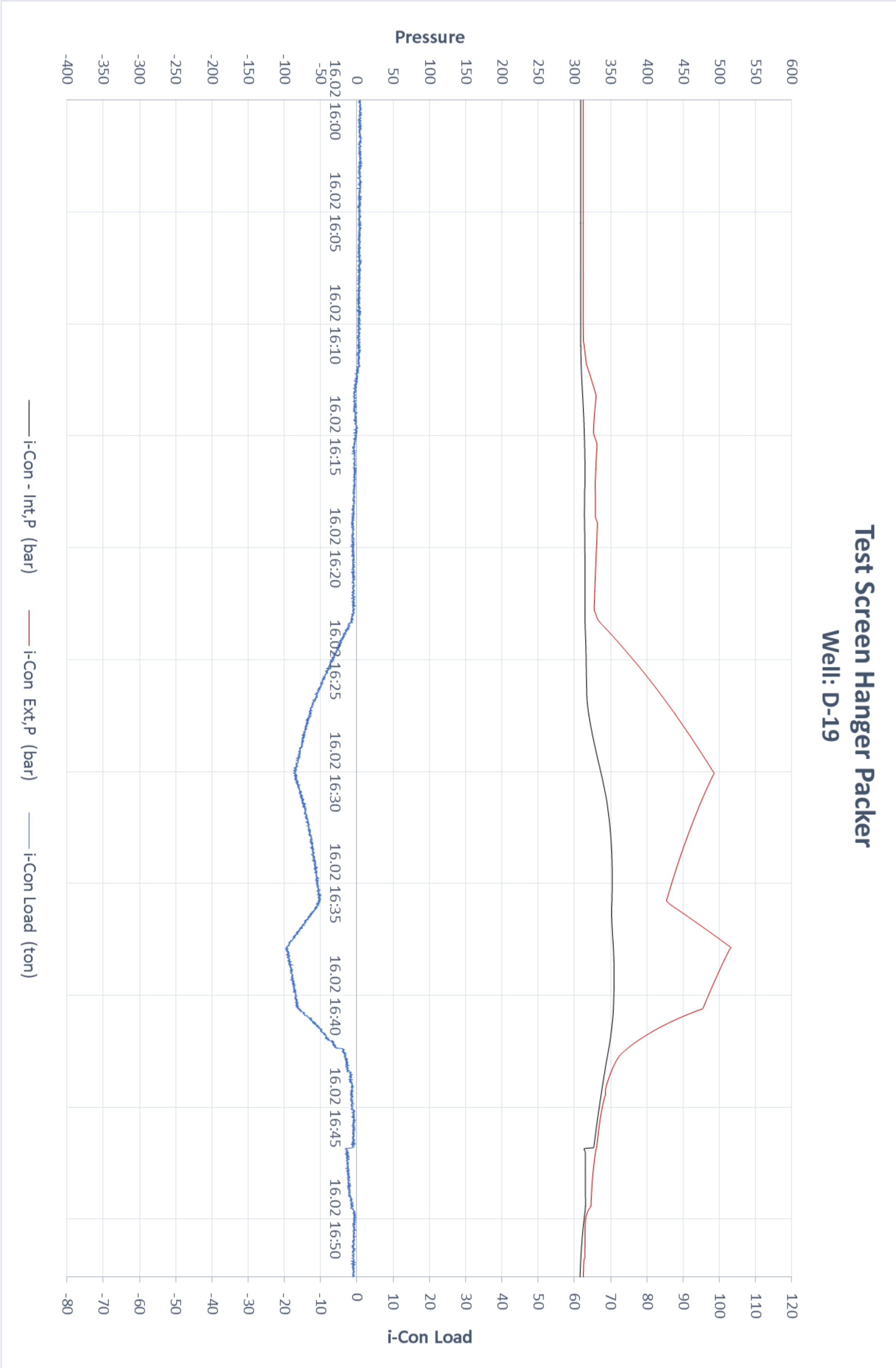

Figure 7-43: Pressure Test of Screen Hanger Packer in Well D-19

The plots presented in Figure 7-41 through Figure 7-43 represent three different pressure tests of the liner hanger packer that was performed in wells D-10, D-11 and D-19 at Ivar Aasen. The included variables in the plots are i-Con load, internal pressure and external pressure. Plots for the other hanger packer pressure tests are displayed in Appendix F. The only test that was considered to be successful was the pressure test performed in well D-10.

Table 7-7 shows the weight set down on the packer prior to pressuring up for the pressure test, and the maximum compression experienced during the pressure test. The table also shows the external pressure leak off rate and the internal pressure loss/gain during the first high pressure test in each well. These values are based on the data presented in the plots found in Appendix F and in this section.

	Compression Prior to Test [ton]	Maximum Compression [ton]	Ext Pressure Leak Rate [bar/min]	Int Pressure loss/gain [bar]
Well D-10	50	74.7	0.3	3 (loss)
Well D-11	16.5	45.8	2.1	1 (loss)
Well D-14 T3	0	29	4	3 (gain)
Well D-16	39.7	41.5	-	-
Well D-19	0	19.6	11.6	43 (gain)

Table 7-7: Compressions and Internal and External Pressure Losses during the Packer Pressure Test

The pressure tests for all oil producers are compared in Figure 7-44. Here the external pressure is plotted versus time. The time intervals used are 300 seconds (5 minutes). The data is adjusted so that all wells are aligned at the time that the well is pressured up for the high-pressure test.

Figure 7-44: Well Comparison of Measured External Pressure during the Pressure Tests of Hanger Packers

7.5.B PRESSURE TEST WELL

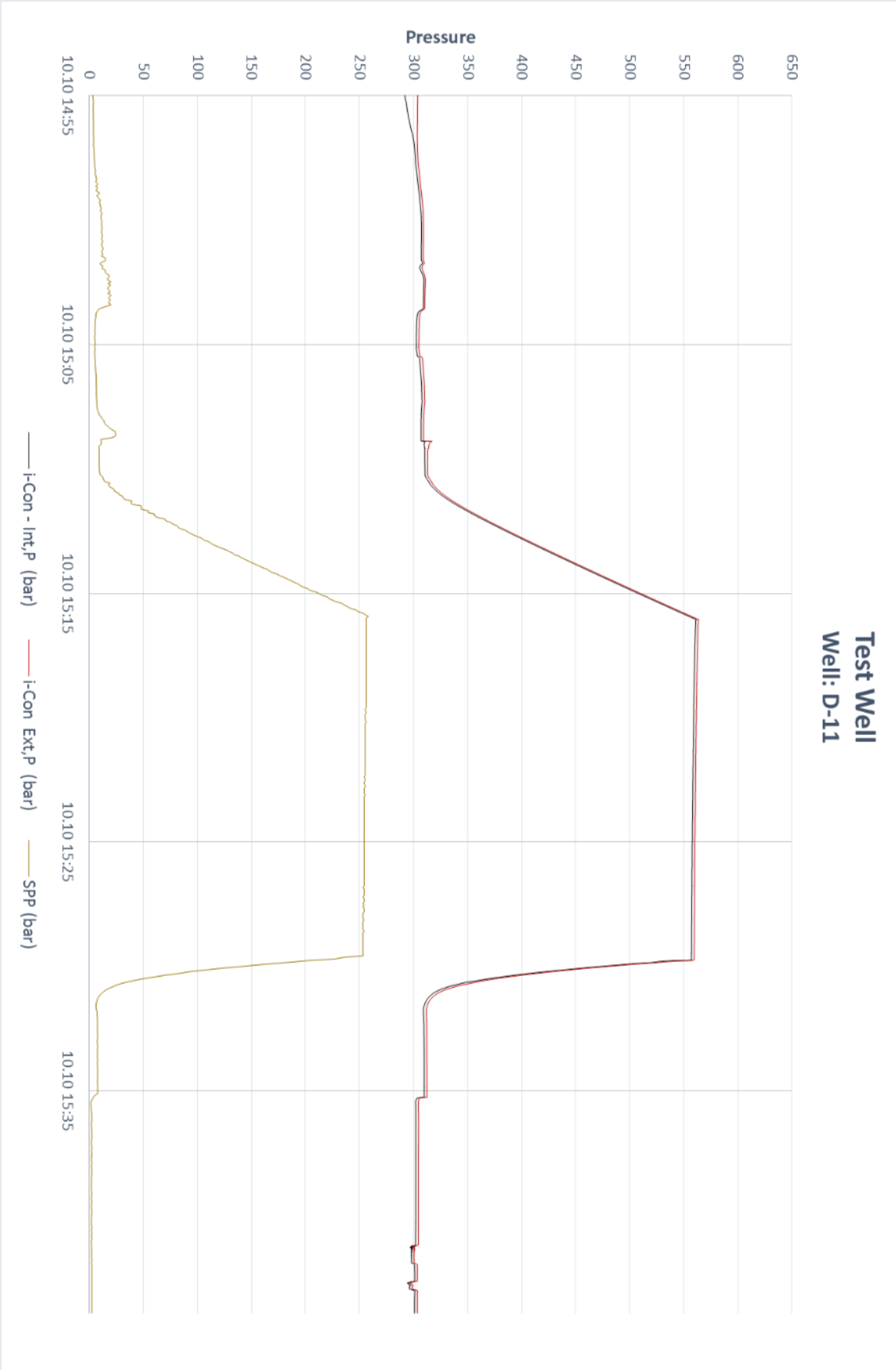

Figure 7-45: Pressure Test of FIV and Hanger Packer in Well D-11

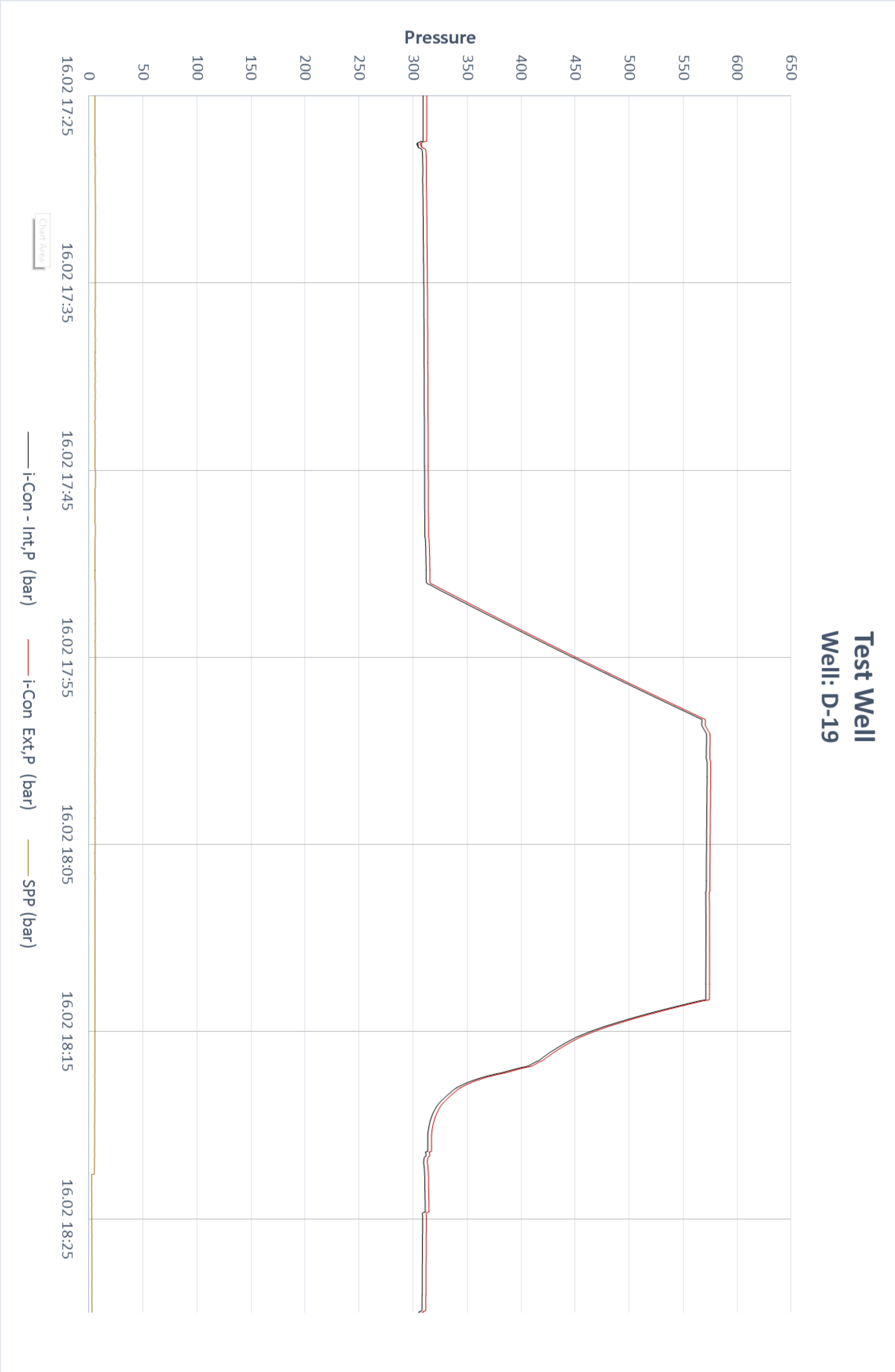

Figure 7-46: Pressure Test of FIV and Hanger Packer in Well D-19

Figure 7-45 and Figure 7-46 show two pressure tests that were done to check the packer and the formation isolation valve in D-11 and D-19 respectively. The variables that are included in the plots are the external and internal pressures, and the SPP. The other plots created for the well pressure test are displayed in Appendix G.

There is a slight variation in the two pressures registered by the i-Con tool during the pressure test. The table below display the measured value of both pressures at a specific point in time for wells D-10, D-14 and D-19. The maximum and minimum values were calculated based on the pressure sensor accuracy of 0.01% (see Table 2-6 and section 2.4.2).

	Int P measured	**Int P, max**	**Int P, min**	**Ext P measured**	**Ext P, max**	**Ext P, min**
	[bar]	[bar]	[bar]	**[bar]**	[bar]	[bar]
Well D-10	**507.804**	507.854	507.753	**499.341**	499.391	499.291
Well D-14	**551.914**	551.969	551.859	**554.714**	554.769	554.659
Well D-19	**571.808**	571.865	571.751	**575.110**	575.168	575.052

Table 7-8: Possible Values for Internal and External Pressures Based on the Sensor Accuracy

Figure 7-47 is a comparison of the external pressure response gained during the well pressure tests performed at Ivar Aasen. The tests are aligned in such a way so the point where the well is pressured up for the high pressure test overlaps. The time intervals used on the x-axis is 300 seconds (5 minutes).

