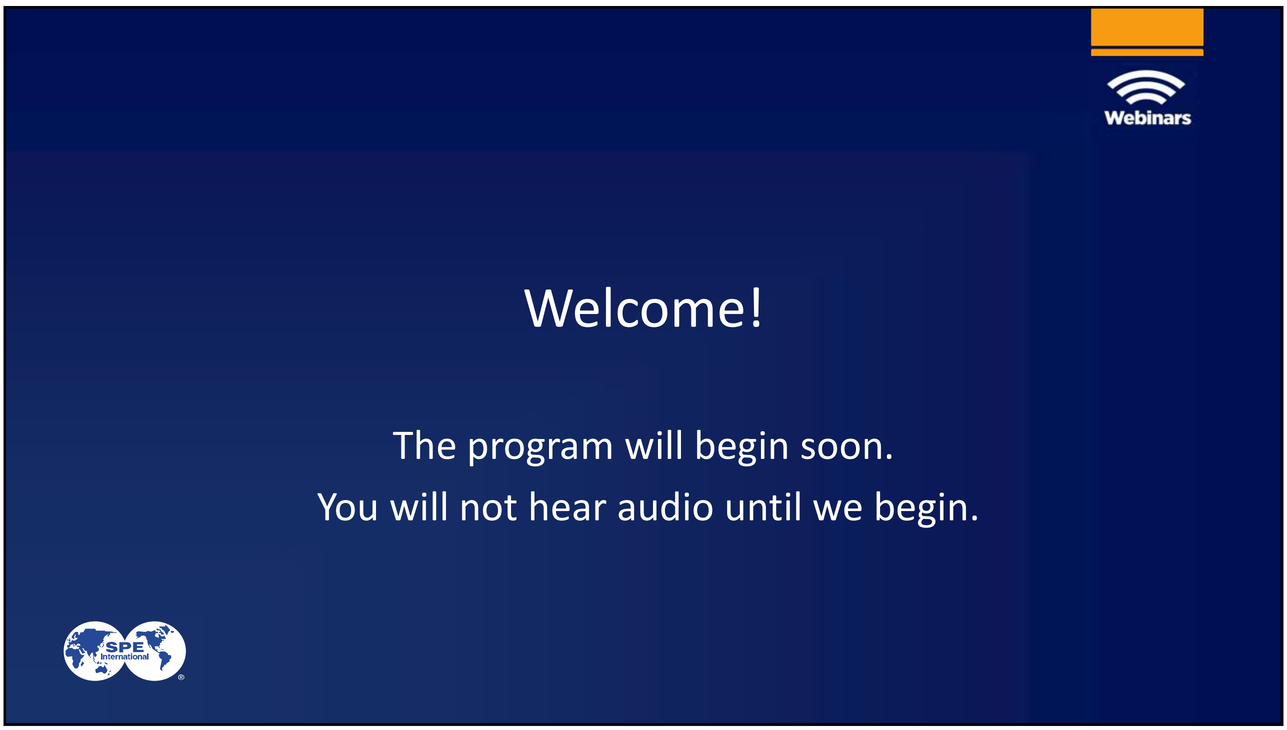
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SPE International

1

Design Considerations and Lessons Learned
in the application of
Intelligent Completions

Ron Nelson

29 June 2023

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Presentation Overview

Objectives

"Info share" to communicate intelligent completion designs, capabilities, and actionable recommendations to improve reliability and operability.

Topics

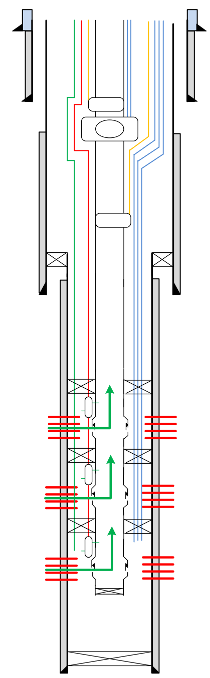
- What is an "intelligent" completion?
- Intelligent completion configurations.
- Sensor design and reliability.
- ICV designs: on-off, choking, hydraulic and electric.
- Design considerations and lessons learned.

