Well Design

Engineering out Cost for Intervention, Rejuvenation and Cessation of Production Operations

Steven Allan Canny

DEC Technology Forum | Well Lifecycle Design
Houston | Texas
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AGENDA

1. Well Design Fundamentals
2. International Well Design Examples
3. Well Integrity – NORSOK D-010
4. Formation Evaluation and Well Development
5. Logging
6. Case Studies
7. Workover with Re-Perforation
8. Reservoir Abandonment
9. Slot Recovery and Infill Drilling
10. Summary and Questions

Well Design - Engineering out Cost for Intervention, Rejuvenation and Cessation of Production Operations

“An international approach to leveraging well design and integrity operations in the construction phase, to reduce the cost of workover, reservoir abandonment and rejuvenation operations.”

Steven Allan Canny
Engineering Lead
Well Abandonment and Intervention Services
Well Design Fundamentals

“A conduit allowing the flow of hydrocarbons to surface”

- A collection of verified well barrier elements that assure integrity of the conveyance path:
  - Casing Tubulars
  - Annular Cement
  - Wellhead Suspension System, Casing Hangers and Lock Down seals
  - Completion Packers
  - Completion Tubulars

- Flow Assurance and Control
  - Downhole Valves
  - Chemical Injection (flow assurance, preventative chemicals)
  - Surface Control Valves and Chokes

Figure 8.8.2, NORSOK D-010, Rev 3
Example Well Design

Reservoir
- Normally Pressurised Gas Reservoir
- Dual Target zones, with further shallow targets identified for mid life re-completion and sidetrack upon reservoir depletion

Casing Plan
- 13-⅜” x 9-⅝” x 7” with 3-½” Completion tubing
- Sand Control Completion
- Open C Annulus to sidetrack 13-⅜” in late life
- Deep Sidetrack intended in 7” Production casing in the case of well integrity issues

Completion
- Retrievable Production Packer to recover during workover
- 7” Production casing to accommodate future artificial lift completion
NCS Well Architecture Examples

Normally Pressurised Horizontal Offset Well

- 30” x 20” x 13-⅜ x 9-⅝ x 7” Liner
- Horizontal Reservoir Section
- High Departure
- High MD and Tvd
- Open 13- ⅜” Annulus for Shallow Sidetrack
- Open 9- ⅝” Annulus for Deep Sidetrack
- 6-⅝ multi-zone open hole completion with multiple control lines
- Gas Lift Completion
- Conductor re-use for planned slot recovery
Norsok Standard D-010 “Well Integrity in Drilling and Well Operations”

- Well Integrity Standard covering Drilling, Well Servicing and Abandonment Operations
- Most stringent international standard, used “as is” or as a base for International Oil Companies internal well integrity standards
- Prescriptive approach to barriers and the verification and monitoring
- Dual Well Barrier Approach in wells with flow potential to surface: “ensure that no single failure of a Well Barrier or WBE can lead to uncontrolled flow of wellbore fluids or gases to the external environment”
- Design, Verification and monitoring of Well Barriers

| Two well barriers   | d) Hydrocarbon bearing formations | e) Abnormally pressured formation with potential to flow to surface |
Well Barriers and Well Barrier Elements

Well Barrier “WB”
“envelope of one or several well barrier elements preventing fluids from flowing unintentionally from the formation into the wellbore, into another formation or to the external environment”

Well Barrier Element “WBE”
“a physical element which in itself does not prevent flow but in combination with other WBE’s forms a well barrier”

Well Barrier Element Acceptance Criteria
“technical and operational requirements and guidelines to be fulfilled in order to verify the well barrier element for its intended use”

<table>
<thead>
<tr>
<th>Primary Well Barrier</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fluid Column</td>
</tr>
<tr>
<td>Drilling mud</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Secondary Well Barrier</th>
</tr>
</thead>
<tbody>
<tr>
<td>Casing Cement</td>
</tr>
<tr>
<td>Annular Cement</td>
</tr>
<tr>
<td>Casing</td>
</tr>
<tr>
<td>–</td>
</tr>
<tr>
<td>Wellhead</td>
</tr>
<tr>
<td>Metallic gasket</td>
</tr>
<tr>
<td>High Pressure Riser</td>
</tr>
<tr>
<td>If Installed</td>
</tr>
<tr>
<td>Drilling BOP</td>
</tr>
<tr>
<td>–</td>
</tr>
</tbody>
</table>