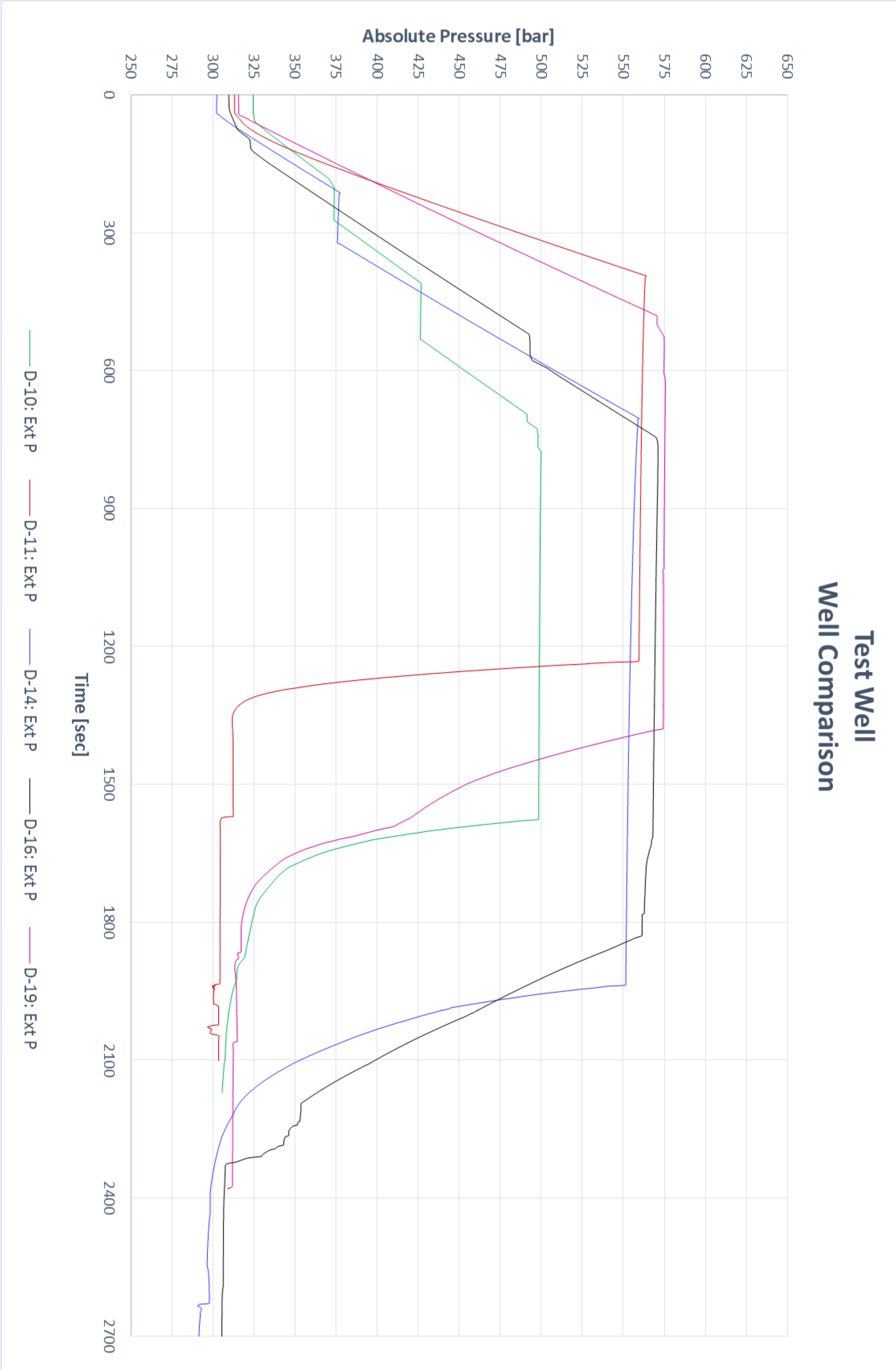

Figure 7-47: Well Comparison of External Pressure during Pressure Test of Wells

8 DISCUSSION

Installation
The relevant surface data when running in hole to the screen setting depth was found to be the SPP. This parameter does not provide much information about what occurs downhole other than when the pumps were turned on. Based on results presented in section 7.1, it can be seen that the installation in D-14 and D-19 (Figure 7-3 and 7-6 respectively) went rather smoothly with no pumping required to get the lower completion to the desired setting depth. This can be seen as the SPP mostly remains low throughout the entire installation. In well D-11 and run 1 in D-16 (Figure 7-2 and Figure 7-4) one can clearly see that the pumps were used for a large part of the installation. Well D-10 and D-16 both required some use of the flow rate when nearing the setting depth.

Considering the downhole data shown for the installation, it is possible to gain more information on what occurs downhole at the point of interest in the installation string. This point is the liner hanger as the equipment with specified limitations is located here. The axial load measured by the logging tool provides information on how easily the lower completion was run in hole. The variations in this parameter enables one to see when reciprocation and working the string down was necessary. When the load varies between tension and compression after the compression depth was reached, the string was reciprocated in order to attempt reaching the final setting depth. Based on this information, it is evident that running in hole with the string during run 1 on D-16 was very challenging (see Figure 7-4). It was also a challenge in D-11. Reciprocation of the string appears in the plots for D-10 and D-16 run 2, though not nearly as much working was required as in D-11 and D-16 run 1.

Based on the values presented in Table 7-2, it is evident that the depth at which the string becomes compressed depends on the length of heavy weight drill pipe (HWDP) in the string. The well with the least amount of HWDP experienced compression furthest from the 9 5/8" casing shoe (4008 m MD), and the well with the most HWDP became compressed closest to the shoe (3633 m MD).

The external pressure measured by the tool is also included in the figures in section 7.1. This variable provides an indication of where in the well the tool is at each time. When the external pressure in the well increases with a relatively stable gradient, it is an indication that the tool is located in the vertical part of the well causing the hydrostatic pressure to increase. Once the build section and horizontal section of the well is reached, the gradient decreases and the pressure eventually evens out. When the progress is slow, the pressure gradient also decreases.

Anchoring

The second event analyzed was the anchoring of the lower completion. Based on the results presented in section 7.2, it can be seen that this downhole event causes very similar responses in all parameters for the wells. This is demonstrated clearly for the tool load and the differential pressure in the well comparison plots in Figure 7-13 and 7-14.

Considering the available surface data for the anchoring, there is a very clear indication in the SPP of the setting ball landing in its seat. There is a marked SPP increase as the ball lands and creates a blockage inside the installation string. This can be seen in all figures from Figure 7-8 to 7-12. A similar variable response can be seen by the downhole data in the same plots. Once the ball lands in the ball seat, the internal pressure of the installation string increases as expected by a value corresponding to the SPP increase. The downhole indications confirm the conclusion of the surface data, as well as provide a complete picture of the actual pressures felt at the point of interest. Hence it can be seen what the ball is actually exposed to.

When the ball lands, the tool load also demonstrates a uniform behavior for all wells. The load suddenly increases (the tool experiences more tension) at the same time as the SPP and internal pressure increases despite the fact that the hook is stationary. This is displayed in Figure 7-14 in addition to all the figures mentioned in the above paragraph. Considering these plots, it is quite obvious that the loads the i-Con tool registers is dependent on the internal pressure. The correspondence between the two curves is due to the fact that the i-Con memory tool is positioned above the liner hanger running tool. Once the setting ball has landed in the ball seat, the volume above this point will be closed. As the drill pipe is pressured up, the pressure pushes against the closed area of the liner hanger so that the entire string is stretched, and hence experiences more tension.

The next step in the anchoring is verifying that the hanger has been set. This is displayed in the plots by the surface data as the hook height decreases meaning the string is lowered into the well. This causes a corresponding decrease in hook load, which is also clearly displayed. On the rig, these two variables are observed during the operation to check if the hanger is slipping. In Figure 7-8 to 7-11, the hook height and the hook load is seen to decrease steadily indicating that the hanger is set. In Figure 7-12 there is an uneven decreasing trend in the load and height which indicates that the hanger is slipping. The tool load also provides a clear verification of whether or not the hanger has been properly set. Considering the presented results, it can be seen that the tool experiences a linear increase in axial load when weight is set down, except for well D-19 where there is an unevenness. Based on these downhole data it can be seen that the liner hanger begins slipping once it experiences approximately 12 tons down weight.

The shearing of the ball seat is clearly demonstrated both by the surface data and downhole data. There is a sudden pressure drop in both the SPP and internal pressure, and a similar increased compression experienced by the logging tool. Hence, the tool does not provide much information that cannot be gained from the surface data, though the additional downhole data causes a much clearer picture of the entire well during the operation.

Circulation

Considering the results from analyzing the circulation through the lower completion, the variable that provides the clearest indication on the pumping sequence of the fluids is the SPP provided by the surface data. In all the wells, the SPP provides an indication of when base oil is pumped (increasing trend), when it enters the open hole (stable trend), and when OBM is pumped (decreasing trend).

However, when the pump rate was kept constant through the whole circulation as it was in D-19, it is possible to see further details of the operation such as those described in section 5.2.3. The variations in SPP that mark the various stages of the circulation are shown in Figure 7-22, along with the external and internal pressures measured by the tool. The internal pressure can be seen to also vary at the same times as the SPP. The first decrease in the internal pressure is thought to be due to the base oil reaching the i-Con tool, and as it has a lower density than the OBM the measured pressure will be lower. The second pressure drop corresponds to the same time as the base oil is assumed to enter the OH. This is because the u-tube effect decreases as the low density base oil enters the OH. Hence, the internal pressure at the logging tool decreases. The final pressure drop occurs as the pumping of the OBM commences, and this is also due to the decreasing u-tube effect.

Though the i-Con load does not provide any direct information on how the pumping of the fluids is going during the circulation operation, it displays similar behavior for all five wells (see Appendix D). As the internal pressure and SPP increases, the load displays a corresponding trend. This is due to an effect called ballooning. This causes the installation string to expand due to the increased internal pressure, and therefore the string becomes shorter. This leads to less weight being set down on the liner hanger, and hence the tool experiences less compression. As one can see from the maximum and minimum loads in Table 7-4 and the circulation graph for well D-10 in Figure 7-16, the string was only in 10 ton compression before the circulation commenced. Therefore, the string experienced tension during the circulation meaning it was lifted off the liner hanger so no weight was set down. This is undesirable as the string can be lifted from the liner hanger, causing the setting dogs to be activated and the seal in the PBR to be pulled out prematurely. Hence, a learning from this first well was done so that more weight was set down prior to circulation in the other wells.

Set Liner Hanger Packer

When setting the liner hanger packer in the well, the relevant surface data was found to be the hook height and the hook load. These two variables contribute to provide a picture of the operations occurring on the surface, but not on what is occurring downhole. In Figure 7-26 it can be seen that the hook height first increases, indicating that the string is lifted. This is confirmed by the hook load as it increases correspondingly. Once the installation string has been picked up to the up weight plus a few meters, the setting dogs should have been pulled out of the PBR and hence activated. The hook is then lowered and weight is set down on top of the PBR, which is seen by the decrease in hook load. This down weight is held for approximately five minutes after which the packer is supposedly set.

When taking certain downhole data into consideration, a much clearer picture of the operation emerges. The relevant downhole data is i-Con load, internal pressure and external pressure. Considering the plots displayed in section 7.4.A, it is evident that new information becomes apparent when zooming in on the relevant variables. From these results one can also see that the downhole data display similar behavior for all wells, as is particularly shown in Figure 7-33 and Figure 7-34.

When setting down weight on the hanger, the hook load has a relatively even decreasing trend. The i-Con load, on the other hand, is much more irregular. In Figure 7-27 through 7-32, marked jumps in the load is evident. This sudden change in the axial tool load is due to the shearing and setting of the packer, which occurs in two steps. In most of the wells both shearing loads are obvious (D-10 and D-19), while in others only one may stand out significantly. However, at closer analysis all the shear loads can be identified based on the downhole data (see Table 7-5). The resulting shearing values are quite similar with averages of 9.68 tons and 24.36 tons. As the packer was pinned to shear at 24/25 tons in all the wells, the acquired values from the downhole data seem reasonable and accurate.

When identifying the i-Con loads that correspond to the packer shears, the external and especially the internal pressure was found to be useful. When considering the same plots as mentioned above, the internal pressure clearly demonstrates irregularities at two to three different times for all the wells. These pressure responses are displayed in Figure 7-34 where the similarity is obvious.

In the plot for D-14 (see Figure 7-29), the pressure responses were at first hard to distinguish. However, a new plot was made with the differential pressure instead of the external and internal pressures. The result was that three irregularities stood out. These correspond with the sudden load changes seen in the same plot, and hence are believed to occur at the time the packer is sheared. Therefore, all wells can be documented and verified properly set through the analysis of the downhole data.

Close FIV

The results from the analysis performed on the data acquired when closing the formation isolation valves are displayed in section 7.4.B. The surface data considered relevant for this particular downhole event is the hook height, as lifting the lower completion (about 25 m) is the main operation occurring on surface. Considering this variable, it is possible to see with what ease the string was lifted the required distance. In wells D-16 and D-19 the string was lifted in one motion. In D-10, though the hook was stationary after it was pulled a few meters, the rest of the distance was pulled continuously. The other two wells (D-11 and D-14) both required to rack back one stand in order to lift the string the required distance.

The downhole data considered to be relevant was i-Con load, external pressure and internal pressure. As the FIV is set to be closed by one ton over pull, this weight was expected to be observed on the i-Con load when the shifting tool passed the FIV. However, this was achieved with various success. The load peak corresponding to the one ton over pull is difficult to identify isolated. In wells D-10, D-16 and D-19 there is a clear indication the FIV is closed if one considers the load and pressures together (see arrows in figures in section 7.4.B). Well D-11, on the other hand, has a very poor indication. The arrow points to the time where the valve is closed according to the installation string tallies. Once this time is known, a slight indication can be observed. Despite this, it is not an indication which would be recognized had it not been for the information gained from the tallies. In D-14, it was also hard to locate the point the valve was closed, and the arrow in Figure 7-37was placed based on the information gained from the tallies and the internal investigation performed on this subject[14].

There is a variation in the i-Con load and the pressures which can be seen in the plots prior to the closing of the valves in all wells. This variation is thought to represent the seal in the liner hanger running tool being pulled out of the PBR. When the seal is pulled out, the i-Con load drops a few tons, which is expected as the friction forces caused when the seal is dragged against the inside of the PBR disappears. This means that the load the i-Con tool will experience (the weight of the liner hanger running tool) decreases once the opposing friction force is eliminated. After the seal is pulled out of the PBR, the internal and external pressures can also be seen to demonstrate near identical behavior (except for in D-11). This is expected as there is no longer any seal or other separation between the inside and outside of the installation string, allowing free pressure communication.

