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# Production Surveillance and Optimisation for Multizone Smart Wells With Data Driven Models

K.C. Goh, Shell Global Solutions International B.V.; B. Dale-Pine and I. Yong, Brunei Shell Petroleum Company Sdn. Bhd.; and P. Van Overschee and C. Lauwerys, IPCOS N.V.



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## Abstract

The Champion West field was discovered in 1975 offshore Brunei, but its oil reserves in a complex web of thin reservoirs were initially deemed too expensive to develop. Field development was slow due to reservoir complexity and technology limitations. The current phase of development of the Champion West reservoirs uses long horizontal snake wells, which create multiple drainage points in sands, effectively achieving a similar drainage pattern of several conventional wells. The snake wells intersect up to 4 kilometers of reservoir intervals with total depth of up to 8 kilometers, and are divided into several zones with external casing packers or swellable packers. Each zone is then equipped with an inflow control valve and pressure and temperature sensors to allow monitoring and optimization of the recovery process from that zone. Historically, for long horizontal wells, the effective control of production profile and effective tracking of production from individual zones have been problematic. Poor tracking of production will adversely impact overall management and ultimate recovery from a reservoir. One solution is to fully utilize surface and downhole pressure data and multirate well tests to generate data driven models to determine zonal inflow, zonal interactions, and flow across inflow control valves, and to compute ICV settings for optimum reservoir management.

FieldWare Production Universe (FW PU) is a software application developed by Shell International Exploration & Production and Shell Global Solutions International, with significant involvement and support from Brunei Shell Petroleum Company Sendirian Berhad (BSP) for robust data driven modelling in an production operations setting that provides continuous real time estimates of well-by-well production. Applied to the Champion West multizonal wells, the FieldWare PU models, built using surface and downhole test data and an understanding of well performance provides regularly validated estimates of zonal production rates using real time surface and downhole data. Using this tool, inflow control valve settings are suggested to the user in order to optimize production on a daily basis through the use of mathematical optimization routines taking into account all available data. The system also provides early warning to the field management team of any wells deviating from well reservoir management guidelines. The intent of this technology is to enable more transparent, sustainable and systematic management of smart well production systems through the use of real time data to improve the understanding of reservoir behaviour and to allow early intervention to optimize production and ultimate recovery.

## Introduction

Up to a few years ago, the Champion West field was the largest undeveloped oil and gas resource in Brunei. In December 2005, the first well of the Phase 3 development came on stream. Since then, a further 8 wells have been drilled from a newly installed CWDP01 offshore platform. The field has significant interest as the first project to be designed from the initial stage as a fully integrated Smart Field project. Champion West is a forerunner of a number of Shell Smart Field projects coming online in the near future. Champion West Phase 3 features the use of innovative long horizontal Smart "Snake" Wells. This paper will report on one particular aspect of the Smart Well technology applied for the Champion West development: how the hardware and measurements of the intelligent Smart Well completions are used in combination with the Shell FieldWare Production Universe (FW PU) data driven modelling technology to allow improved surveillance and management of the Champion West reservoirs. In particular, this paper reports on the use of FW PU application to systematically use the data from the Champion West Smart Wells to:

- allocate production from each zone of the Smart Well.
- provide recommendations for the adjustment of the Smart Well Zonal Inflow Control Valves.

## The Champion West Development

The Champion West field was discovered in 1975, but its significant oil reserves lay dormant for 30 years, locked 2,000-4,000m beneath the seabed in a complex web of thin reservoirs deemed initially too expensive to develop. Hydrocarbons were found offshore in up to 1000 shallow marine reservoirs distributed over an area of approximately 7.5 miles by 3 miles (12 km by 3 km). These vertically stacked, structurally dipping reservoirs are complex and contain various fluid fills ranging from gas only to gas with oil rims to oil. Field development has been slow due to reservoir complexity and the need for a step change in development concepts to meet investment hurdles. The development challenges are outlined in detail in references [1] and [2] which discuss the geology and the phasing of the overall development.

The current Phase 3 development of the Champion West reservoirs uses long horizontal snake wells, which create multiple drainage points in each sand layer, effectively achieving a similar drainage pattern of several conventional wells at a fraction of the cost. References [2], [3] discuss adoption of the snake well concept. The snake wells intersect up to 4 kilometers of reservoir intervals with total depth of up to 8 kilometers, and are divided into several zones with external casing packers or swellable packers.

Figure 1: BSP CWDP01 platform in the South China Sea, with Seadrill West Pelaut rig alongside.

**Production Surveillance in Long Horizontal Wells**

Historically, for long horizontal wells, the effective control of production profile and effective tracking of production from individual zones have been problematic and have become obstructions to realizing the full value of the wells and their wider deployment. Poor tracking of production along a long horizontal well can very adversely impact overall management and ultimate recovery from an asset. In addition, non-uniform drawdown along the horizontal section of the wells can lead to sub-optimal recovery.