Figure 5.8.1, NORSOK D-010, Rev 3
### Table 22 - Casing cement

<table>
<thead>
<tr>
<th>Features</th>
<th>Acceptance criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>A. Description</strong></td>
<td>This element consists of cement in solid state located in the annulus between concentric casing strings, or the casing liner and the formation.</td>
</tr>
<tr>
<td><strong>B. Function</strong></td>
<td>The purpose of the element is to provide a continuous, permanent and impermeable hydraulic seal along hole in the casing annulus or between casing strings, to prevent flow of formation fluids, resist pressures from above or below, and support casing or liner strings structurally.</td>
</tr>
<tr>
<td><strong>C. Design, construction and selection</strong></td>
<td>1. A cement program shall be issued for each cement job, maximum covering the following: a. casingliner centralization and stand-off to achieve pressure and sealing integrity over the entire required isolation length; b. use of fluid spacers; c. effects of hydrostatic pressure differentials inside and outside casing and ECD during pumping and loss of hydrostatic pressure prior to cement setting up; d. the risk of lost returns and mitigating measures during cementing. 2. For critical cement jobs, HPHT conditions and complex/foam slurry designs the cement program shall be verified independent (internal or external), qualified personnel. 3. The cement recipe shall be lab tested with dry samples and additive from the rig to represent well conditions. The tests shall provide thickening time and compressive strength development. 4. The properties of the set cement shall provide lasting zonal isolation, structural support, and withstand expected temperature exposure. 5. Cement sources used for isolating sources of inflow containing hydrocarbons shall be designed to prevent gas migration, including CO₂ and H₂S, if present. 6. Planned casing cement length: a. Shall be designed to allow for future use of the well (sidetracks, recompletions, and abandonment). b. General: Shall be minimum 100 m MD above a casing shoe/window. c. Conductor: Should be defined based on structural integrity requirements. d. Surface casing: Shall be defined based on load conditions from wellhead equipment and operations, TOC should be at surface/sealed. e. Production casing/liner: Shall be minimum 200m MD above a casing shoe. If the casing penetrates a source of inflow, the planned cement length shall be 200m MD above the source of inflow. a. Note: If unable to fulfill the requirement when running a production liner, the casing cement length can be combined with previous casing cement to fulfill the 200m MD requirement.</td>
</tr>
<tr>
<td><strong>API/RP 10B</strong></td>
<td>ISO 10426-1</td>
</tr>
</tbody>
</table>

**Table 22, NORSOK D-010 Rev 004**
### Table 24 – Cement plug

<table>
<thead>
<tr>
<th>Features</th>
<th>Acceptance criteria</th>
<th>See</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>A. Description</strong></td>
<td>The element consists of cement in solid state that forms a plug in the wellbore.</td>
<td></td>
</tr>
<tr>
<td><strong>B. Function</strong></td>
<td>The purpose of the plug is to prevent flow of formation fluids inside a wellbore between formation zones and/or to seal surface leakages.</td>
<td></td>
</tr>
<tr>
<td><strong>C. Design, construction and selection</strong></td>
<td>1. A program shall be issued for each cement plug installation. 2. For critical cement jobs, HPHT conditions and complex slurry designs, the cement program should be verified by independent (internal or external) qualified personnel. 3. The cement recipe shall be laboratory-tested with dry samples and additives from the rig site under representative well conditions. The tests shall provide an indicative time and compressive strength development. 4. Cement slurries used in plugs to isolate sources of inflow containing hydrocarbons should be designed to prevent gas migration and be suitable for the well environment (CO₂, H₂S). 5. Permanent cement plugs should be designed to provide a lasting seal with the expected static and dynamic conditions and loads. 6. It shall be designed for the highest differential pressure and highest downhole temperature expected including installation and test loads. 7. A minimum cement batch volume shall be defined to ensure that a homogeneous slurry can be made, taking into account all sources of contamination from mixing to placement. 8. The minimum cement plug length shall be:</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Open hole cement plugs</th>
<th>Cased hole cement plugs</th>
<th>Open hole to surface plug (incorporated in surface casing)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 m MD with minimum 50 m MD above any source of inflow/leakage point. A plug in transition from open hole to casing should extend at least 50 m MD above and below casing shoe.</td>
<td>50 m MD if set on a mechanical/cement plug as foundation, otherwise 100 m MD</td>
<td>50 m MD if set on a mechanical plug, otherwise 100 m MD.</td>
<td></td>
</tr>
</tbody>
</table>