The pressures acquired during the operations vary greatly and do not exhibit a common behavior for the various wells. However, when studying the pressure responses for each well separately, the internal and external pressure exhibit the same behavior. In D-11 however, this is not the case. There was only an external pressure response, and barely any indication in the load as shown in Figure 7-36. It can be seen that the pressure difference prior to the operation is very large compared to the other wells with an external pressure greater than 305 bar and an internal pressure of about 277 bar. The pressure difference can have caused damage to the seal during the operation, which would explain the unexpected pressure responses.

In conclusion, when isolating the inside of the lower completion by closing the FIV, there is no common indication in the wells at the time the valve is closed. There is a slight weight indication in most wells, and some sort of pressure response in the internal and external pressure. However, the specific behavior of these responses vary from well to well. Therefore, other measurements have to be used to confirm the FIV is closed (i.e. pressure test).

Test Packer

When pressure testing the hanger packer in the wells, only downhole data was included. The variables included were internal pressure, external pressure, and i-Con load. During this test, the annulus is pressured up to see that the packer is sealing properly. This is obvious in the displayed plots in section 7.5.A and in Appendix F where the external pressure increases both

[14]Internal investigation performed by Trican and Det norske to identify closing of FIV

for the low and high pressure test while the internal pressure mostly remains relatively unchanged.

In the figure displaying the hanger packer test performed in well D-10 one can see that the pressure barely leaks off both during the low and high pressure tests by studying the external pressure curve. The annulus is first pressured up with 25 bar (300 to 325 bar), followed by a 175 bar pressure increase (325 to 500 bar), and at the end of the test the pressure has decreased with 4 bar (496 bar). This is a minimal pressure leak which is well within bounds of what is accepted. The internal pressure remains nearly constant during the entire pressure test (3 bar pressure loss), indicating no communication between the high and low pressure volumes.

However, the pressure tests performed in the other wells display different external pressure responses. In Figure 7-42, the data acquired during the pressure test in well D-11 is shown. The initial external pressure increase is from 304 bar to 547 bar, followed by a further increase to 556 bar, causing a total increase of about 250 bar. The pressure leaked off at quite a high rate (see Table 7-7) so the string was refilled at various times. This caused an uneven pressure curve. Several pressure tests were performed in D-11, and all were unsuccessful. The internal pressure curve remained relatively constant during the pressure test, with a slight pressure drop of 1 bar. Similar behavior was seen for all the other tests done at Ivar Aasen (see Appendix F and Figure 7-44), except in D-19.

Figure 7-43 shows the pressure test performed in well D-19. The low pressure test is not constant as the well was pressured up at several times in order to attempt having a constant pressure. During the high pressure test, the annulus was pressured up to 492 bar and 515 bar respectively, but the pressure leaked off at a high rate. Unlike the other wells, the internal pressure in well D-19 increases during the test rather than staying constant. This indicates that there is in fact communication between the annulus and the installation string. Hence, there may be a leak located somewhere in the installation string rather than in the hanger packer[15].

The only successful packer test at Ivar Aasen was the one performed in D-10, where the external pressure leak rate was 0.3 bar/min, and the internal pressure loss was 3 bar. In the successive wells, the external pressure leak rate was seen to be increasing, and the internal pressure losses decreased and turned to pressure gain. This is shown in Table 7-7. As the conclusion in well D-19 is that the leakage may be located in the installation string rather than

[15]A study performed in late April, 2016 by Det norske concluded that the pressure leak during the packer pressure test was due to a leaky HWDP used in the installation string in wells D-11 through D-19.

the packer or liner hanger running tool seal, this may also be the case for the previous wells (D-16, D-14 and D-11). This is based on the fact that there is a common trend for all wells (except D-10) in both the pressure leak rate and in the pressure loss seen during the pressure test. Hence, the wells may have the same pressure leak issue.

The i-Con load does not provide information on whether or not the pressure test is successful, but it provides information on what the downhole equipment is experiencing. The load can be seen to display a typical behavior for all the wells. There is a clear correspondence between the external pressure and the load felt by the memory tool in the well. This is due to reverse ballooning effect. As the pressure in the annulus increases, the installation string is squeezed. This causes a smaller cross sectional area which in turn results in an elongated string. Hence, more weight is set down on the liner hanger during the pressure test, and the logging tool experiences increased compression. The impact of the reverse ballooning effect can be seen when reviewing downhole data, which enables procedures to be updated should it be required. This was done at Ivar Aasen when the data from well D-10 was reviewed. Prior to the pressure test there was 50 tons set down on the PBR which resulted in 74.7 tons during the test. This was considered too high, and therefore less weight was set down for the following wells, as shown in Table 7-7.

Test Well

During the well test, the SPP was included. However, due to the fact that the SPP remained unchanged during the pressure test for some of the wells, the internal and external pressures were included to be able to gather information on what the downhole isolation experienced during the test. The external and internal pressure curves in Figure 7-45 and Figure 7-46 remain constant during the pressure test, meaning that there is no leakage in the FIV nor hanger packer. The same behavior was seen in the plots for the other wells displayed in Appendix G. Hence, the isolation in all wells was verified to be successful prior to pulling out with the installation string and commencing the succeeding operations.

Accuracies

During the final pressure test of the lower completion, the installation string is pulled out of the lower completion so that it is hanging freely in the well with no seals to the annulus. Therefore, there is pressure communication between the inside of the string and the annulus, meaning the internal and external pressure sensors should read the same values. This should occur directly after seal on the liner hanger running tool was pulled out of the liner hanger right before the FIV closed. Hence, the pressure values should be the same from this point in time. Despite this, the internal and external pressure can be seen to be slightly different for all the wells.

According to the data presented in Table 2-6, the accuracies of both the pressure sensors is ±0.1%. The table in section 7.5.B shows a representative measurement of the internal and external pressure taken at the same time in three wells, and the maximum and minimum values that would still be within the sensor accuracy. As it is clear that the two pressures do not produce the same value even with the uncertainties included, it can be concluded that the values are in fact different. This difference can be due to many factors. Some theories are that the pressure sensors see fluids with two different densities, the fluid column varies for the installation string and the annulus causing a higher hydrostatic pressure in one of them, different pressure gradients inside the string and the annulus causing two different fluid densities, calibration variations between the two sensors, or sensor inaccuracies.

If one is to eliminate any doubt about whether the readings from the tool are accurate or not, the calibration history of the tool should be checked to see when it was last calibrated. A post job calibration check of all the sensors in the tool could also be performed in order to uncover any differences in the measured values and real values. If this was the case, it could indicate that something had occurred during the operation to cause the sensors to be more inaccurate, or that the tool should have been recalibrated prior to the job.

9 CONCLUSION

The main conclusions gained from the work done in this thesis is presented in this chapter. The conclusions from each analyzed downhole event are presented together. Finally, some general conclusions are made.

- When **installing the lower completion** in the well, the i-Con tool adds new information regarding when the string becomes compressed by considering the axial load measured by the tool. When the value is positive, the tool experiences tension while negative values correspond to compression load. The axial load also provides the possibility of confirming how much weight that was actually set down on the lower completion equipment during the installation.
- Considering the variation between compression and tension which occurs while running in the open hole section, the reciprocation of the string can be confirmed using the downhole data.
- These downhole measurements relative to surface loads can be used for determining friction factors allowing the actual load on the downhole tools to be more precisely predicted. This can make future completions more robust.

- There is an evident fingerprint behavior of both the surface and downhole data during the **anchoring of the lower completion** which can be identified in all the lower completion installations. This fingerprint behavior is seen in the SPP, internal pressure and axial load.
- During the anchoring operation, the i-Con tool provides new information about the axial loads experienced at the point of interest in the installation string. Though there is no surface movement of the installation string, the axial load displays a similar behavior to the internal pressure. This is because the installation string is stretched causing tension.
- The downhole data does not provide much information that cannot be gained from the surface data, though the additional data gives a much clearer picture of the entire well during the operation. The data do confirm actual downhole loads and provide verification that planned forces has been exerted on the tools. This will be particularly useful to troubleshoot failures.

- During the **circulation of base oil through the lower completion**, the SPP does show a similar development in all relevant wells. The SPP increases when base oil is pumped down the installation string, when it reaches the top of the sand screens it levels out, and when base oil is chased with OBM the SPP decreases.

- When the pump rate was kept constant during the circulation, details regarding the operation were seen by observing slight pressure variations in the SPP. These provide indications on when the base oil enters the open hole. When the flow rate is constant, the downhole data (internal pressure) provides additional information on when the lighter base oil reaches the memory tool and enters the open hole.
- The axial loads measured by i-Con varies during the circulation due to ballooning effect. This effect causes the string to shorten while pumping, which can result in tension at the liner hanger. This can indicate that the liner hanger running tool was lifted from the PBR prematurely.

- There is a very clear fingerprint behavior in the internal pressure and axial load acquired when **setting the liner hanger packer** in each well. There are two evident shears the packer experiences when it is being set. By observing the axial load measured by the tool, the two shears are confirmed to occur when an approximate weight of 9.7 tons and 24.4 tons is set down on the PBR. The internal pressure indicates these shears by pressure peaks at the same times as the axial load.
- A confirmation of the packer shears is not seen in the surface data. Hence, the downhole data is helpful to verify that the packer has been correctly set. This information will be particularly useful to troubleshoot failures.

- When isolating the inside of the lower completion by **closing the FIV**, there is no verification in the measured variables in the wells at the time that the valve is closed. Hence, the downhole data does not provide any immediate evidence of the FIV closing.

- During the **hanger packer pressure test** in the wells, the downhole data display similar behavior for all the wells. There is an apparent and expected external pressure increase which corresponds to the pressure applied from surface.
- The axial load above the liner hanger running tool also displays the same trend in all wells. This is increased compression seen when pressuring up the annulus, which is caused by reverse ballooning effect.
- The downhole data provides additional information when there is a significant pressure leak from the annulus into the installation string as this causes the internal pressure to increase. It also provides additional information on the loads experienced downhole so the initial compression on the string can be adjusted.

- When **pressure testing the well**, the internal and external pressure display fingerprint behavior for all wells. The behavior of the pressure curves corresponds, while the value is slightly different.
- The downhole data provides detailed information on the pressure the lower completion experiences downhole, and the integrity of the isolation is easily confirmed by the constant pressure curves during the high pressure test.

In conclusion, the downhole data acquired by the i-Con Logging Tool is helpful when it comes to analyzing the downhole events that occur during the installation of lower completions as more detailed information is made available. The tool provides a way of confirming installation operations, and an opportunity to adjust and fine tune coming operations. The tool will help in making completion operations more predictable and more robust. Lost time can be expected to be reduced by using the data actively through a campaign, as was done at Ivar Aasen.

The downhole data will also be very useful in a failed operation. It will be valuable to investigate the failure, and help in pinpointing where and when a failure occurred. Mitigations can then be put in place based on the observations. In the failure case, the data from the tool can also aid in making future operations more robust.

In the post-Macondo oil industry of today, requirements for documentation and verification is becoming more and more important. Tools and data, as discussed in this thesis, can provide means to provide the verifications required.

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11 APPENDICES

Appendix Contents

ELECTROCHEM
CREATING TOMORROW

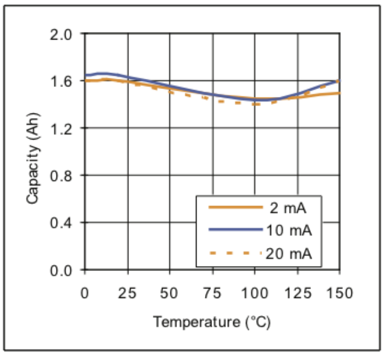
LOW RATE LITHIUM CELL
14-50-150LR SERIES: 4204
SIZE AA

LITHIUM THIONYL CHLORIDE CELL

Technical Overview

Open Circuit Voltage (25°C)	3.67 V
Rated Discharge Current	10 mA
Rated Capacity	1.6 Ah
Maximum Current to Achieve 100% Capacity	20 mA
Cell Diameter (nominal)	13.46 mm (0.52 in.)
Cell Length (nominal)	48.30 mm (1.9 in.)
Cell Weight	19 g
Lithium Weight	0.5 g
Self Discharge	2% per year at 25°C
Operating Temperature	-40°C to +150°C
	-40°F to +302°F

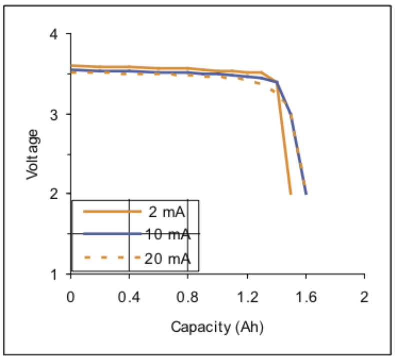
Capacity as a function of current and temperature



Key Features:

- Primary chemistry (non-rechargeable)
- Low rate capability
- Bobbin style construction
- Stainless steel container
- Hermetic glass-to-metal sealing
- Wide operating temperature range as low as -40°C and up to +150°C
- Low self discharge rate (2% per year at 25°C)
- Restricted for transportation (Class 9)
- Custom terminations available

150°C discharge



Main Applications:

- Memory back-up
- Animal telemetry
- Low current downhole oil and gas

NOTE: This list does not include all potential applications, please consult Electrochem for your specific application needs.

NOTICE: The information on this datasheet is for single cells only. Please consult with Electrochem if you are interested in additional information. The information in this document is subject to change without notice and does not constitute a warranty of performance.

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APPENDIX B ACCURACY AND CALIBRATION OF MEASUREMENT SENSORS

The i-Con Logging tool contains several different sensors in order to record all the various measurements. The four sensors which are always in use and require (re)calibration are:

- Sensor 1: Internal pressure sensor [bar]
- Sensor 2: External pressure sensor [bar]
- Sensor 3: Torque sensor [kNm]
- Sensor 4: Strain sensor [tons]

All of these sensors are (re)calibrated when one of the incidents below take place:

- New tool
- I-Con tool is run 10 times
- If tool is subject to conditions that fall outside the given specifications
- The tool experts evaluate that the tool needs to be recalibrated
    - This can be based on experience, measured values or wear

The accuracy of the sensors vary as very different sensors are being used. For the temperature measurement, a PT1000 sensor is used which has been certified according to the IEC 751 Class B criteria. Hence, the uncertainty of the temperature sensors varies from ±0.4°C at 20°C conditions to ±0.95°C at 130°C conditions. The pressure sensors that are implemented in the tool have a maximum pressure rating of 2 100 bar/30 000 psi. These sensors have an uncertainty of ±0.1% Best Fit Straight Line (BFSL) at the maximum pressure. In order to measure the axial loads and torque, sensors with a 0.3% accuracy are implemented.