To partly address this problem, the Champion West wells are completed as multi zone "Smart Wells". The term "Smart Well" will be used in this paper to refer to wells that incorporate technology that enables downhole monitoring and control from the surface. Each zone of a Smart Well is isolated with external casing packers or swellable packers and equipped with an inflow control valve (ICV) and tubing and annulus permanent downhole pressure and temperature sensors to allow monitoring and optimization of the recovery process from that zone. References [2], [3] and [4] discuss the need for smart well completions in the Champion West development, and the early operating experience in this field. A typical Smart Well completion is shown in Figure 2.

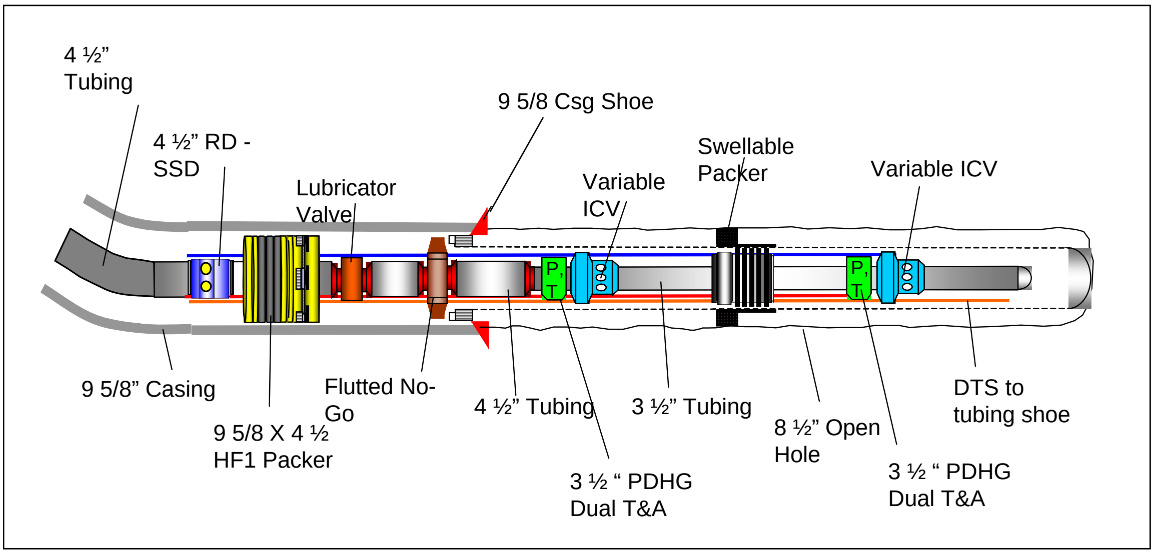



Figure 2: A typical smart well completion with two zones.

Reference [5] provides a wide survey of the benefits of smart well completions in general. Reference [6] discusses earlier BSP experience with smart wells. References [7] and [8] discuss the possibilities for optimizing ultimate recovery via the optimization of ICV settings. However, while the techniques discussed for the optimization of ultimate recovery are clear of great value in the initial planning for a development project, there are few if any reports of the sustained operational applications of the concepts of [7] and [8] in actual production environments. This is partly due to the initial problems that were experienced with the reliability of downhole gauges, let alone the vastly more complex downhole inflow control valves.

Equally as important, the advent of smart multi-zonal wells also raises basic questions regarding the operational management of the wells. For example, the fundamental problem of allocation and surveillance of production from each zone of the well is discussed in [9]. The allocation and tracking of oil, water and gas production to individual zones based on conventional single rate well production testing, even on a zone by zone basis, with all the other zones shut in, is problematic for multizonal wells. In addition, there is significant interaction between zones during normal production when all zones are producing that needs to be incorporated into the understanding of flow performance.

Recent work addressing the issue of zonal allocation from a rigorous modelling point of view includes that of [10], [11]. However, it is well known that the sustained use of physical models (even for surface flow estimates) is challenging in practice in an operational environment. This is partly because rigorous models are derived based on assumptions such as phase changes as flow goes through ICVs, and assumed quantities such as ratios of specific heats, oil API, valve discharge coefficients, downhole fluid densities, etc. which are difficult in practice to determine or to verify and are subject to variation. Conventional solutions are to install permanent downhole flow meters (currently unproven), or periodically deploy downhole production logging tools, exposing the well to the risks associated with intrusive downhole interventions. In this paper, expanding on [16], an alternative approach is discussed, which is to work mainly from production well testing data and real time data, and to construct zonal production allocation and real surveillance models based on these data. A similar approach has been reported in [22] where the pressure and temperature differences across the ICVs are used to estimate production from individual zones by relating the differences to surface measurements.