Intelligent Completions

What is an "intelligent" completion?

- Flow from or to **two or more distinct intervals.**
- Like a "normal" well, is equipped with **downhole sensors** to provide real-time temperature and pressure data.
  - *Electronic pressure and temperature sensors are most common.*
  - *May deploy fibreoptic and/or other data sources; distributed acoustic and temperature sensing (DAS & DTS) are becoming more common.*
- In addition to sensors, an intelligent completion is equipped with **surface-controlled Interval Control Valves** (ICVs, aka Downhole Flow Control or DHFC) to control flow to or from each zone.

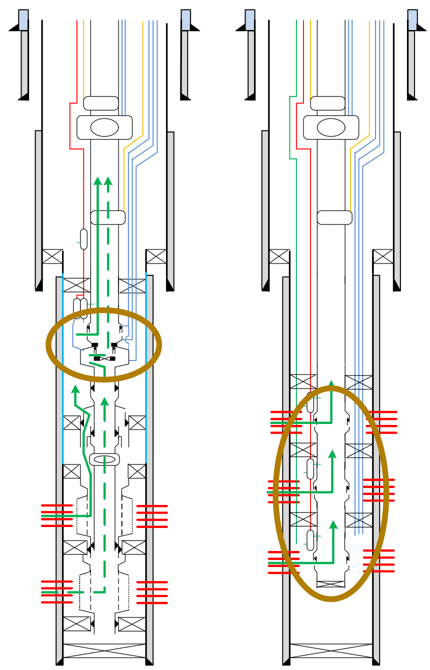
Downhole sensors provide data. The ICV provides the ability to act upon that data at any time, without the need for intervention.



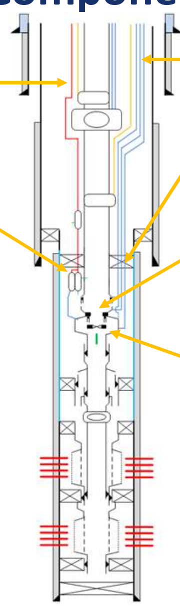
Deepwater Intelligent Completions

Often limited to two zones

- Most deepwater reservoir sands in GoM and West Africa require sand control.
- Sand screen IDs preclude most ICVs from being deployed across sand face, requiring them to be run above the reservoirs.
- Concentric flow paths limit number of ICVs that can be run.
  - *Downhole wet-mate connectors (hydraulic & electrical) can allow ICV integration into screens being deployed but most not (yet) "field-proven".*
- Typical deepwater two-zone intelligent completion on left, with two ICVs above reservoir intervals.
- Non- sand-control completion with multiple ICVs across reservoirs on right.



Intelligent Completion Components



Tubing Encapsulated Conductor (TEC) and/or fibre (TEF) for pressure & temperature (P/T) sensors

Pressure & Temperature Sensors
More to follow

Hydraulic lines for ICVs and SCSSV

Feed-Thru Production Packer
Allows ICV lines, TEC and TEF to pass

Upper (annulus to tubing) ICV
Controls flow from upper zone

Lower zone (tubing to tubing or "shrouded") ICV with diverter plug
Controls flow from lower zone

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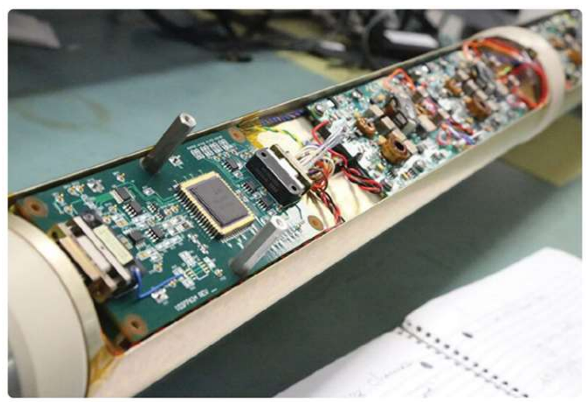
Downhole Sensors & Electronics