Each sensor has a separate calibration procedure, where each procedure has different acceptance criteria. The location at which the sensors are calibrated also various. Pressure and temperature is calibrated at the Trican workshop, torque is calibrated at IOT[1] and the axial load sensors at IRIS[2].

The different calibration procedures require various amounts of data points for the calibration, and the acceptance criteria for the sensor accuracy also varies. The required amount of sample points and acceptance criteria are displayed in **Error! Reference source not found.Error! Reference source not found.**. The acceptance criteria represent the difference between the measured sensor value and the calibration unit value. These differences for all the sensors are calculated using i-Con software version 3.15. While the calibration procedures vary, they all require sample points that fall outside the acceptance criteria to be re-sampled should the total amount of sample points require it.

[1]Independent Oil Tools AS

[2]IRIS AS - International Research Institute of Stavanger

Sensor	Sample Points (90°C)	Sample Points (ambient temp)	Acceptance Criteria
Internal Pressure	-	45	±0.3%
External Pressure	-	45	±0.3%
Torque	45	45	±1.5%
Axial Loads	45	45	±1%

Table APX - 1: Required Sample Points and Acceptance Criteria for Sensor (Re)Calibration

When a sensor is calibrated, it is often done using a maximum test, as well as a staircase test which are both performed after the initial testing. The strain curves the i-Con tool experiences during a calibration of the axial load sensors are provided in **Error! Reference source not found.** through Figure APX - 3. A calibration procedure for these sensors include compression, tension and staircase tests performed both in cold and in hot conditions. These are done in order to ensure a correct calibration of the tool at the maximum and minimum values as well as all the points in between. Similar test curves can be found for the other sensors mentioned above.