## Data Driven Modelling and FieldWare Production Universe

FieldWare Production Universe (FW PU) is a software application developed by Shell International Exploration & Production and Shell Global Solutions International that provides continuous real time estimates of well-by-well oil, water and gas production based on data driven models constructed from well production testing data. The software is introduced in [12] and [13], and is intended to fully leverage on increasingly abundant real time data to address fundamental gaps in the management and surveillance of oil and gas production operations.

### The Production Well Testing Process and FW PU Real Time Well Production Estimates

In conventional oil and gas operations, three phase oil, water and gas production from each individual well is usually measured via the periodic routing of each of the wells to a shared test separator or a multiphase meter, the "production well testing" process. The duration of the test is normally 6 - 24 hours or longer with the test frequency varying from weeks to months. The usual reported result of a well test is a set of spot readings and totalized or averaged numbers such as oil production rate, watercut, gas-oil-ratio and tubing head pressure. The production of a well is then assumed to be constant at the tested production rates between well tests, other than at various intervals when the well is designated to be "closed-in". Sub-normal production rates, unstable production or increases in gas or water production are typically not detected until the next well test. Validation of well tests and detection of erroneous well tests are also often problematic in large operations where there can be hundreds of wells. Historically, there have been a number of approaches using well physical (or first principles) models combined with real time wellhead pressures and temperatures to predict 3-phase flow in real time or near real time. In practice, well physical models were found to be difficult to set-up, calibrate and maintain in an operating environment.

The data driven approach of FW PU was designed to take full advantage of the well test and production metering available in conventional production operations, and also to be operationally sustainable in the face of changing well conditions and operational constraints (such as loss of some instrumentation). Whilst conventional single rate well testing can be used to input to FW PU models, it is required that at least one "Deliberately Disturbed Well Test" (DDWT), an abbreviated multirate well test, is conducted. The DDWT and conventional well test trends from the well and test facility are recorded in a Process Data Historian, and are then input to FW PU for the modelling process to generate the FW PU "data driven" well models. These models relate the production from the well on test with signals from the wellhead instrumentation such as tubing head pressures and temperatures, lift gas injection rates and production choke openings.

Given FW PU data driven models of the wells derived from the well tests, real time data from the wellheads is then used to estimate the flow of individual wells, even when the wells are not on test. FW PU is therefore used here as a "virtual meter", as noted in [12] and [13]. FW PU also generates individual well daily production volumes, computed from its real time estimates over the course of a day. To provide immediate and regular partial validation of the accuracy of the individual well production estimates, the FW PU well by well estimates are summed and compared against metered single-phase flows from the production separator or the export meters. To further increase the fidelity of the estimates, daily dynamic reconciliation can also be performed between FW PU estimates and the metered single-phase flows from the production separator or the export meters.

### Simplicity and Robustness of Data Driven Models

The practical algorithmic and numerical implementation in software of the FW PU requires systematic and expert application of real time signal processing, process controls and matrix computation capability. Once installed, the FW PU application has easy to use graphical user interfaces allowing the overall systems to be setup, well test data to be loaded and displayed, and well models configured, created, validated and brought online by suitably trained operational staff. Well tests can be automatically uploaded into FW PU as they are conducted, ready for model validation or updating. Algorithms within FW PU also indicate when a model requires updating.

The use of data driven models for well production surveillance provides a number of advantages, one of which is the simplicity of the approach and its intuitive extension of the conventional well testing process. No numerical assumptions need to be made about the underlying physics of the well. For example, there is no requirement for calibrated well inflow or vertical lift performance models and no assumptions on GOR or downhole liftgas injection depths, etc.. FW PU requires only repeatable well measurements; within limits, absolute measurement accuracy at the wellhead is not critical.

To date, FW PU has been installed for the surveillance of well by well production in a significant number of production facilities onshore and offshore worldwide, including the Americas, Europe, Africa, the Middle East and the Far East. FW PU surveillance covers a whole range of wells, including free flow wells, gaslifted wells, jet pumped wells, ESP lifted wells, subsea wells, lean and rich gas wells. While in some sites it can remain a challenge to put workflows in place to sustainably maintain FW PU models and to use FW PU data, FW PU has proven to be a clear success in many other sites, becoming very much part of the way of working, see for example [14], [15].

**Extensions to Optimization and Testing by Difference**

The basic data driven modelling capability has been extended to allow FW PU to be used also for real time optimization and also for real time well production estimates of well clusters with no dedicated well test facilities, see for example [16], [17] and [18]. The FW PU data driven models used to estimate well flow in real time can also be used to generate predictions of well production for given values of commonly manipulated well production variables, such as production choke position, lift gas injection rates; in combination with the well tubing head or flowline pressures. The FW PU Optimizer can thus use its data driven well models to optimize total oil production from a cluster of wells (or a single well) by computing the choke or lift gas "set points" for maximum oil or gas production, subject to various constraints, for example, to keep the gas/oil ratio below a value required for good reservoir management and to prevent coning, or to keep total liftgas injection rate within pre-specified limits. FW PU has also been used for the testing of wells by difference and for constructing well models from the dynamics from long periods of production data. This allows the real time surveillance of well by well production even in the absence of conventional well test facilities. The foregoing discussion has described the use of FW PU as an application for setting up data driven models for surface well production surveillance and optimization. The rest of this paper will discuss extensions to the FW PU capability and scope of coverage to multizonal smart wells, building on the previous work. This work has been briefly noted in [15] and [16].