9. Placing one continuous cement plug in a cased hole is an acceptable solution as part of the primary and secondary well barriers, when placed on a verified foundation (e.g., pressure tested mechanical/cement plug). 10. Placing one continuous cement plug in an open hole is an acceptable solution as part of the primary and secondary well barriers with the following conditions: a. The cement plug shall extend 50 m into the casing. b. The requirement is to be set on a foundation (TD or a cement plug(s) from TD). The cement plug(s) shall be placed directly on top of one another.

11. A casing liner shall have a shoe track plug with a 25 m MD length.

**D. Initial verification**

1. Cased hole plugs should be tested in both directions of flow from above.
2. For the shoe track to be used as a WBE, the following applies:
   a. The bleed back volume from placement of casing cement shall not significantly exceed the calculated volume, and
   b. It shall be either pressure tested and supported by overbalanced fluid (see EAC 1) or inflow tested.
3. The strength development of the cement slurry shall be verified through observation of surface samples from the mixing, cured on site in representative temperature.
4. The plug installation shall be verified through evaluation of job execution taking into account estimated hole size, volumes pumped and returns.
5. The plug shall be verified by:

<table>
<thead>
<tr>
<th>Plug type</th>
<th>Verification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open hole</td>
<td>Tagging.</td>
</tr>
<tr>
<td>Cased hole</td>
<td>Tagging.</td>
</tr>
</tbody>
</table>

E. Use: None.

**F. Monitoring**

For temporary abandoned wells: The fluid level pressure above the shallowest set plug shall be monitored regularly when access to the bore is available.

**G. Common well barrier**

If one continuous cement plug (same cement operation) is defined as part of the primary and secondary well barriers, it shall be verified by drilling out the plug until hard cement is confirmed.

1. An open hole cement plug extended into the casing shall be pressure tested.

**Table 24, NORSOK D-010 Rev 004**
Well Barriers in Suspension and Abandonment

**Example 1**
Verified Annular Cement Well Barrier Elements in B and C Annulus.

 Verified Casing Well Barrier Elements in place

Cased hole plugs required with section milling in WB3

**Example 2**
Non-verifiable annular cement in B and C annulus. Removal and “Rock to Rock” Well Barriers Required

Verified Casing Well Barrier Elements in place

Extensive section milling or perforate and wash cementing required
Surface Equipment Requirements Base on Downhole SOR

Example 1
- 1x squeezed cement plug
- 3x Cased hole plugs
- 7” Casing cutting and recovery
- 10-¾” window milling (25 ft)

Required Surface Equipment

Rigless or Light Intervention Equipment
- Pressure Control Equipment
- Axial Hoisting – Casing Jack
- Well Servicing Pump
- Wireline PCE and Toolstrings

Example 2
- 1x Formation to Formation Plug
- 2x Formation to Formation Plugs
- 1x Cased hole plugs
- Lower Completion Pilot Milling
- 7” Casing Section Milling (70 ft window)
- 7” Casing Section Under reaming (70 ft window)
- 7” Casing cutting and recovery
- 10-¾” Casing Section Milling (70 ft window)
- 10-¾” Casing Section Under reaming (70 ft window)
- 10-¾” Section Milling (25 ft)

Required Surface Equipment

Well Construction Drilling Equipment
- Drilling Equipment Structure and Drilling Support Module
Formation Evaluation

Mud Logging
- Establish Lithology of Hole Sections
- Establish Fluid Properties

Coring
- Establish Lithology and Stratigraphy
- Establish Undisturbed Fluid Properties

Logging
- Extensive Open Hole and Cased Hole options available

Reservoir Testing
- Transient pressure response allowing measurement of S, PI, Skin, PVT etc.
Logging While Drilling – Azimuthal Sonic Tool

Geosteering | Pore Pressure Evaluation | Structural Geological Evaluation | 360° Anisotropy Borehole Imaging
Integrated Log Analysis – Groundwater Fluid Isolation