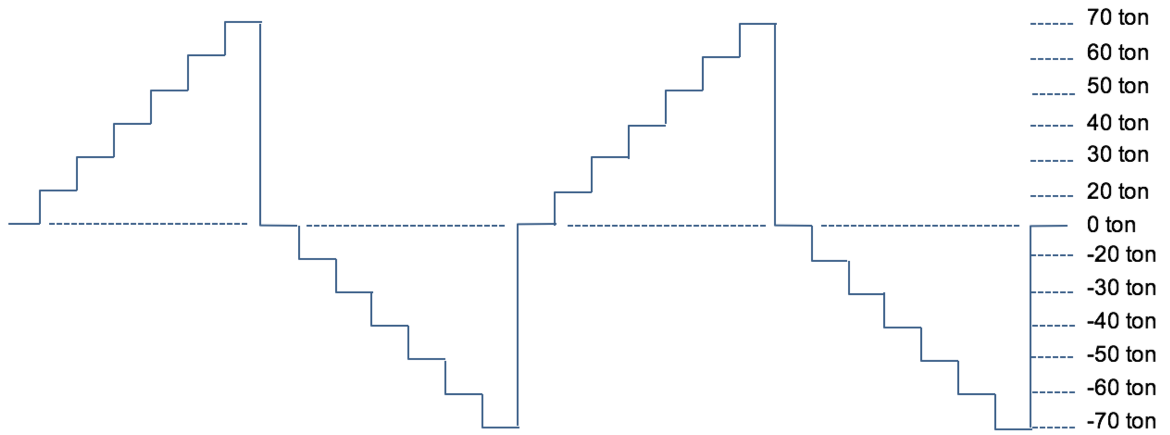

Figure APX - 1: Staircase Test of an Axial Load Sensor

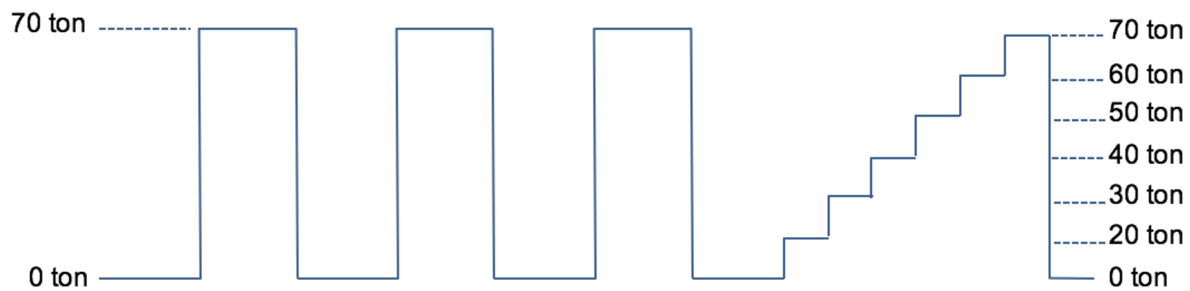

Figure APX - 2: Maximum Tension Test of an Axial Load Sensor

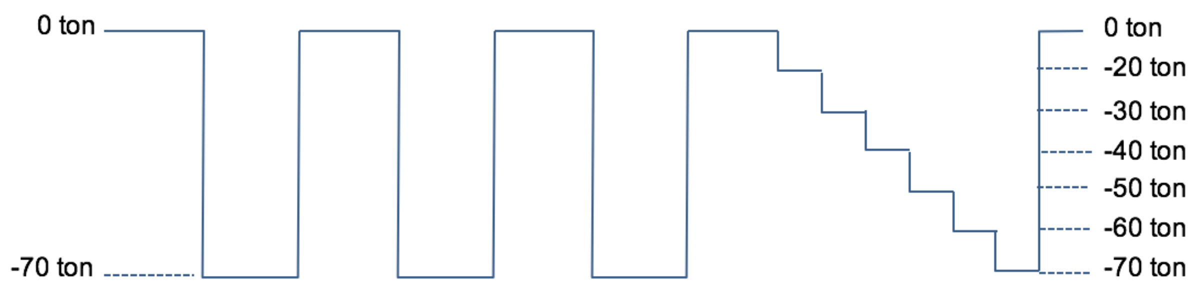

Figure APX - 3: Maximum Compression Test of an Axial Load Sensor

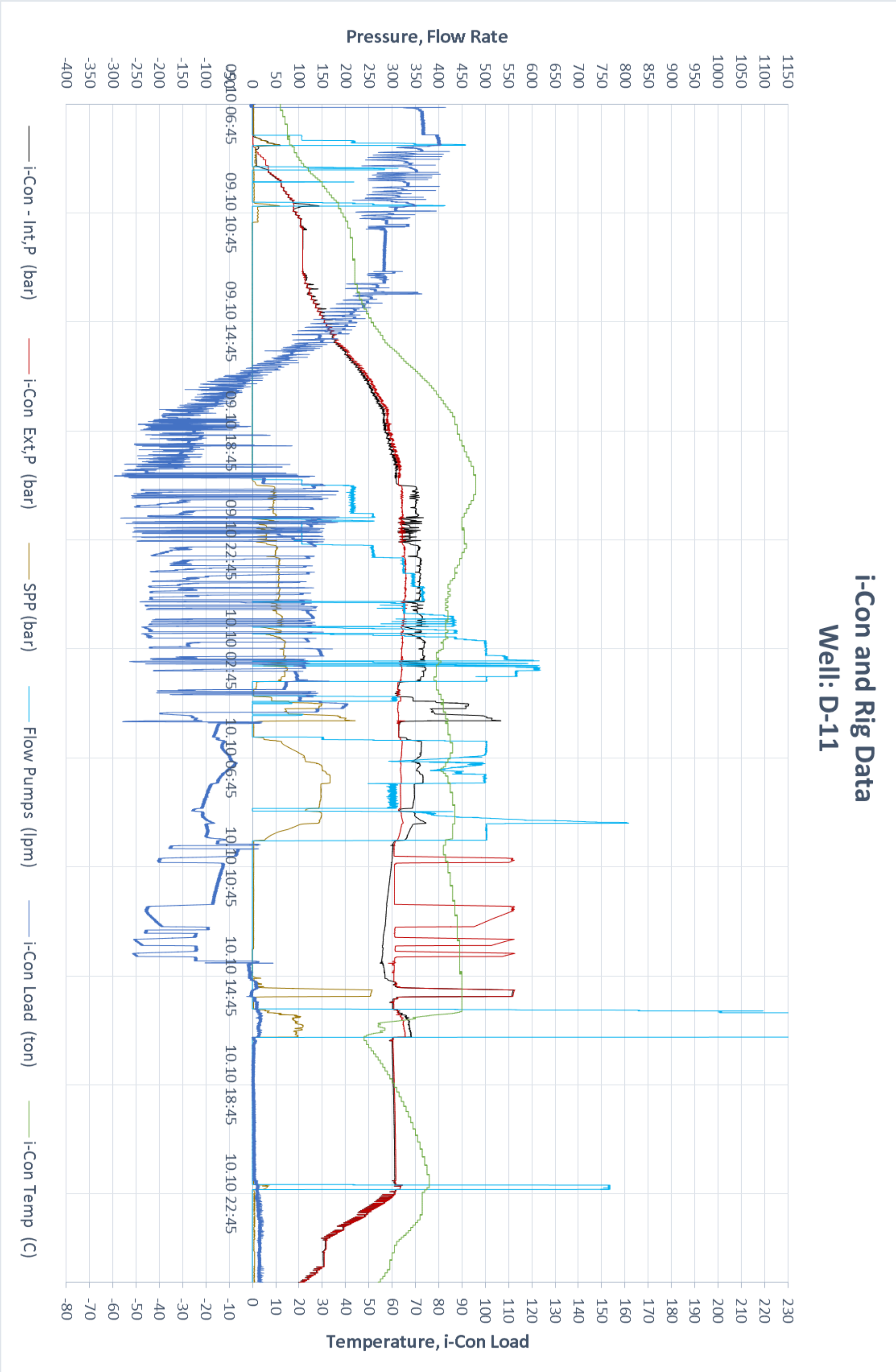

Figure APX - 4: Overview of Lower Completion Installation at Well D-11

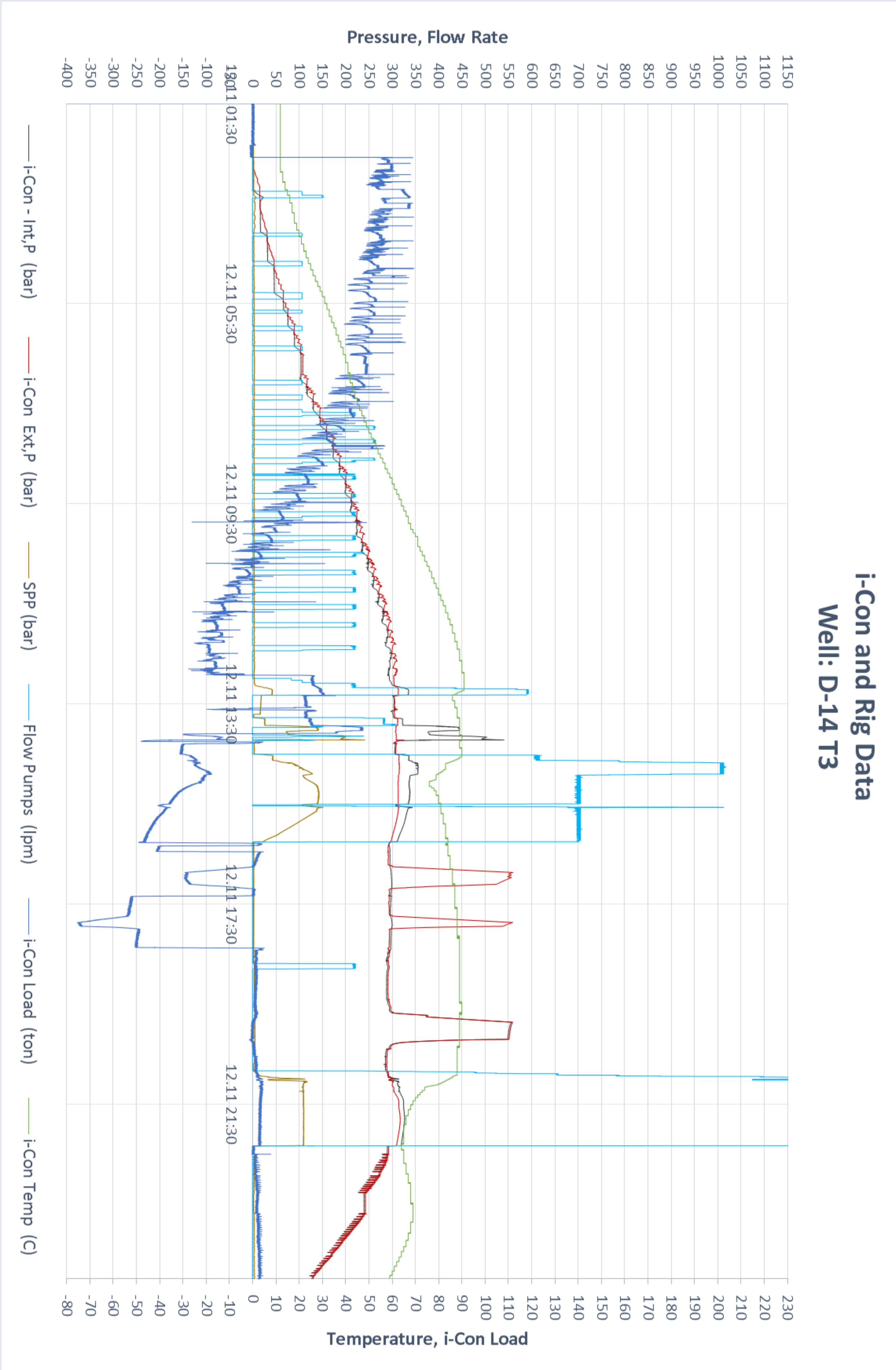

Figure APX - 5: Overview of Lower Completion Installation at Well D-14 T3

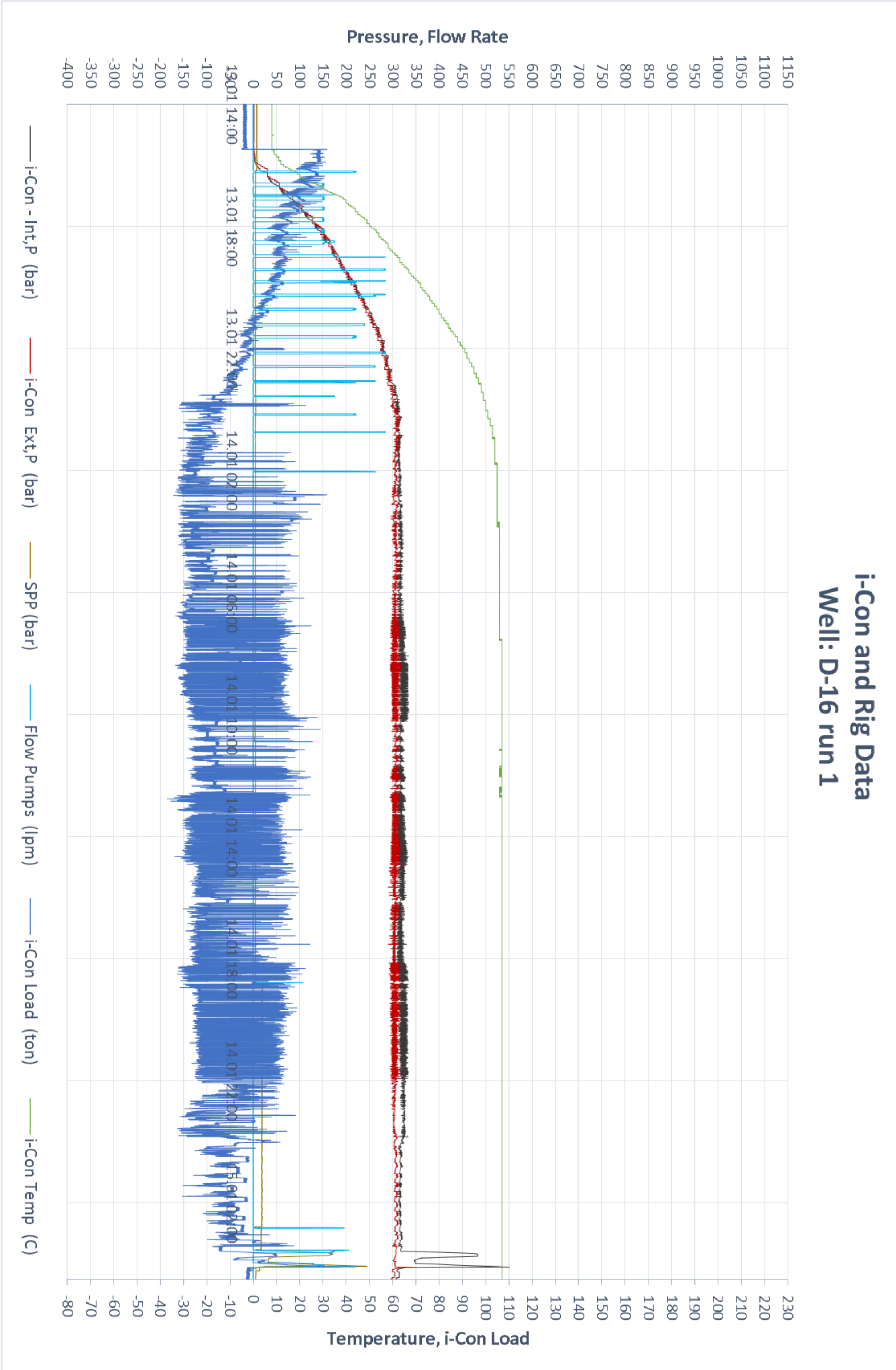