## Zone by Zone Production Testing in Multizonal Wells

While multizone smart wells will have surface production well testing facilities, the challenge remains as to how to efficiently test and characterize the individual zones, and to track their production during normal commingled production. As noted above, the accurate and verifiable real time and daily tracking of production flowrates and volumes from even simple wells (single zone wells with only surface instrumentation) is often a challenge. The subdivision and allocation of the well production to the individual producing zones of multi-zone wells, even with downhole gauges, is of course more complex. However, a degree of success has been achieved in extending FW PU to esimtate individual production from each of the zones of multizonal wells. Using well mechanical configuration, annulus and tubing downhole pressures, and the associated inflow control valve openings, FW PU data driven models may be generated for the individual zones of a multizone well, working from experience using FW PU in operations where no test facility is available. The FW PU zonal models then provide estimates of production from the individual zones in real time, working from the real time downhole pressure gauge readings.

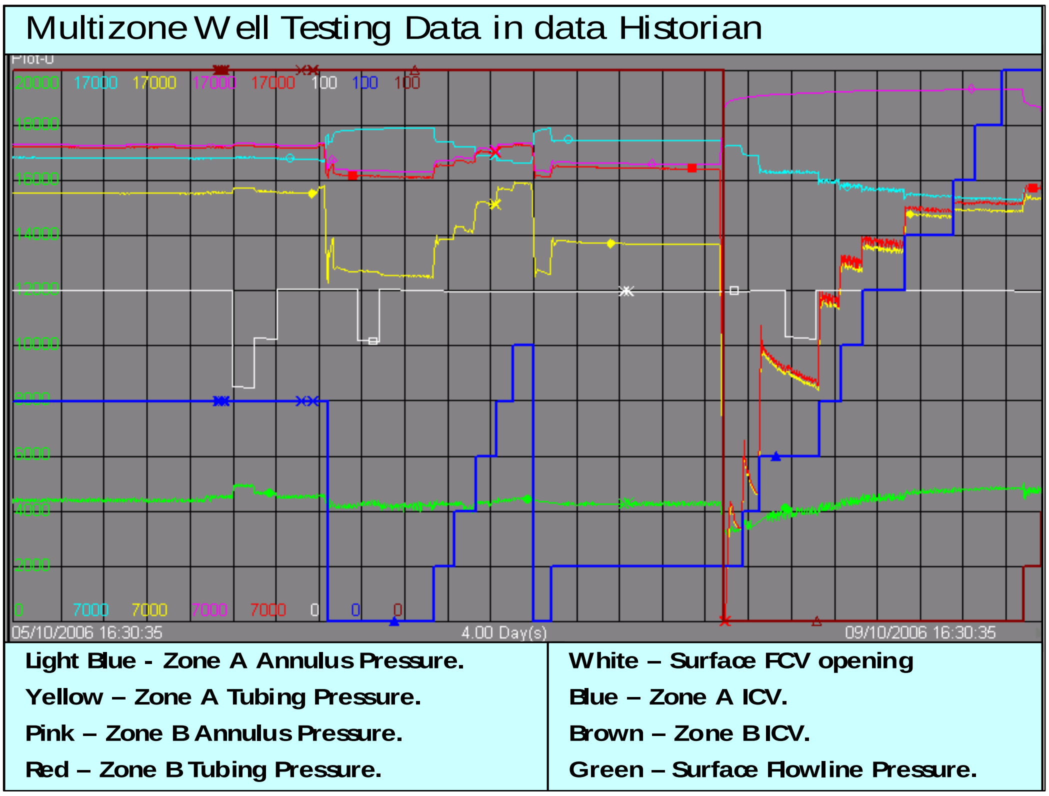



Figure 3: Typical multizone well test for a two zone well (Zone A and Zone B). The downhole and surface data is stored in a data historian and then retreived into FW PU for modelling.

In order to build the FW PU data driven models for the zones, it is required to do a series of specifically designed tests whereby individual zones and combinations of zones of the smart well are tested by routing the well to a surface multiphase flow meter. The zonal ICV settings are then varied and the downhole and surface pressures and temperatures recorded. The ICV and downhole pressure gauge data from part of a typical multizone test is given in Figure 3. In general it will be inadequate to test the well by merely flowing one zone at a time, as the pressure regimes will be different when all zones are flowing together. The zones also interact with one another. It is therefore desirable to have the zones flow together at least part of the test.

