Joint Industry Project
“Added value from Intelligent Well & Field systems Technology (IWFsT)”
Review 2011/13

David Davies & Khafiz Muradov
Intelligent Fields: Why Do We Need Intelligence?

- Accelerate Production Buildup
- Reduce Well Count & Extend Plateau
- Reduce Well Intervention frequency
- Improve production monitoring and control
- Improve safety and project economics

Field Production Profile with Added Value:
History & Technology: of the IWFsT Project

- Completions providing a well with real-time, zonal production control and monitoring (Intelligent Well Technology) began in 1994.
- HWU’s own R & D involvement started in 1998.
- This project began in 2001 to meet industry demands for analysis of the technology’s feasibility, reliability, application envelope & risks.
- The initial (2004) deliverables included an I-Technology evaluation methodology, including the role of reliability plus several case studies.
- The 2nd phase (to 2010) developed tools for evaluating active & passive advanced completions, began Intelligent Well monitoring research & the integration of Intelligent Wells into Intelligent Fields.
- The current phase, started in 2011, concentrated on developing optimisation methodologies for I-field design & control assisted by improved monitoring techniques, plus a number of case studies.
- The 2014-2016 extension of the JIP proposes to explore new, downhole flow control technologies screened for different reservoir types, develop comprehensive, closed-loop, I-field control procedures using advanced downhole, soft, multi-phase flow metering.
The 2013 IWFsT JIP Sponsors

- Chevron
- Eni Norge
- nexen
- Petrobras
- JOGMEC
- Petroleum Experts
- Statoil
- PETRONAS
- Weatherford
- Total
IWFsT JIP

Project History & Achievements 2011-2013

The early Project History & Achievements (for 2004-2010) are available on request
**Project Evolution (2008-2013)**

The IWFsT project is steered by the sponsors, continuously evolving by responding to research leads, technology developments & sponsor insights.

Three projects begun 2008-2010 were completed during 2011-2013.

<table>
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<tr>
<th>#</th>
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<td>Evaluate the “Increased Added Value” of IWFsT by reducing the production uncertainty</td>
<td>Guidelines, Techniques &amp; Workflow</td>
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<td>Develop an online optimiser based on model update via a feedback decision loop for optimising injection</td>
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**Project A: Added IWFsT Value by Minimising Uncertainty**

**Well Liquid Rate Constraint:**
- IW completion reduces oil and water production uncertainties
- **Both** Dynamic & Static Uncertainty
- **IW reduces** reservoir heterogeneity & Uncertainty

**Well Pressure Constraint:**
- IW completion reduces oil & water production uncertainties
- Increased pressure drop in IW completion reduces oil production
- Effective Control Strategy required *(see WC_{critical}-based reactive control studies: Project 12)*

**Deliverables:** Problem Analysis, Uncertainty minimization, case studies, publications & thesis
Project B: Water Injection Management

Waterflooding monitoring and management: Approaches investigated

- **Pressure management**
  - Common techniques of monitoring waterflooding reviewed
  - Type curves developed to control total injection rate of water in to the reservoirs

- **Allocation management**
  - Techniques used to quantify inter-well connectivity studies.
  - New techniques introduced to determine water allocation factors

**Deliverables:** Methods for improving performance of water flooding in order to:
- Maintain reservoir pressure
- Delay water breakthrough
- Enhance hydrocarbon recovery
- Decrease water production

**Results** summarised in a thesis

Project C: Online for water injection allocation optimisation

Reservoir response is quantified and used to predict the optimal injection allocation:

Input: $\Delta u(t)$

Output: $\Delta y(t)$

Deliverables: Workflow developed & coded in Matlab suitable for liquid constrained production & injection where reservoir shows linear behaviour
## Project Evolution: New Projects started 2011-2013