Figure APX - 6: Overview of Run 1 of Lower Completion Installation at Well D-16

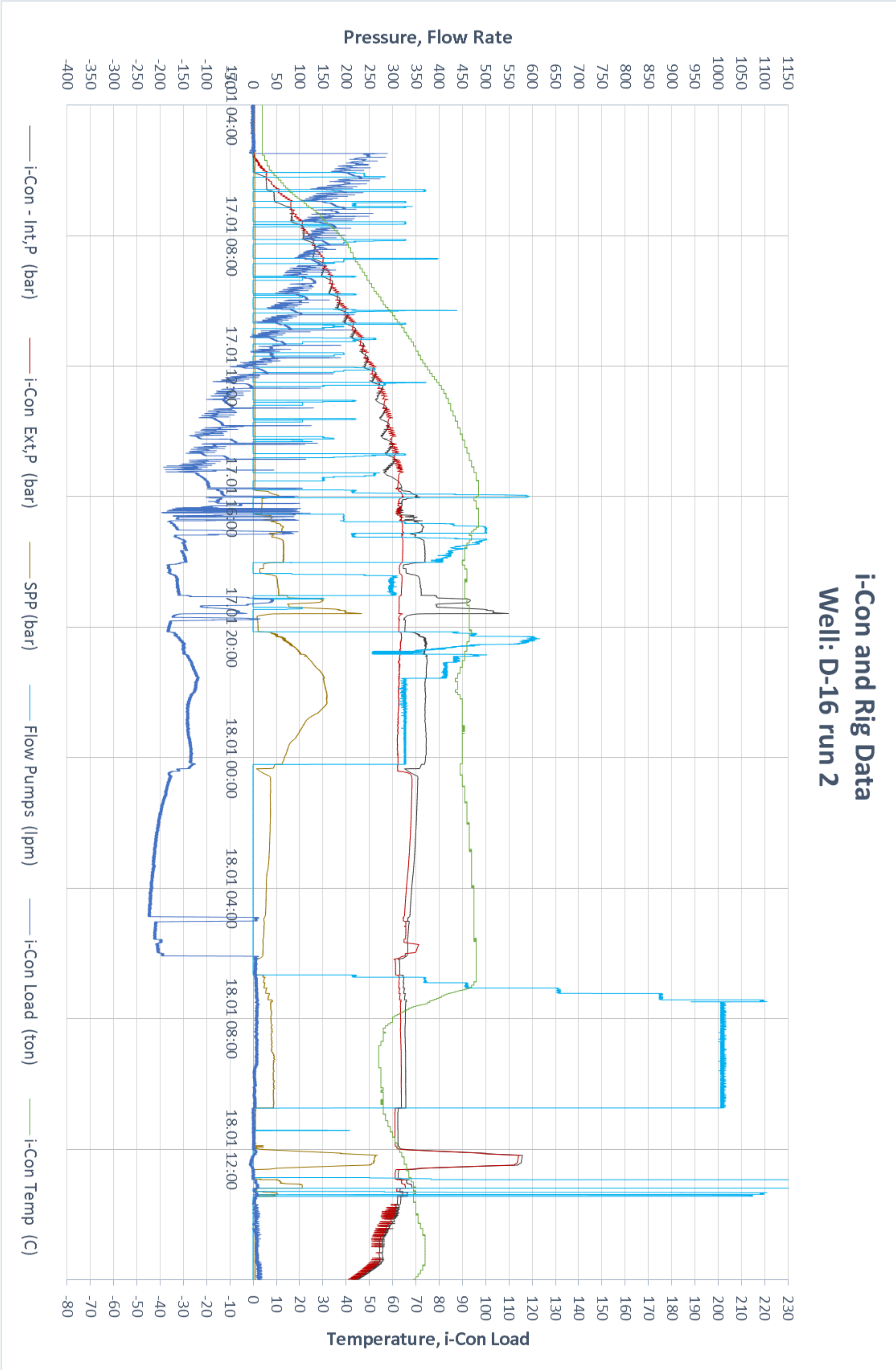

Figure APX - 7: Overview of Run 2 of Lower Completion Installation at Well D-16

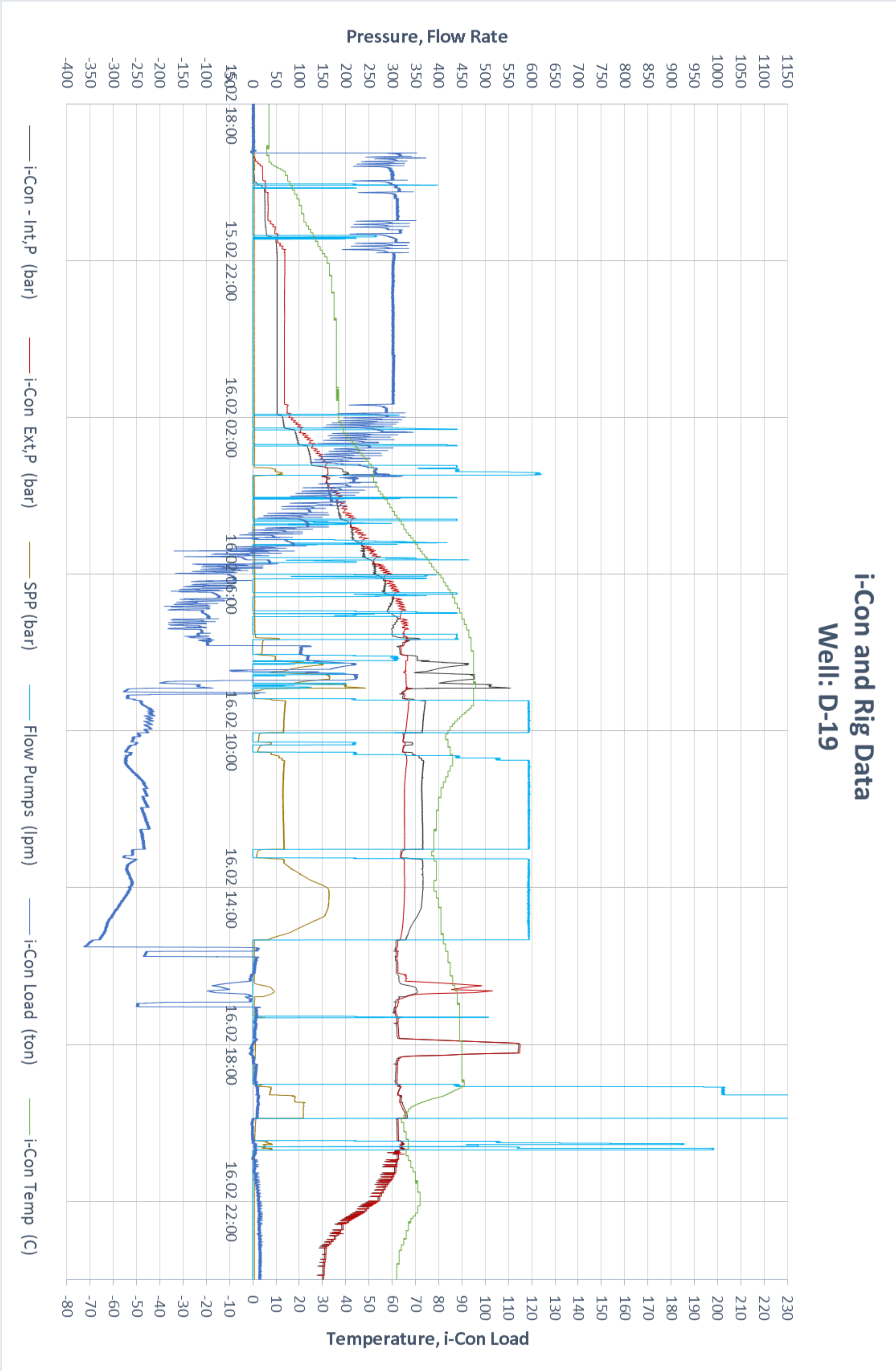

Figure APX - 8: Overview of Lower Completion Installation at Well D-19

APPENDIX D CIRCULATION THROUGH THE LOWER COMPLETION

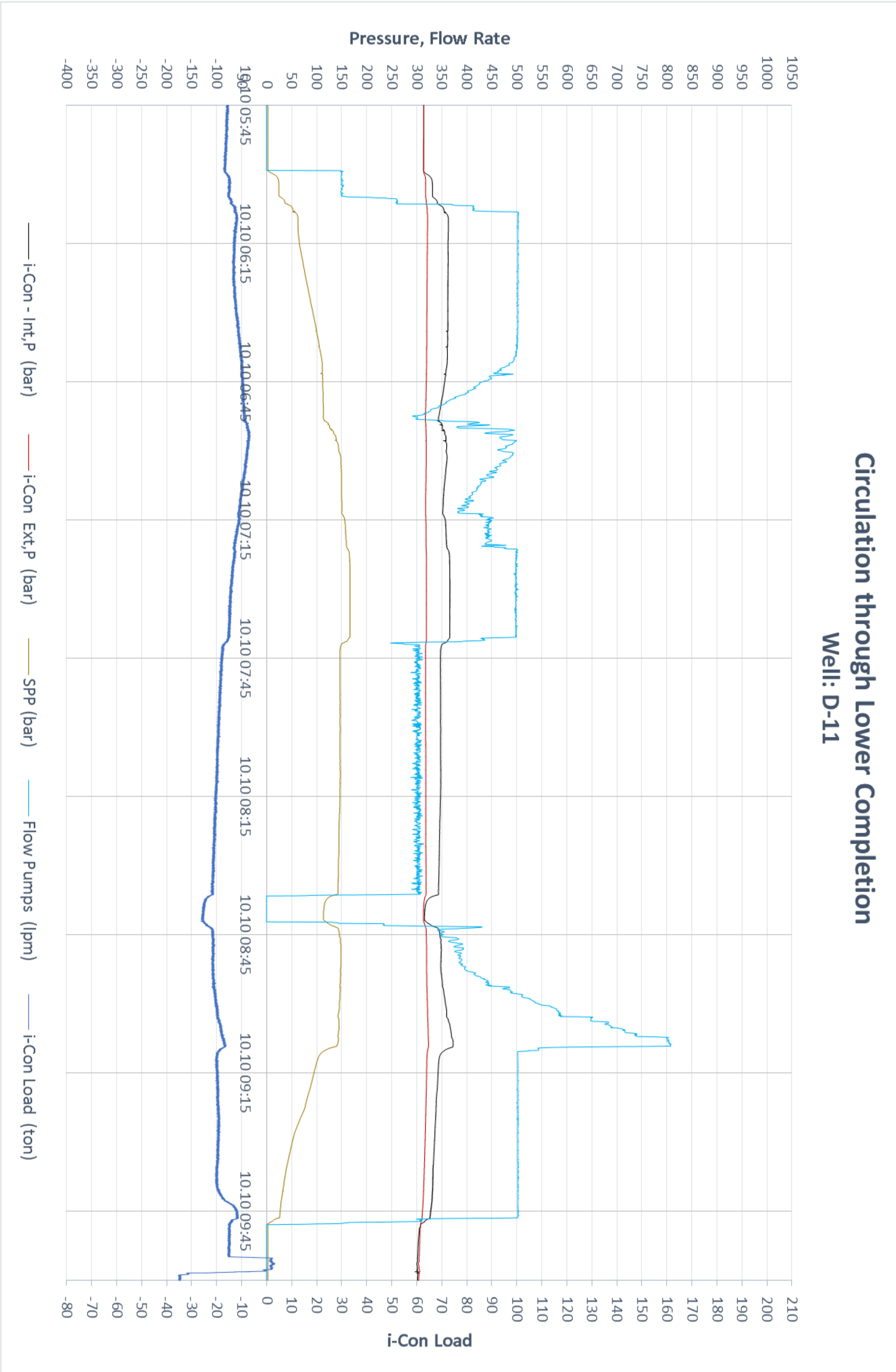

Figure APX - 9: Circulation through Lower Completion in Well D-11

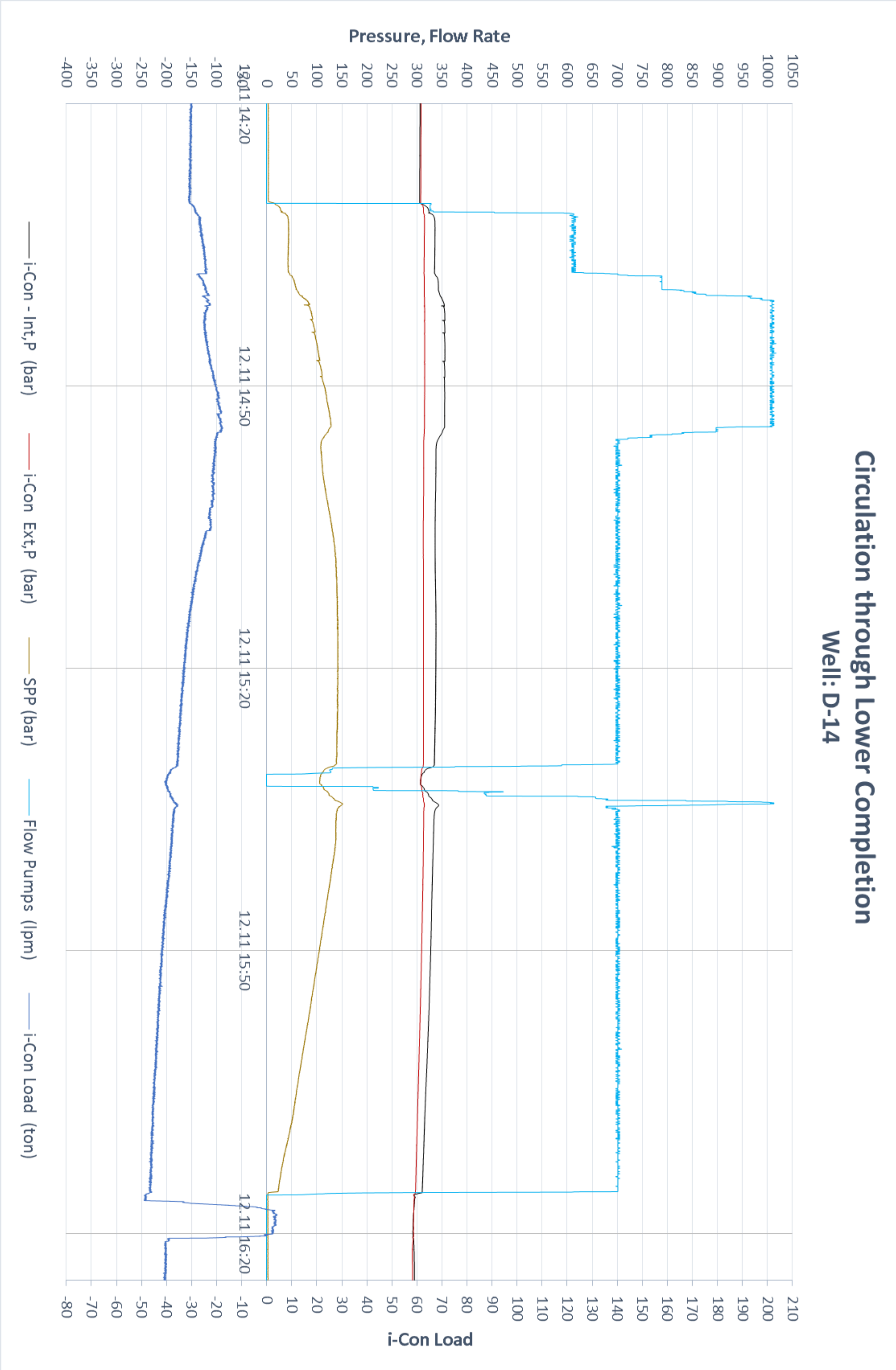

Figure APX - 10: Circulation through Lower Completion in Well D-14 T3

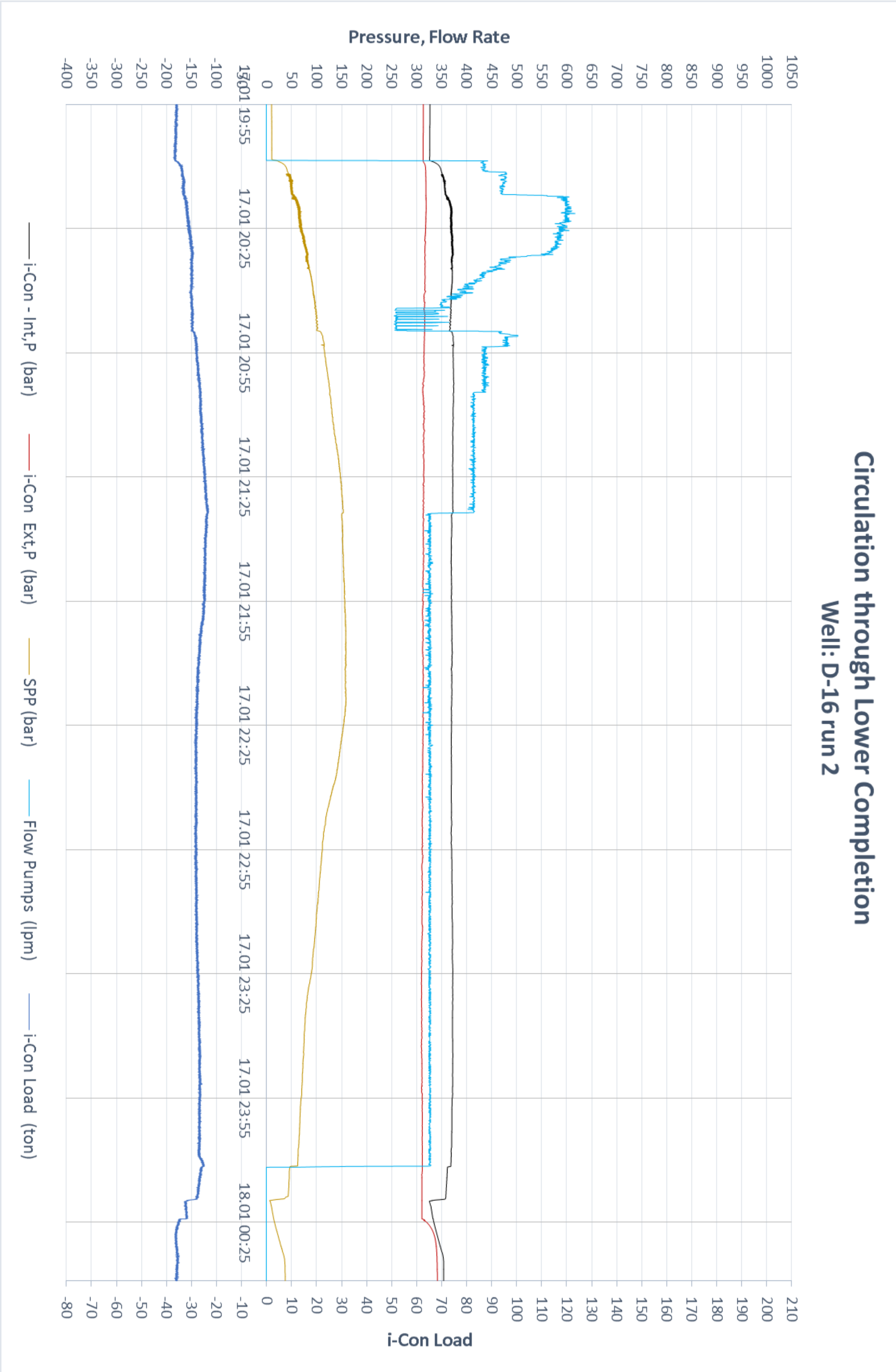