Casing Imaging Log | Multi-sensor Calliper Log | Bond Log | Ultrasonic Radial Scan Log | Noise/ & Temperature Log
Integrated Log Analysis – Casing Integrity

CalView Tool - Calliper Log | FluxView Tool - Magnetic Flux Log | BondView Tool - Bond Log
Integrated Log Analysis – Annular Casing Cement Bond

BondView Tool - Bond Log  |  Slim Sector Bond– Bond Log
Cased Hole Logging

Data Collection During Workover Operations

Casing Integrity
- Ovality
- Parted Connections
- Burst/Collapsed Tubing

Fluids
- Pore and Fracture Pressure Prediction
- Annular Mud Settlement
- Annulus Crossflow

Cement Integrity
- Bond to casing and formation
- Micro channelling and annuli
CASE STUDIES

Workover with Re-Perforation and Artificial Lift
Reservoir Abandonment
Slot Recovery and Infill Drilling
Workover with Re-Perforation
Mid Life Well Strategy Case Study
Reservoir Re-Completion

Challenge
- Abandon existing reservoir in Mature Well
- Wellbore Cleanup and conditioning for TCP
- Perforate production target with Shoot and Pull TCP string
- Install new artificial lift upper completion

Constraints
- Mature Well with Integrity monitoring
- Conductor Integrity issues with open E-Annulus to marine environment
- Annular pressure buildup during well shut down and start up thermal cycle
Typical Scope of Work – Reservoir Abandonment, Re-Perforation and Re-Completion

**Facility Integration and Interfacing**
- Mobilization of Surface Equipment
- Establish Well Barriers with PCE

**Well Abandonment**
- Displace well to KWM and Access Well
- Through tubing Permanent Reservoir Abandonment
- Recover Upper Completion and Packer

**Wellbore Conditioning**
- Displace well to KWM, remove Kill String and Access Well
- WBC Runs and Fluid Conditioning

**Lower Completion, Fracturing and Stimulation**
- Run Sump Packer
- Lower Zone Shoot and Pull Perforation
- Run Lower Zone Completion and Spacer Assembly
- Gravel packing and acidisation
- Fracturing

**Upper Completion**
- Run Upper Completion

**Well Clean Up**
- Hand Well over to Production and Skid to next Well
Reservoir Abandonment
Cessation of Production Case Study
Well Abandonment – Operation Phases

**Phase I**
*Primary Reservoir(s)*

“The reservoir has been permanently isolated”

- Isolation of the primary reservoir perforations to the environment, through establishing a verified primary well barrier
- Typically pumped cement conveyed “thru tubing” or via coiled tubing
- Verification via Tagging TOC and pressure testing

**Phase II**
*Intermediate Reservoir(s)*

“All intermediate zones with flow potential have been isolated”

- “With flow potential” – zones with permeability and a pressure differential to surface
- Evaluation of which is a key aspect to the basis of the well abandonment design
- Typically casing cutting and recovery to expose formation and deeper annuli
- Focused Well Abandonment Units

**Phase III**
*Surface Abandonment*

“Well is abandoned after removing the wellhead and conductor”

- Typically involves an environmental well barrier being placed
- Mechanical or Abrasive severance of the wellhead (subsea) or conductor
- Cut below mudline (subsea);
  - Oil and Gas UK – “5 ft”
  - Norsok D-010 – “Sufficient to prevent conflict with other marine activities”

Definitions are per the Oil & Gas UK, Guidelines for the Abandonment of Wells, Issue 5, July 2015
Reservoir Abandonment Design

The Basis of Design Requires...

I. Well Configuration:
   – Depths and specification of formations which are sources of inflow
   – Casing strings
   – Casing cement
   – Wellbores and sidetracks

II. Stratigraphic sequence of each wellbore showing reservoir(s) and information:
   – Current and future production potential
   – Reservoir fluids
   – Reservoir pressures (initial, current and in an eternal perspective)

III. Logs, data and information from cementing operations

IV. Formations suitable to be used as WBEs

V. Specific well conditions such as scale build up, casing wear, collapsed casing, fill, H2S, CO2, hydrates, benzene or similar issues
Basis of Design