<table>
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<tr>
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<tbody>
<tr>
<td></td>
<td>1</td>
<td>IWFS'T field design workflow</td>
<td>Is the workflow for designing an IWFS'T field different from a conventional field. Why? What are the differences? Can the process be automated?</td>
<td>Guidelines &amp; workflow</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Application of Genetic &amp; other Algorithms for control of I-wells.</td>
<td>Identify the preferred stochastic production optimization method for both I-well &amp; I-field control</td>
<td>Test feasibility. Workflow &amp; Guidelines</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Design an ideal device for downhole flow control to meet production optimization</td>
<td>Reconsider the available (JIP &amp; other) approaches to choosing a particular device, its location and control principles. Propose a methodology for choosing the best device or group of devices that meets a particular well, field and/or production objective.</td>
<td>Guidelines/Methodology</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>ICV/AICD design based on predicted life-time production</td>
<td>ICD/(A)ICD design is often carried out on a “snapshot” basis at one time in the well’s lifetime. Apply dynamic design principles to ensure that long-term production conditions &amp; objectives are also met.</td>
<td>Workflow, Proof of design feasibility, guidelines, examples</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>I-Single-boreholes and I-Multilaterals. Are they different?</td>
<td>Are the JIP findings for single-bores applicable to multilaterals? What are the differences? This includes: injectivity study between the laterals; interference while monitoring/clean-up; loss or gain of control flexibility</td>
<td>Comparative results supported by example studies.</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>Develop Temperature Transient Analysis (TTA)</td>
<td>Further development of the TTA and its application guidelines for horizontals/verticals gas/oil producers/injectors.</td>
<td>TTA methodology &amp; Examples</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>Advanced methods for interpretation of downhole data from multiple measurement devices</td>
<td>Analysis of data from multiple measurement devices is a wide area. Application to the I-well/field measurement and control system is promising. Manipulation of ICVs to increase the information content of the data is included here.</td>
<td>Methodology; Examples of the application</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>Interference of I-well design and control strategies with production network</td>
<td>Investigate how changes in the production network (i.e. an existing/newly installed pump/gas lift/separator/another well tie-back) can cause the I-well control strategy to become unstable. Investigate design principles &amp; benefits.</td>
<td>Research results</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>“Value of IWFS'T, a 2nd look”</td>
<td>Re-evaluate the “Value of Flexibility offered by IWFS'T” using Real Options</td>
<td>Rejected by sponsors</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>Heavy Oil production with IWFS'T</td>
<td>Develop design methodology for a heavy oil I-Well completion with artificial lift designed to mitigate water fingering with an ICD completed horizontal well.</td>
<td>Methodology &amp; Examples</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>Workover scheduling</td>
<td>Methodology for proactive workover scheduling</td>
<td>Case study – N2-field</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>WCrit based reactive control</td>
<td>Methodology for fast and robust, reactive ICV control and ON/OFF application area</td>
<td>Thesis, publications</td>
</tr>
<tr>
<td></td>
<td>13</td>
<td>N-field case study</td>
<td>Test well completion design and control methodologies: both reactive and proactive</td>
<td>Results</td>
</tr>
<tr>
<td></td>
<td>14</td>
<td>DTS feasibility</td>
<td>Forecast DTS response to water influx for a heavy-oil producing, advanced well</td>
<td>Results</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>ICS comparison and design</td>
<td>Compare Inflow Control Systems (ICS). Suggest (A)ICD design methodology</td>
<td>Methodology. Thesis</td>
</tr>
</tbody>
</table>
Project 1: I-Field Design Workflow & Project 2: Application of Genetic & other Algorithms for control of I-wells

Achievements:

<table>
<thead>
<tr>
<th>Well Placement</th>
<th>Production String Design (ICDs)</th>
<th>Optimise the Control Strategy</th>
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<td>✔️</td>
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</table>

- Optimum strategy becomes more critical as transmissibility increases.
- Best Conventional Well Trajectory can be the best I-well trajectory

Developed procedure is being tested with a real field model

Deliverables by December 2013: *extra project 11* and:
- Step-by-Step workflow
- Guidelines for optimisation setup
- Comparison with the conclusions from the synthetic model
Project 2: Application of Genetic & other Algorithms for I-well control

**Progress**
- Slow loop activated ONLY when needed
- Control frequency of the slow loop

**Deliverables:**
- New algorithm for proactive optimisation
- Guidelines for limiting the proactive, optimisation to essential periods only
- Workflow to define optimum control frequency
- Guidelines for modifying available tools for proactive optimisation

**Problems:**
- Large number of variables
- Large, full-field model
Project 3: Customise Design of Downhole Flow Control Devices for Production Optimization

Standard Design

ICV or ICD?