Figure APX - 11: Circulation through Lower Completion in Well D-16

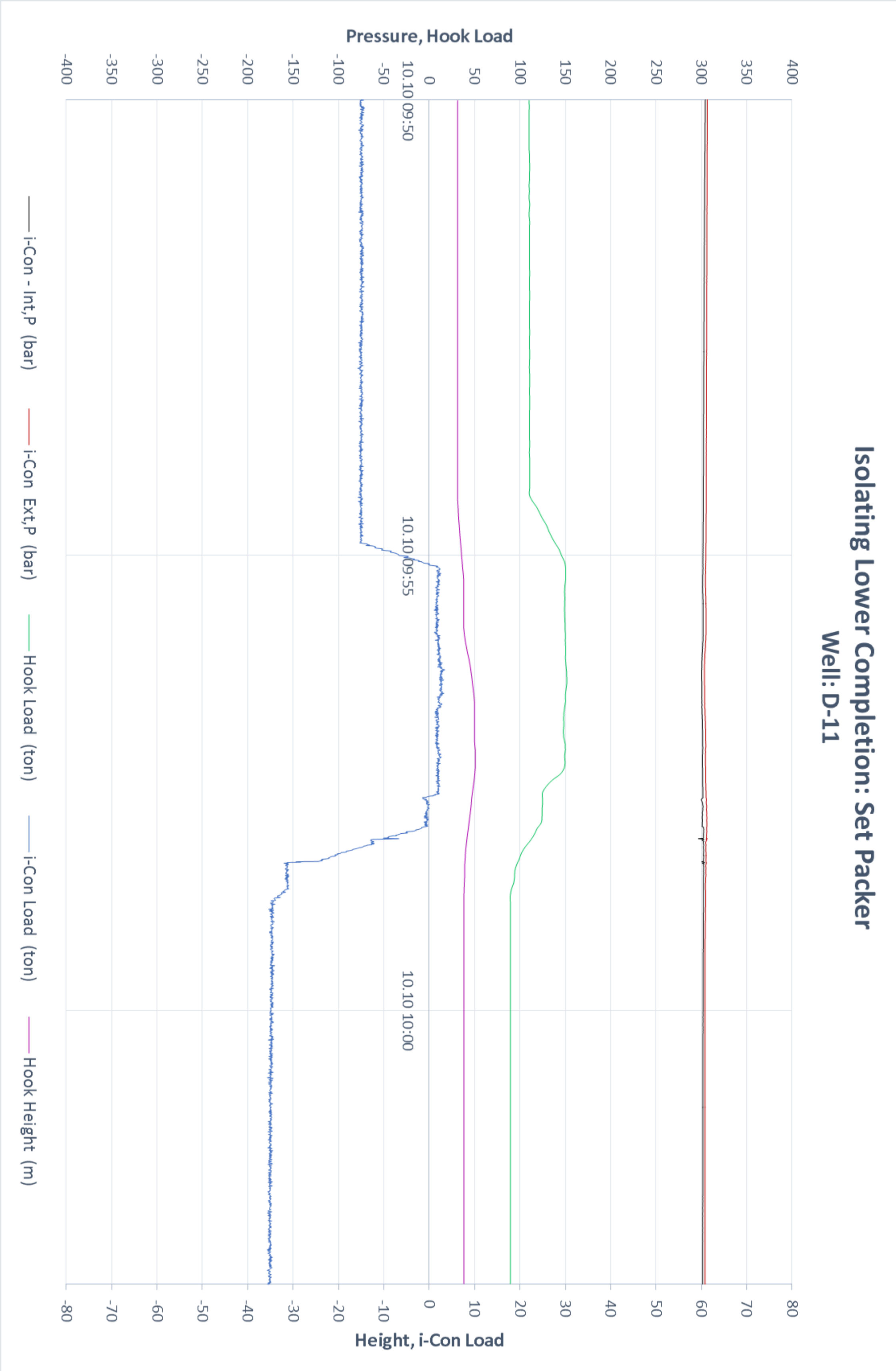

Figure APX - 12: The Setting of the Liner Hanger Packer in Well D-11

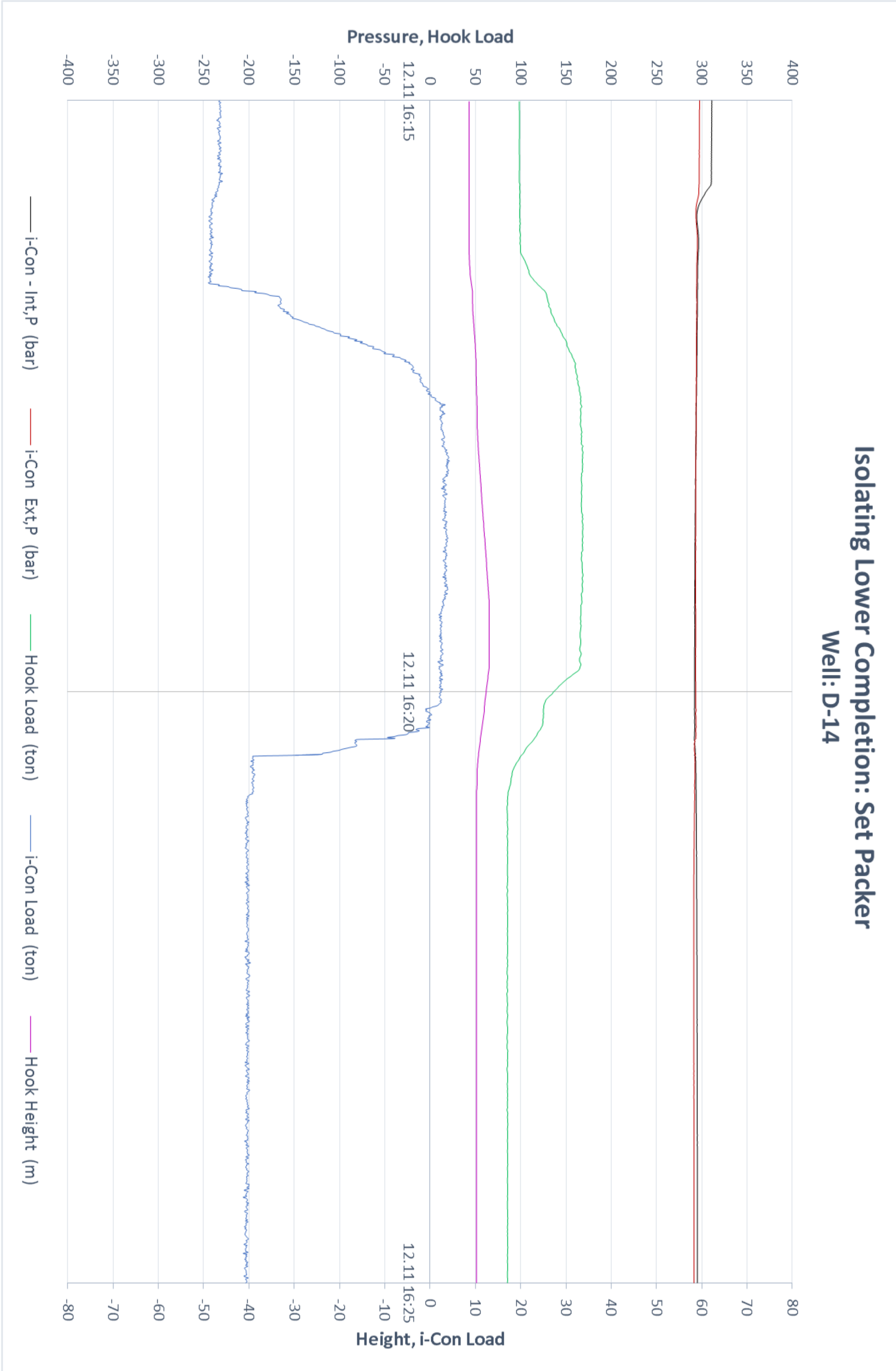

Figure APX - 13: The Setting of the Liner Hanger Packer in Well D-14 T3

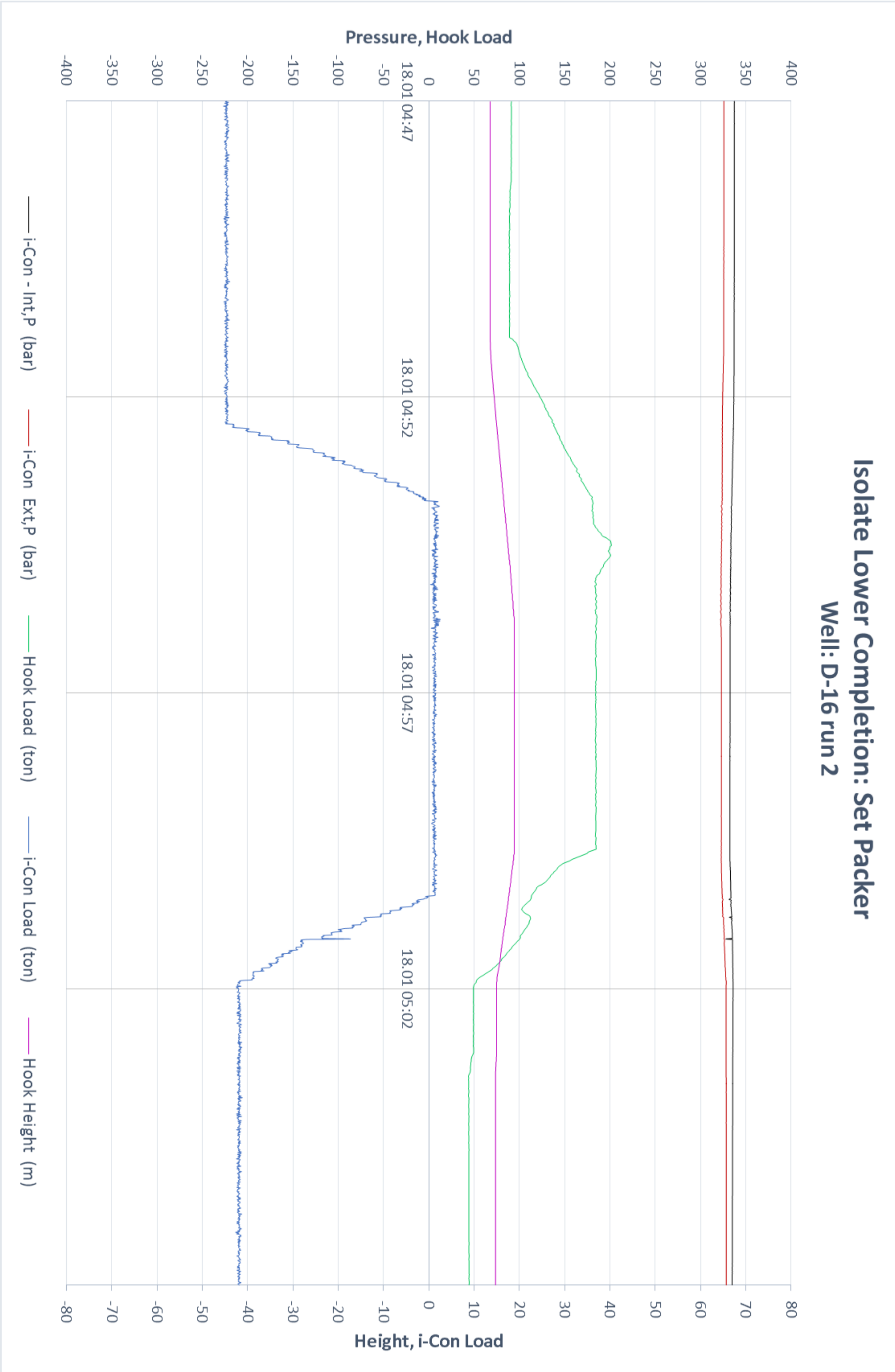

Figure APX - 14: The Setting of the Liner Hanger Packer in Well D-16

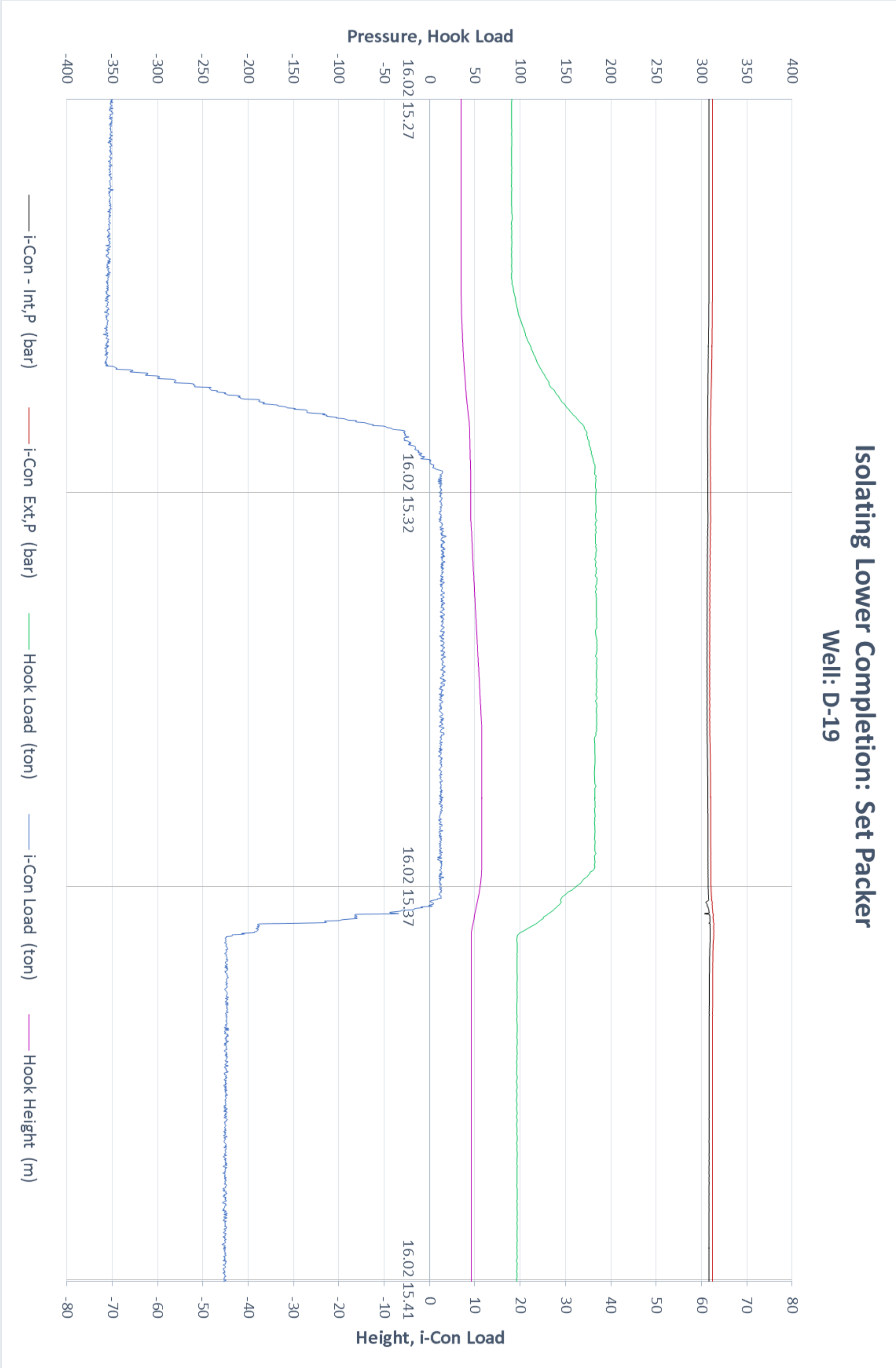

Figure APX - 15: The Setting of the Liner Hanger Packer in Well D-19

APPENDIX F PRESSURE TEST LOWER COMPLETION – TEST PACKER