The test shown in Figure 3 is for a two zone well. Tubing and annulus pressures are shown, together with the ICV changes and surface parameters. It may be noted from the pressure changes across Zones A and B in Figure 3 when the ICVs of the other zones are closed that there is significant interaction between the two zones, for example when Zone B ICV is closed (brown line), the pressures in Zone A decrease but the difference between the Zone A annulus (light blue) and tubing (yellow) pressures very significantly increases. The duration of some of the steps are such that the well inflow did not fully stabilize before the next ICV move is conducted. This approach allows the test duration to be reduced thus minimizing production deferment. As a result, the inflow of the zone is not fully characterized during the steps and near well bore and reservoir effects such as coning are not fully captured. If effects such as coning need to be captured then longer testing periods are required. It may also be noted that for longer horizontal wells, if the steps are too short and there is significant variation in GOR or watercut between zones, there may be insufficient purging of the wellbore. In practice, these effects have been found to have only minor impact on the overall accuracy of the FW PU models.

## FieldWare Production Universe Zonal Modelling and Allocation

From the tests, FW PU models can be derived to estimate individual zonal production for oil, gas and water based on, for example, ICV position and differential pressure across the ICVs.

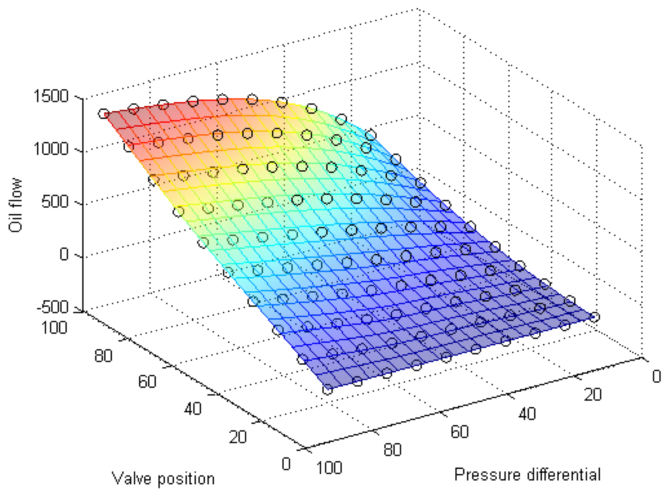



Figure 4: A simple example of a data-driven model for oil from the most downstream zone of the tested zone. The inputs have been normalized to lie between 0 and 100.

Models were derived for each of zones (for oil, water as well as for gas) by comparing the measured surface production with the multirate test data. It should be emphasized that the modelled and estimated oil, water and gas rates are at surface well test facilities conditions, and FW PU estimates are the estimates of oil water and gas rates as measured by the test facility *as if the well or zone were to be on test*. In particular, shrink and flash factors are not included in raw FW PU estimates and any correction for reservoir or stock tank conditions is to be conducted elsewhere. If the smart well has a dedicated permanent multiphase flow meter, then FW PU can be configured to compare and reconcile the sum of the production estimates for each of the zones with the total production flow measured at the surface by the multiphase flow meter on a daily basis for the validation and improvement of the estimates.