Customised Design

Ideal performance of the best device?

Example: I-injector’s design, PUNQ field, WAG injection

Using a 6 position ICV with this trim design

Optimal Zonal Pressures for I-injector

Requires this performance:

Deliverables: PUNQ study showed that knowledge of optimal rate or FBHP required to make the optimum design. A comprehensive, unified design is part of Projects 1 & 2.
Project 4: ICV/ICD/AICD Design based on Life-time Production

Achievements:

- Optimising life-time production delivers significant improvements
- Chosen economic model is the critical factor.

Deliverables planned late 2013:
- Work flow
- Optimisation Guidelines
- Economic parameter sensitivity
- ICD/AICD/ICV recovery comparison
Project 6: Further Development of Temperature Transient Analysis

T & P transient interpretation methods being developed

T & P zone-by-zone analysis workflow developed

Deliverables: Methodology developed & tested

SPE 164868: Some Case Studies of Temperature and Pressure Transient Analysis in Horizontal, Multi-zone, Intelligent Wells
Project 7: Advanced Methods of Downhole Data Interpretation from Multiple Measurement Devices

Multi-zone I-well

1 Pressure Measurement (steady state & transient)

2 Temperature Measurement (steady state & transient)

3 P Data
Data analysis using all available measurements

Objective: - Maximise Information content for a minimum measurement effort
• “Deliberately disturbed well tests”

T Data
DTS data from multi-zone measured during I-well multi-rate tests

Deliverables: Workflow & examples for “Minimum measurement effort” monitoring during multi-rate flow tests using either ICVs or wellhead choke
Project 8: Interference of I-well & ESP Production Control Strategies

Interaction between ESP Artificial lift & Downhole Flow Control Devices
- Requires proper design, operation & ability to adapt to changing production conditions

ESP Performance Plot

Deliverables: Two ESP-ICV/ICD/AICD design methods proposed, tested, reported & published (see also Project 10)
Project 10: Heavy Oil production with IWFsT & ESP

Pilot study: Heavy-oil production with an AICD completion: “Snap-shot” performance of Integrated completion modelled

Deliverables:
- Snap-shot design completed
- Dynamic modelling
- Effect of gravel pack

During 2013
1. Dynamic modelling
2. Effect of gravel pack
Extra Project 11:
Optimum workover schedule for wells in a sector of a real field

GA for proactive workover scheduling (4 wells, total 12 zones)

Optimal Case Evolution

2% recovery increase by choosing optimum schedule

Deliverables: Workflow & MEPO add-on for proactive, work-over scheduling
Extra Project 12: The Critical Water-Cut concept: Application Area of ON/OFF ICV Reactive Control

- On/Off valves optimal in 90% cases:
  - For reactive control of vertical wells with fixed THP only
  - No gas inflow
  - Not for viscous oil

- Optimum valve position found based on the zonal, Critical Water Cut (CWC) criterion:

\[
WC_n \geq 1 - \frac{\Delta P_{BHP}}{J_n \cdot dP_n} \sum_{i \neq n} J_i (1 - WC_i)
\]

Deliverables: CWC concept systematically analysed + tested using several synthetic & real field models.
Extra Project 13: Real-field case study combining reactive & proactive production optimisation methods

A large, real-field model used as a production optimisation test-bed for:

1. Several proactive well control methods &
2. CWC reactive control (*CWC is fast, robust without the convergence problems often experienced by commercial optimisation simulators*)