- Not all downhole gauges are alike – *do not treat these as "commodity items".*
- Differing electronics construction on the market: *PCB, Ceramic Hybrid, SOI, ASIC, MCM, etc.*
- Most gauge suppliers procure sensor from same supplier, so gauges of very different construction can have similar performance characteristics (accuracy, resolution, etc.)
- Downhole environment is hostile to electronics: heat, vibration, pressure, conductive fluids.
- Reliability needs to be a factor in our selection process (and don't rely on vendor-supplied run histories)



Printed circuit board assemblies on a wireline tool chassis. From "Downhole Electronic Components: Achieving Performance Reliability", JPT, July 31 2013.

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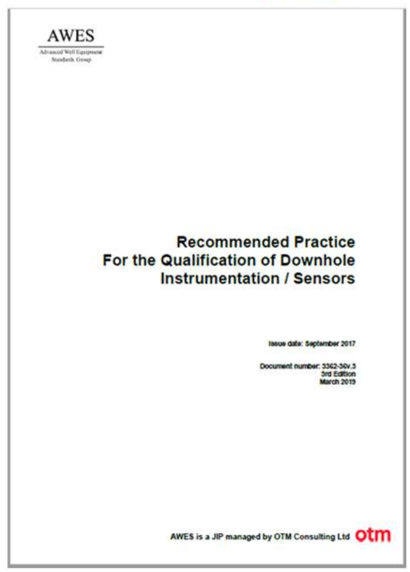
Accelerated Life Testing (ALT)

Webinars

- AWES RP 3362-36 widely used for gauge electronics validation.
- Accelerated lifetime testing (ALT) is an excellent tool for assessing electronics reliability (only):
  - *Does not assess TEC, connectors, splitter blocks, or any aspect of the system other than the electronics in the housing (great tool to assess electronics construction need for redundancy).*
- Electronics aging is a chemical process that accelerates predictably with warming, up to the temperature at which damage occurs.
  - *Predictable using Arrhenius equation*
  - *Life expectancy approximately doubles for every 10 deg C drop in temperature (2x 10 rule)*


AWES
Advanced Well Equipment Standards Group

Recommended Practice
For the Qualification of Downhole Instrumentation / Sensors

Issue date: September 2017

Document number: 3362-36v.3
3rd Edition
March 2019

AWES is a JIP managed by OTM Consulting Ltd otm

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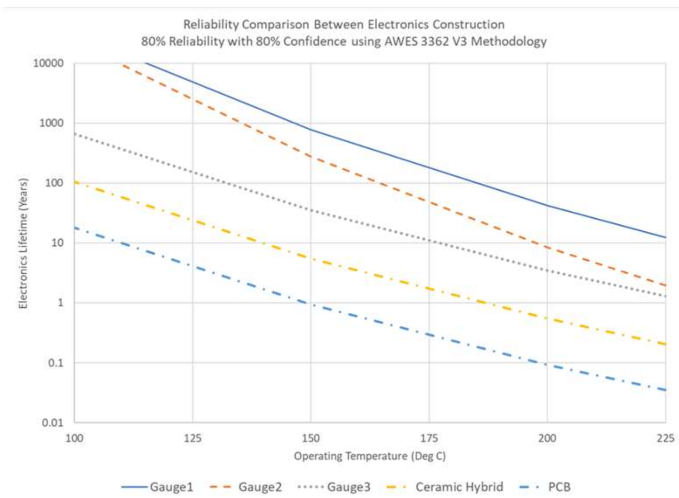
Accelerated Life Testing (ALT)

- When testing, populations of gauges are placed in ovens and operated for months or years at elevated, constant temperatures.
- Larger populations of gauges operated at higher temperatures for longer time periods yield greater statistical confidence for longer “in-well” operational lifetimes.
- Testing at multiple temperatures allows more accurate reliability calculation, including determination of “activation energy”, an important factor in ALT calculations.