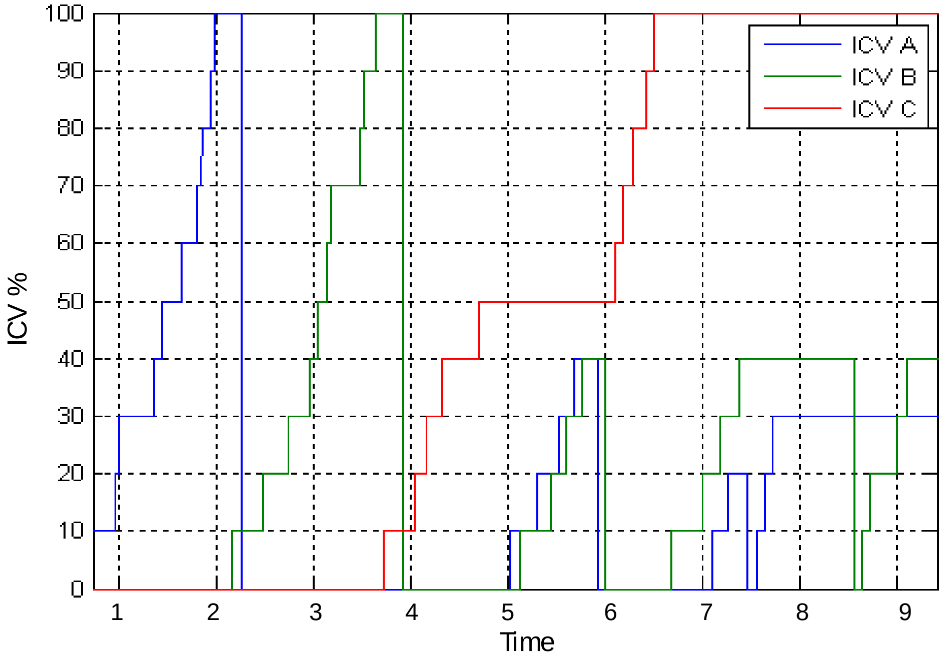
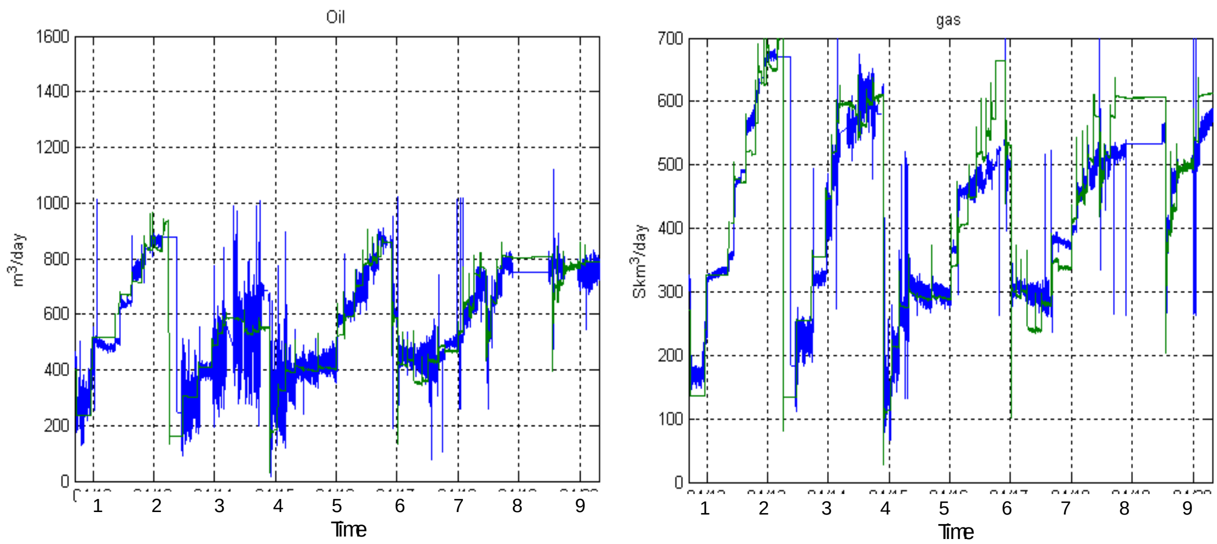



Figure 5: ICV testing sequence for a three zone well.

As an example, for a three zone well, tested using the ICV movement sequence as per Figure 5 above, FW PU zonal models are constructed for each zone. The parts of the test where only one zone is flowing allow characterization of the performance of the individual zones. The other parts where multiple zones are flowing simultaneously reveal the interactions between the different zones. The resulting zonal production models fit the surface production measurement data well, as can be seen from the comparison of the surface measurements and sum of the estimates per zone for oil and gas as shown in Figure 6 and Figure 7.

Figure 6: Total measured oil or gas flow (blue) and sum of zonal model simulations for oil or gas (green)



## Zonal allocation and interaction

The identified subsurface models are used to allocate productions to individual zones. The zonal estimates for the three zone smart well during the test-period are shown in Figure 7.

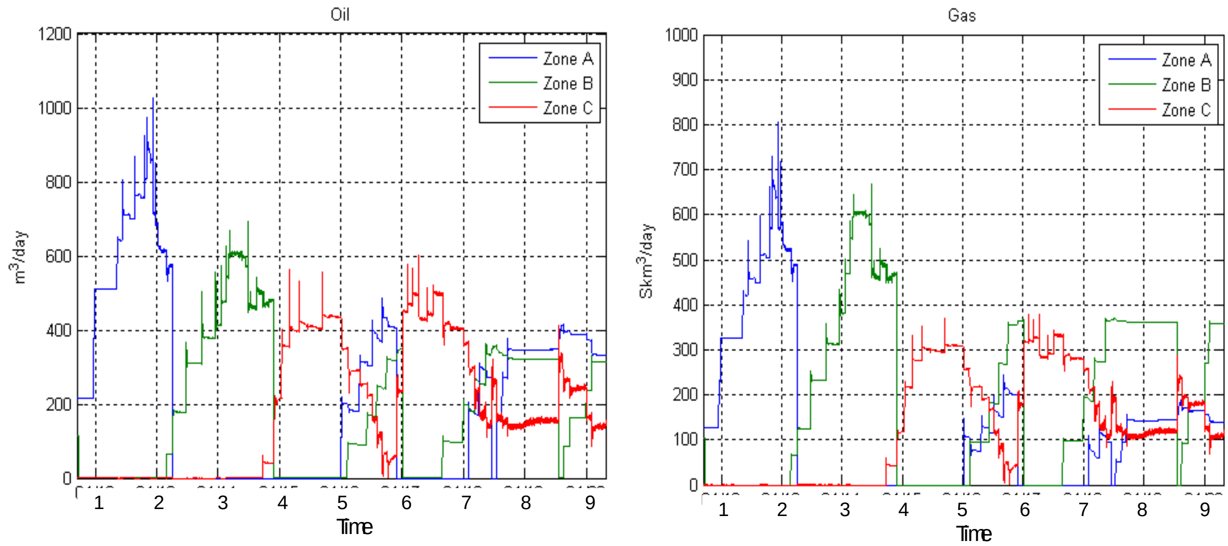



Figure 7: Zonal allocations for oil and gas flow.