**First Level:**
- Genetic Algorithm optimisation
- Zonal control by optimising ICVs

**Second Level:**
- Eclipse well prioritization option
- Control production from all wells with a total oil production rate constraint

**Deliverables:** Real-field control studies by developing & testing:
1. Reactive Control (commercial optimisers & CWC)
2. Proactive Control (optimal control, GA).
Extra Project 14: Evaluate the application of DTS in an AICD-equipped, heavy oil production well

DTS response to zonal water break-through in a long horizontal well has been evaluated using the HWU simulator

*Early production Temperature profile*  
(clear water influx signature observed)

*Late production Temperature profile*  
(T-profile should be smoothed)

**Deliverables:** DTS system’s long-term resolution requirement defined by this real well feasibility study
**Extra Project 15: Comparison & Design of Inflow Control Systems (ICS)**

Comprehensive review & comparison of Inflow Control Systems:

<table>
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<tr>
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<th>ICD vs. cased hole</th>
<th>ICD vs. ICV</th>
<th>AICD vs. ICV</th>
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<tbody>
<tr>
<td>Uncertainty in Reservoir Description</td>
<td>ICD</td>
<td>ICV</td>
<td>AICD</td>
</tr>
<tr>
<td>More Flexible Development</td>
<td>ICD</td>
<td>ICV</td>
<td>ICV</td>
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<tr>
<td>Length of Control Interval</td>
<td>ICD</td>
<td>ICD</td>
<td>AICD</td>
</tr>
<tr>
<td>Tubing Size</td>
<td>=</td>
<td>ICD</td>
<td>AICD</td>
</tr>
<tr>
<td>Value of Information</td>
<td>=</td>
<td>ICV</td>
<td>ICV</td>
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<td>Control of Lateral</td>
<td>=</td>
<td>ICV</td>
<td>ICV</td>
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<td>Control within Lateral</td>
<td>ICD</td>
<td>ICD</td>
<td>AICD</td>
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<tr>
<td>Commingled Production</td>
<td>ICD</td>
<td>ICV</td>
<td>ICV</td>
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<tr>
<td>Long Term Equipment Reliability</td>
<td>Conv</td>
<td>ICD</td>
<td>ICV</td>
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<tr>
<td>High Formation Permeability</td>
<td>ICD</td>
<td>ICD</td>
<td>=</td>
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<tr>
<td>Mid-to-Low Formation Perm.</td>
<td>ICD</td>
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<td>Modelling Tool Availability</td>
<td>Conv</td>
<td>ICV</td>
<td>ICV</td>
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<tr>
<td>Reservoir Isolation Barrier</td>
<td>=</td>
<td>ICV</td>
<td>ICV</td>
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<tr>
<td>Acidizing / Scale Treatment</td>
<td>ICD</td>
<td>ICV</td>
<td>ICV</td>
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<tr>
<td>Improved Well Clean-Up</td>
<td>ICD</td>
<td>ICV</td>
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<td>Equipment Cost</td>
<td>ICD</td>
<td>ICV</td>
<td>AICD</td>
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<tr>
<td>Installation Complexity</td>
<td>ICD</td>
<td>ICV</td>
<td>AICD</td>
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<tr>
<td>Installation Risk</td>
<td>Conv</td>
<td>ICD</td>
<td>AICD</td>
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<tr>
<td>Installation Time</td>
<td>ICD</td>
<td>ICV</td>
<td>AICD</td>
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<tr>
<td>In-situ Gas Lift</td>
<td>Conv</td>
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<td>ICV</td>
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<td>Gas Fields</td>
<td>Gas Inflow Equalisation</td>
<td>ICD</td>
<td>ICV</td>
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<td>Water Production Control</td>
<td>Conv</td>
<td>ICV</td>
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Nodal analysis based ICD & AICD design & sizing workflow developed & tested