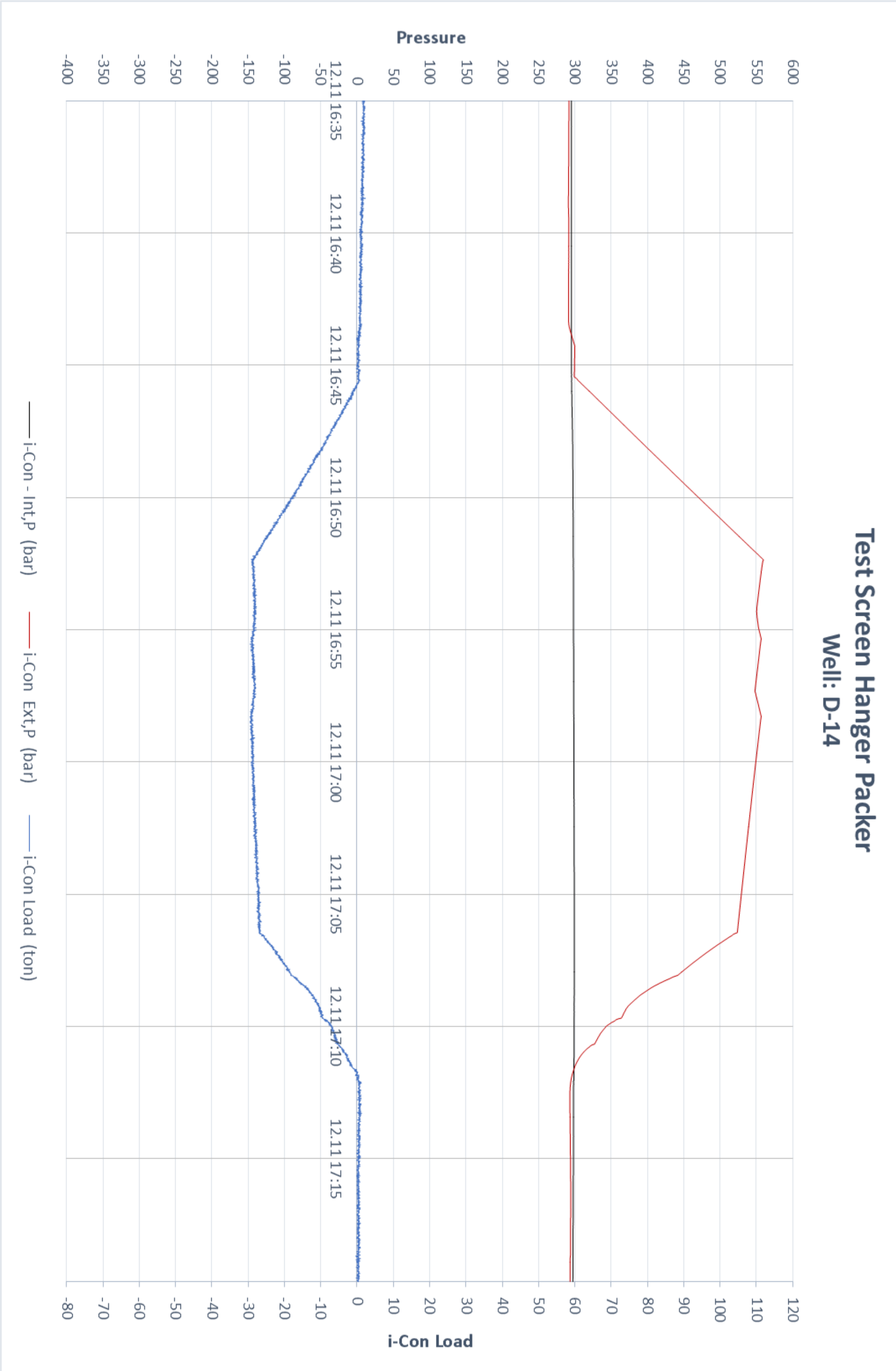

Figure APX - 16: Pressure Test of Screen Hanger Packer in Well D-14

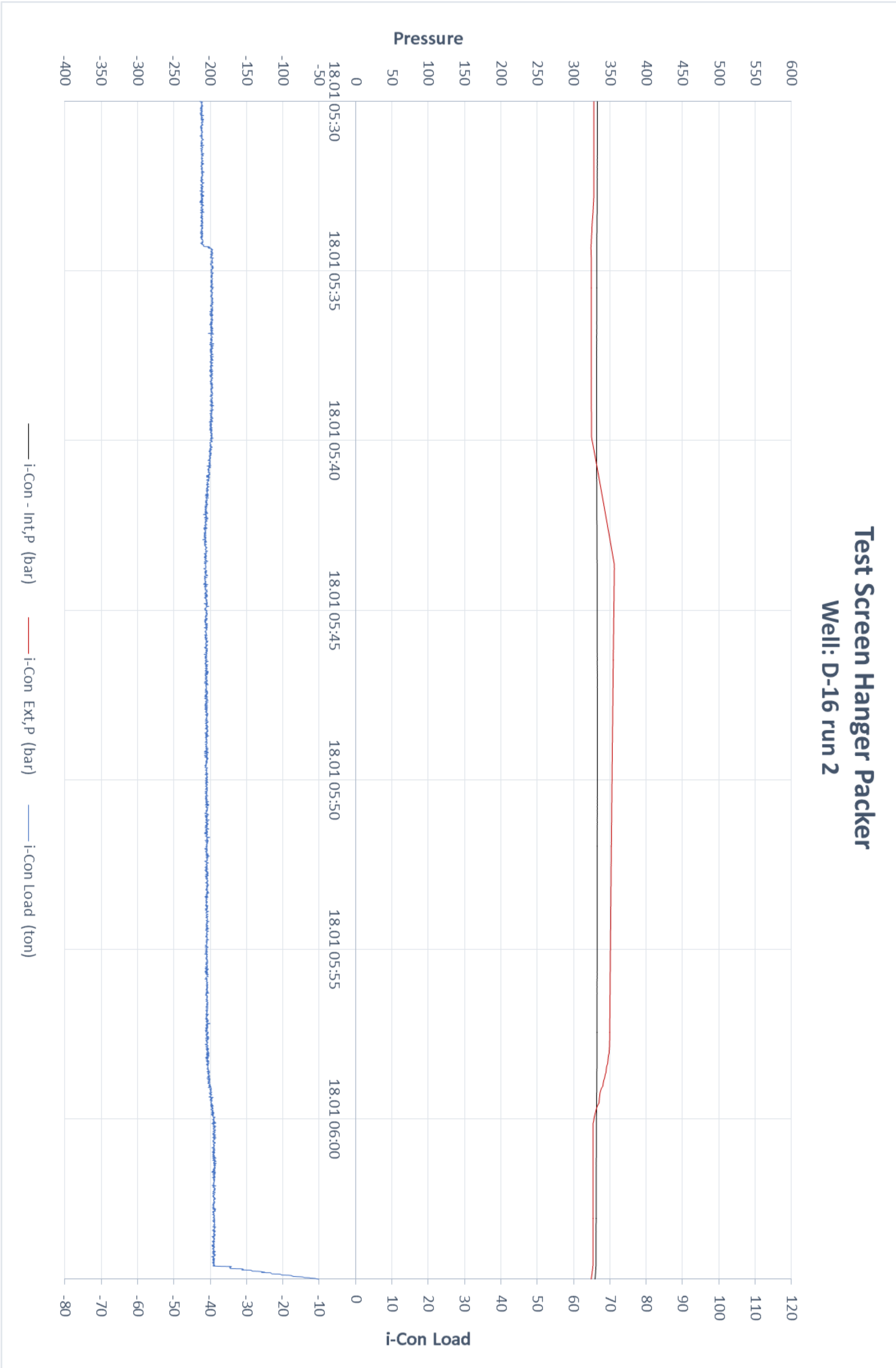

Figure APX - 17: Pressure Test of Screen Hanger Packer in Well D-16

APPENDIX G PRESSURE TEST LOWER COMPLETION – TEST WELL

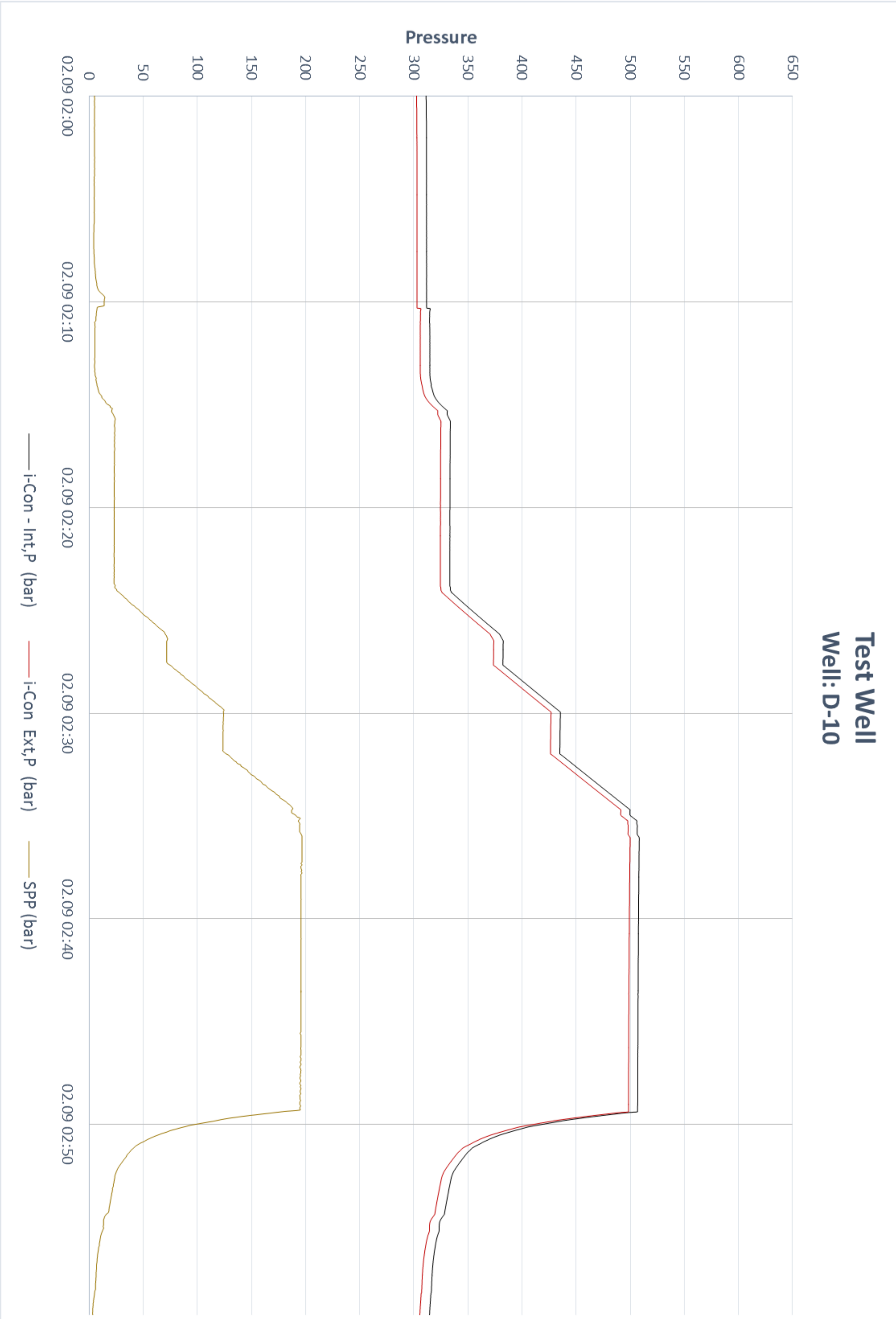

Figure APX - 18: Pressure Test of FIV and Hanger Packer in Well D-10

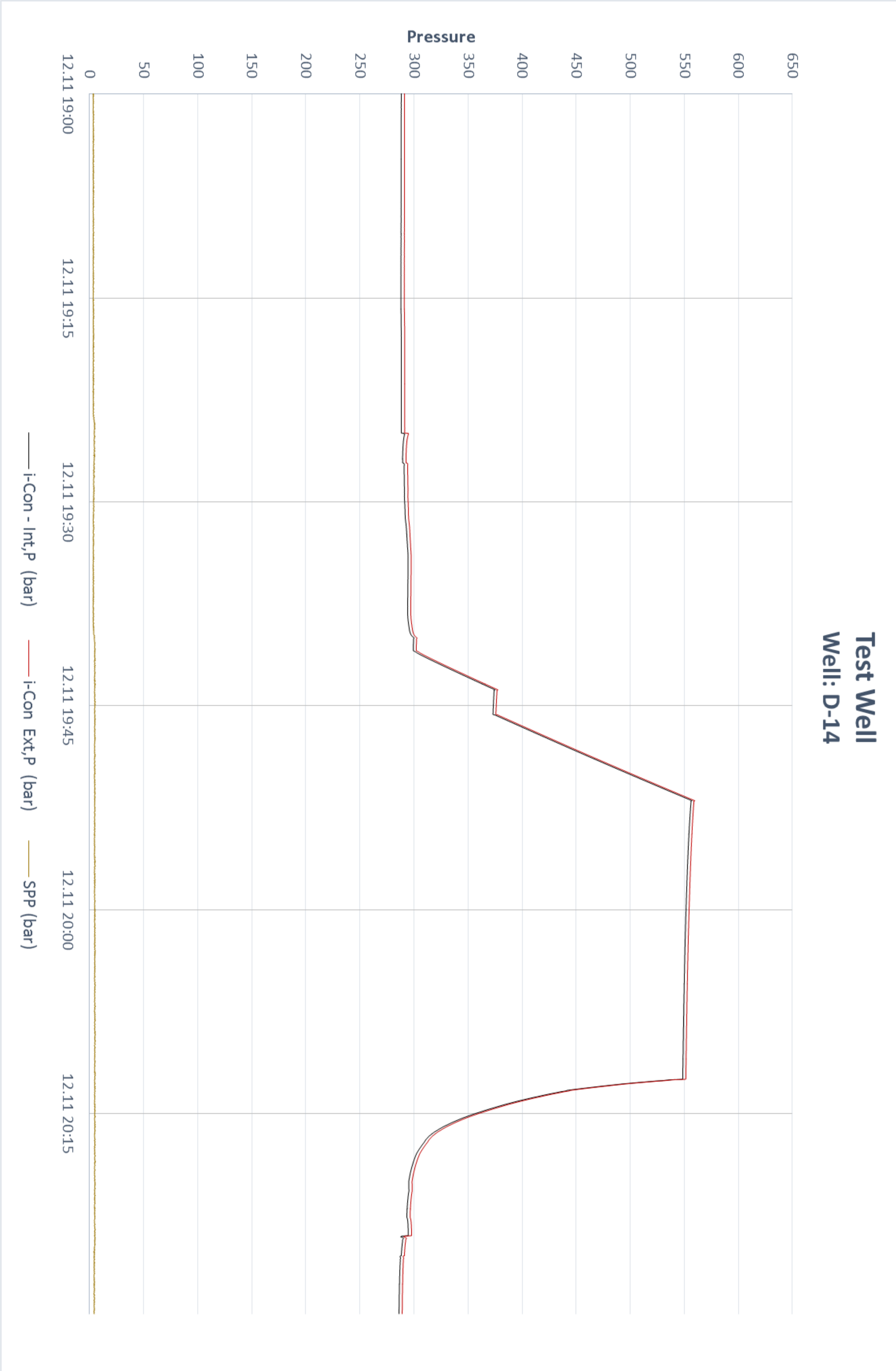

Figure APX - 19: Pressure Test of FIV and Hanger Packer in Well D-14 T3

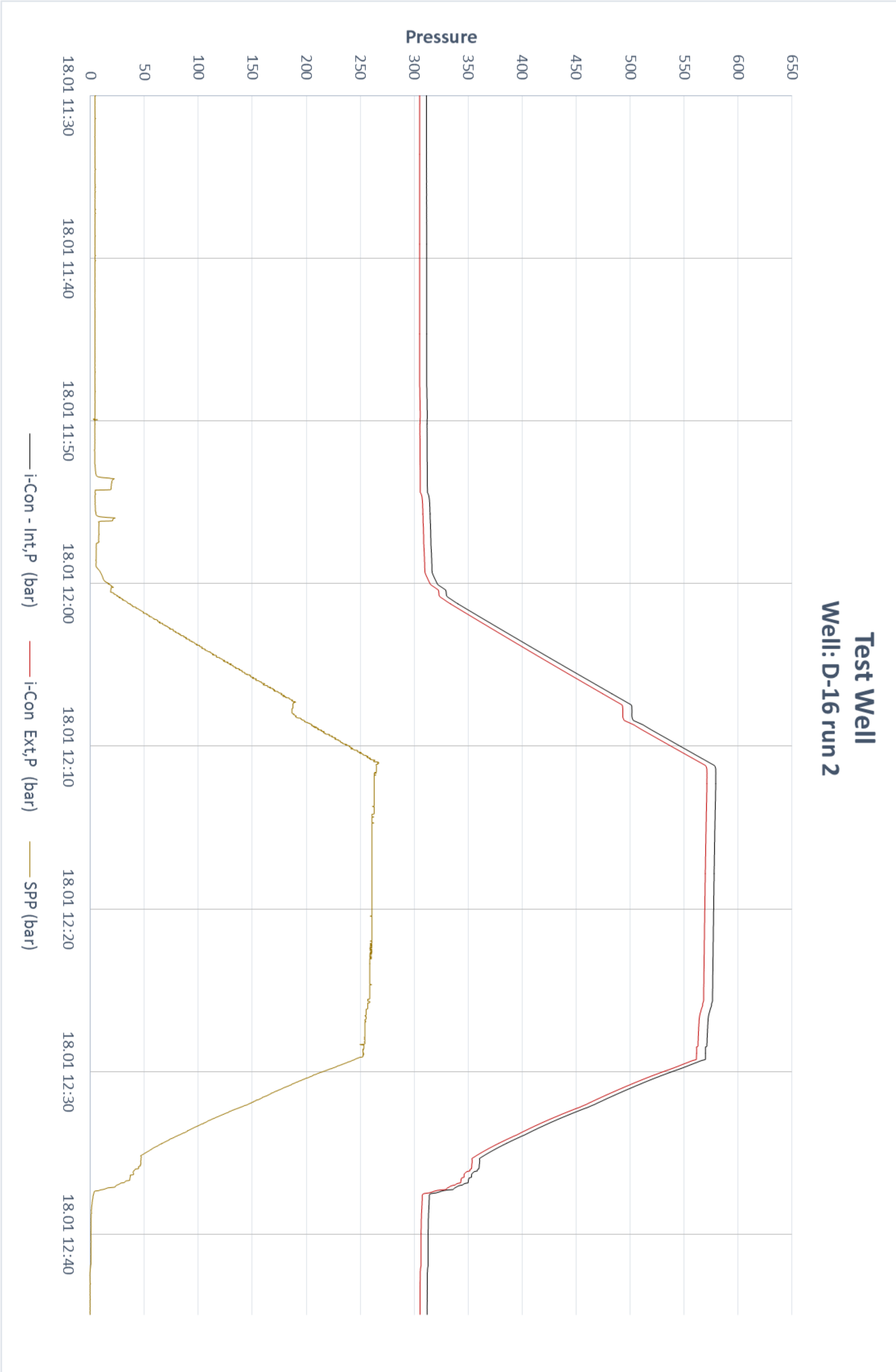

Figure APX - 20: Pressure Test of FIV and Hanger Packer in Well D-16