From Figure 7, it is clear that Zone A is the largest oil contributor, while Zone B produces less oil and has a higher GOR. Zone C produces almost as much oil as zone B, when flowing individually. However, at the setting of the ICVs as set at the end of the test (Zone A ICV: 30% open, Zone B ICV: 40% open, Zone C ICV: 100% open), the oil production of Zone C is reduced to less than half of its full potential because of backpressure effects due to the production of Zones A and B. The Figure 8 shows the zonal allocations and properties for the zones as if each zone is flowing only by itself. From Figure 8, it is appears that the zones are differentiated with different productivity indices (PI), and different GOR and watercuts.

| | **Zone A** | **Zone B** | **Zone C** |
|---|---|---|---|
| **ICV Opening** | 100 | 100 | 100 |
| **Oil ($m^3$/d)** | 819 | 597 | 426 |
| **Gas (kS$m^3$/d)** | 695 | 623 | 304 |
| **Water ($m^3$/d)** | 10 | 261 | 22 |
| **GOR (Sm3/m3)** | 848 | 1040 | 713 |
| **WC (%)** | 1 | 30 | 5 |
| **Flowing annulus pressure (bar)** | 172 | 160 | 101 |
| **CI annulus pressure (bar)** | 178 | 178 | 185 |
| **PI ($m^3$/d / bar) (oil)** | 136 | 33 | 5 |

Figure 8: Zone ICV full open production potentials (with only that zone producing)

## Real Time Estimates of Zonal Production

On completion of the well testing and modelling, the models are put online. Based on real time data on ICV positions as well as downhole pressures, the zonal models are used to estimate production from each zone in real time and produced volumes are reported on a daily basis. The FW PU zonal data driven models require to be updated periodically with well test data. Ideally multizone well tests in which the ICVs of the individual zones are varied should be conducted regularly. However, it is also useful to update the models using normal surface well test data.