**Deliverables:** Comprehensive comparison of ICS & optimum (A)ICD design.
Conference papers:
1. **IPTC-15215** Use of Distributed Temperature for Zonal Flow Rate and Pressure Estimation, *IPTC 2011*, Bangkok
2. Temperature Monitoring and Interpretation in Intelligent Wells, *3rd International Oil Production Intensification Conference*, Jul 2011, Tomsk, Russia

Scientific papers:
1. Application of inflow control devices to heterogeneous reservoirs - *JPSE published Volume 78, Issue 2, August 2011*, pp 534-541
IWFsT JIP Achievements (2011-2013) Publications 2012

Conference papers:
1. SPE 150138 - Temperature Transient Analysis in a Horizontal, Multi-zone, Intelligent Well; SPE Intelligent Energy, March 2012
3. SPE 154472 - A Novel Optimisation Algorithm for Inflow Control Valve Management; SPE EUROPEC, June 2012

Scientific papers:
2. Early-time Asymptotic, Analytical Temperature Solution for Linear Non-adiabatic Flow of a Slightly Compressible Fluid in a Porous Layer; Transport in Porous Media
3. Temperature Transient Analysis Application Workflow, Problems and Advantages; Journal of Petroleum Science and Engineering
IWFsT JIP Achievements (2011-2013) Publications 2013

Conference papers:
1. **SPE 164868** - Some Case Studies of Temperature and Pressure Transient Analysis in Horizontal, Multi-zone, Intelligent Wells, *SPE Europec*, June 2013

Theses:
1. “A Comprehensive Approach to the Design of Advanced Well Completions” by Faisal Al-Khelaiwi
2. “Intelligent Well Transient Temperature Signal Reconstruction” by Manoel Feliciano da Silva Junior
3. 2 further theses expected during 2013
Research, Design & Value Demonstration of many aspects of Advanced Completions has been done using Sponsor’s Real Field Models.

Field Case Studies:

a) S Field
b) NH Field
c) BG Field
d) Ch Field
e) BP Field
f) H Field
g) N Field
h) N2 Field
i) E Field
j) C-gas-field
k) U-field
l) ...
# Project Evolution

The IWFsT project is steered by the sponsors, continuously evolving by responding to research leads, technology developments & sponsor insights.

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Projects finished by 2010...contributed to the current projects (2011-2013) ...and formed the basis for the proposed 2014-2016 projects

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<td>1</td>
<td>Inflow Control System Comparison (ICV vs. ICD)</td>
<td>Inflow Control Systems Compared (ICV/ICD/AICD)</td>
<td>• Reservoir types suitable for (A)ICD • I-well design for multilaterals</td>
</tr>
<tr>
<td>2</td>
<td>Advanced well modelling</td>
<td>...is the integral, ever developing part of all JIP studies: current and proposed</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Automatic optimisation of ICV settings</td>
<td>Results provide a the base case control scenario in reactive well control studies</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Online Well Control</td>
<td>Inspired the field controller (#1 below)</td>
<td>-</td>
</tr>
<tr>
<td>5</td>
<td>Reconcile short-term optimisation &amp; long-term management</td>
<td>Inspired the reactive vs. proactive control studies</td>
<td>• Multi-objective optimisation • Controls for different Reservoir types</td>
</tr>
<tr>
<td>6</td>
<td>Integrate downhole T &amp; P data into well modelling</td>
<td>• Fundamental solution to extend the Pressure and Temperature Transient Analysis • Well modelling experience used in the Active Monitoring studies</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Field case studies: H &amp; SH Fields</td>
<td>Modelling and analysis experience applied to E, N, N2, PUNQ, AINSA II models</td>
<td>Modelling experience to be applied to the case studies</td>
</tr>
<tr>
<td>8</td>
<td>Evaluate Clean-up techniques</td>
<td>Experience with dynamic flow modelling</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Value &amp; application envelope of IWFsT</td>
<td>I-well designs suited to Reservoir types</td>
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<td>10</td>
<td>I-well value as a source of information</td>
<td>Reconciled active monitoring &amp; control</td>
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