**Drilling Data**
- Formation Evaluation
- Open Hole Logs
- Cased Hole Logs
- Inflow Testing

**Workover Data**
- Pore Pressure Logs
- Calliper Logs
- Cement Bond Log
- Pressure Test

**Establish Basis of Abandonment Design**
- Pore Pressure
- Crossflow Potential
- Recharge Potential
- WB Rated Pressure

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**Pore Pressure & Fracture Pressure vs MD**

- Max. Pore P
- Min Fracture P
- Max Fracture P
- Full Gas Discharge

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**Well Lifecycle Design**

- Basis of Design
- Workover Data
- Establish Basis of Abandonment Design
Example Abandonment

**Primary Well Barrier**
Barrier set in Competent formation above primary reservoir with the following WBEs. **Verification** – Tag top of cement, pressure test.
- B Annulus Cement (Logged)
- 7” Production Casing (Pressure Tested)
- Cased Hole Cement Plug set on gas tight retainer

**Secondary Well Barrier**
Barrier set in Competent formation onto the Primary Well Barrier with the following WBEs. **Verification** – Tag top of cement, pressure test.
- B Annulus Cement (Logged)
- 7” Production Casing (Pressure Tested)
- Cased Hole Cement Plug set on Gas tight retainer
- Verified gas tight Primary Well Barrier below

**Surface Well Barrier**
B & C Annulus Barrier set on visco-reactive pill with the following WBEs. **Verification** – Tag top of cement, pressure test.
- 9-⅝” Intermediate Casing (Pressure Tested)
- 7” Production Casing (Pressure Tested)
- Multi-Annuli Cased Hole Cement Plug set on visco-reactive pill
Slot Recovery and Infill Drilling
Field Rejuvenation Case Study
Reservoir Re-Entry Sidetrack

**Challenge**
- Abandon existing reservoir in Mature Well
- Mill Casing Exit and Rathole
- Drill 6” sidetrack hole section from motherbore for 2,000 ft, to target attic hydrocarbon in mature reservoir
- Complete Well and hand over to well testing

**Constraints**
- Limited space available on wellhead platform for Drilling Equipment Set and Drilling Support Module
- Marginal prospect, thus must be cash flow positive project to be sanctioned
- 5 wells per platform to be sidetracked
- Marine support vessel required
Reservoir Re-Entry Sidetrack Planning

**Drilling Data**
- Formation Evaluation
- Open Hole Logs
- Cased Hole Logs
- Inflow Testing

**Workover Data**
- Pore Pressure Logs
- Calliper Logs
- Cement Bond Log
- Pressure Test

**Well Design**
- Open B or C Annulus for Casing Exit
- Verified Well Barriers
- Formation Evaluation to plan Casing Exit
**Typical Scope of Work – 2,000 ft Geosteering Sidetrack**

**Facility Integration and Interfacing**
- Mobilization of Surface Equipment
- Establish Well Barriers with PCE

**Well Abandonment**
- Displace well to KWM and Access Well
- Recover Upper Completion and Packer
- Permanent Reservoir Abandonment

**Casing Exit and Reservoir Re-Entry**
- Condition well an WBC run to displace to OBM for Drilling
- Whipstock Installation and Milling Operations to Exit Casing

**Drilling and Completion**
- Sidetrack drilling to TD
  - Build and Turn Section from Rathole
  - Drain Section to TD

**Completion**
- Open Hole Sand Screen Lower Completion Installation
- Fluids Displacement and Breaker to remove mud cake filter
- Hand over to Well Testing Clean Up

**Access Next Well**
- Skid to Wellslot and Establish Well Barriers with PCE
Summary and Discussions
**Well Construction**
Drilling Phase

*Create:*
- Exploration Data
- Seismic, Coring, Logging
- Reservoir Testing

*Production Data*
- Sampling, Logging
- » Well Construction Data

**Mid Life Operations**
Workover

*Use:*
- Well Construction Data

*Plan Operations:*
- Intervention
- Stimulation
- Workover
- Re-perforation
- » Well Construction Data
- » Mid Life Data

**Cessation of Production**
Reservoir Abandonment

*Use:*
- Well Construction Data
- Mid Life Data

*Plan Operation:*
- Reservoir Abandonment
- Infill Sidetrack
- Infill Drilling
- New Target Sidetrack Drilling
- » Well Construction Data
- » Mid Life Data
- » COP Data