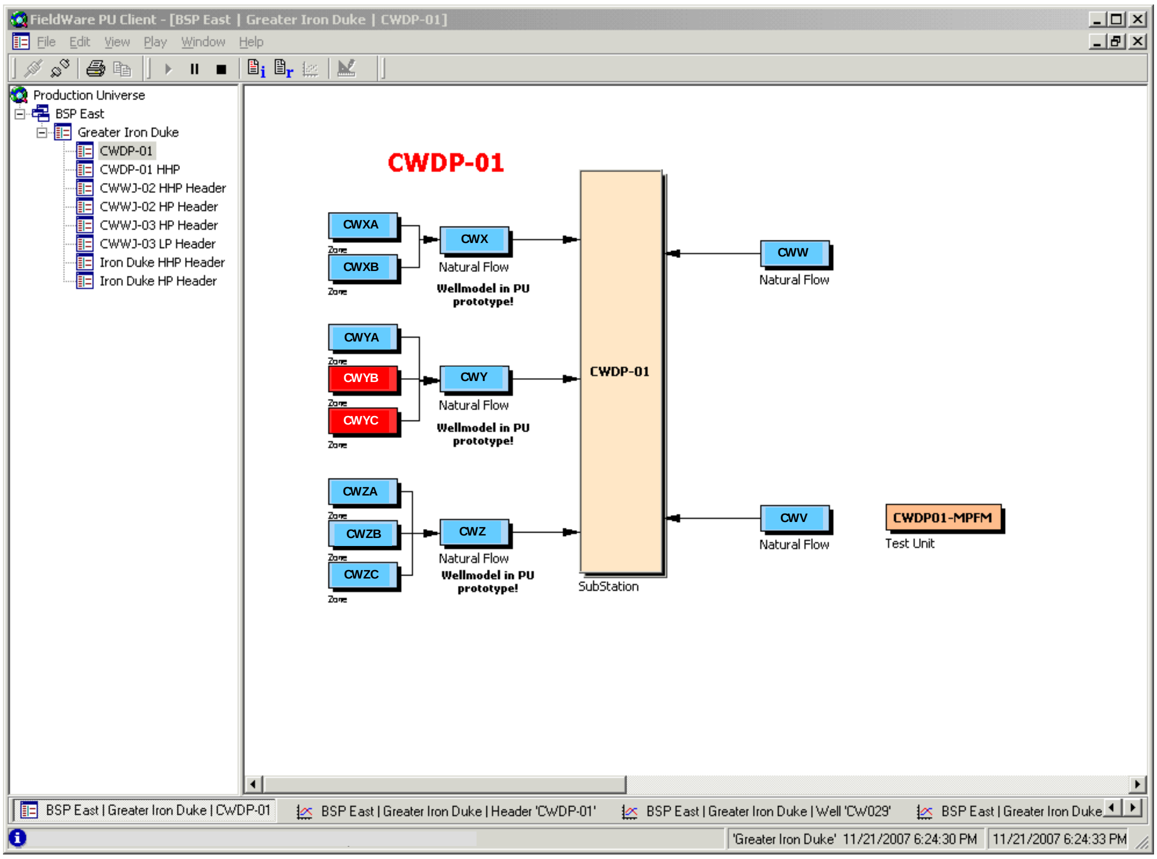



Figure 9: Production Universe User Interface for CWDP01.

## Computation of ICV Settings

A key factor in the management of long horizontal wells is the requirement to control the production profile along the length of the well consistent with well reservoir production philosophy. References [5], [7], [8] discuss the adjustment of the zonal ICVs in the context of maximizing ultimate recovery. References [19] and [20] advocate a nodal analysis framework based on physical models of, e.g., [11] for the computation of the required ICV settings. Indeed, reference [21] provides an example of ICV optimization using nodal analysis. In the context of using data driven models, the FW PU data driven optimization work presented in references [16] and [18] can be expanded to multizonal wells. This allows the computation of desired zonal ICV setpoints using data driven models to achieve specific zonal and overall well pressure and production targets. While the use of data driven models is also substantially based on a nodal analysis framework, the underlying models are constructed mainly from well test data, with an expected advantage of simplicity and consistency with well test results and actual measured production.

As an example, for the Champion West snake wells, one common objective is to equalize drawdown among the zones, to ensure the "heel" of the well is not produced at the expense of the "toe" of the long horizonal well, whilst also maintaining GOR below predetermined levels to maximize ultimate recovery.

As an example, Figure 10 shows the ICV combinations of a two zone Smart Well that will equalize drawdown without affecting production. The table shows the best 10 combinations of Zone A ICV and Zone B ICV settings ranked in terms of minimizing the difference in the annulus pressures of the Zones A and B. "Delta DHP" denotes the difference between the annulus pressures of Zones A and B. "DHP Ann" denotes the annulus pressure of Zone A. It may be noted that the ICV setting combination (#1) corresponding to the smallest difference in annulus pressures is expected to have a significantly lower oil production. As such, ICV combination number 5 (ICV A 30% and ICV B 100%) seems to be the most favorable ICV combination to be used, trading off a still acceptable difference in annulus pressures with a higher oil production. While is is entirely possible to obtain similar ICV settings by educated guesses, excel files and trial & error, the automated quantitative computational framework presented here allows a more transparent, systematic and sustainable approach to the management of larger numbers of smart wells.

| # | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Delta DHP (bar) | 0.1 | 0.4 | 0.6 | 1.0 | 1.3 | 1.3 | 1.3 | 1.4 | 1.5 | 1.6 |
| ICV A | 10 | 20 | 20 | 20 | 30 | 20 | 30 | 30 | 20 | 10 |
| ICV B | 30 | 50 | 40 | 60 | 100 | 70 | 90 | 80 | 80 | 40 |
| DHP Ann (bar) | 152 | 152 | 151 | 152 | 150 | 152 | 150 | 150 | 152 | 153 |
| Oil prod | 679 | 792 | 771 | 804 | 849 | 811 | 849 | 849 | 815 | 736 |

Figure 10: Computation of ICV settings for equal drawdown while maintaining an acceptable level of oil production.

## Summary and Conclusion

This paper reports on how the hardware and measurements of the intelligent Smart Well completions are used in combination with the Shell FieldWare Production Universe (FW PU) data driven modelling technology to allow improved and systematic surveillance and management of the Champion West wells. FieldWare Production Universe (FW PU) is a software application developed to provide continuous real time estimates of well-by-well oil, water and gas production using data driven models. The extension of FW PU techniques to the real time surveillance and production allocation of the multizone smart wells is regarded as a significant advance in the practical management and operation of such wells.

Real time pressure data combined with data driven models calibrated using multi rate zonal well tests allow real time zonal production allocation. Furthermore, these data driven models allow the automated computation of ICV position settings to allow the well to remain within the reservoir management philosophy. A system has been implemented to feedback to the users on a daily basis zonal productions, deviations from agreed well production philosophy as well as to suggest changes to ICV position to optimize production. The FW PU functionality, combined with the other smart well hardware, is targeted to allow a more transparent, sustainable and systematic management of downhole production to realize higher ultimate recovery.

## Acknowledgements

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