Images courtesy of Baker Hughes

Relative Reliability



- ALT reliability predictions from five gauges of four differing construction types shown at left, using oven testing data and AWES methodology.
- Gauges 1, 2 and 3 are current offerings and include ASIC and MCM construction.

Conclusion*: modern gauge electronics are far more reliable than legacy offerings and if correctly built (ie, good QA) should meet most field's design life requirements*

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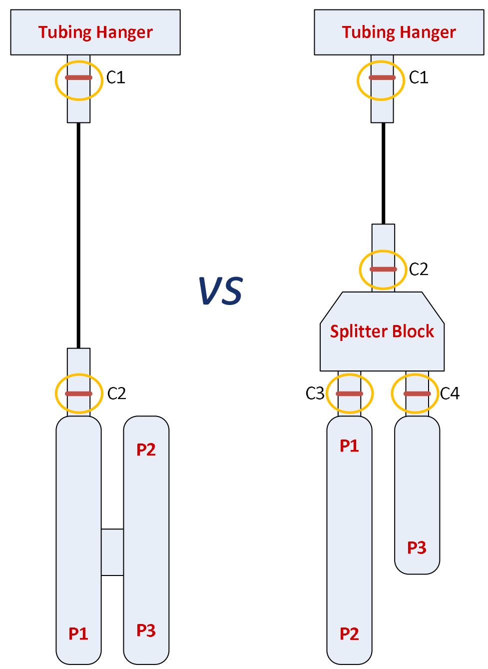
System Design & Reliability

- Given greatly improved electronics reliability, focus should now be on TEC and connectors.
- In most cases, a single TEC or connector failure will result in loss of ***all*** sensors on that line.
- Consider two commonly offered designs for triple sensor package: integrated triple vs dual & single with "splitter block".
- Triple (left) requires two dry-mate connectors, whereas dual + single and splitter requires four; *twice as many leak (failure) paths.*



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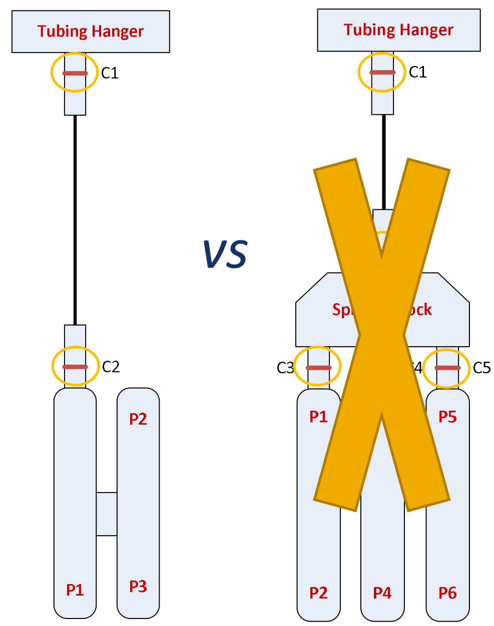
Sensor Reliability & Redundancy

Redundancy always feels better, right?

Consider impact of redundancy on required cable connections …

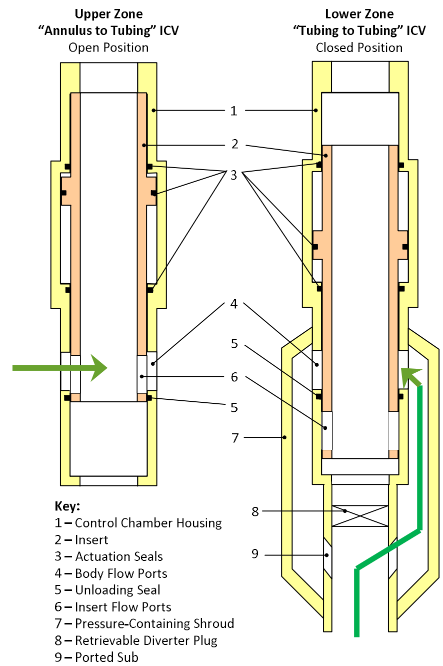
*In light of modern electronics reliability, and consequence of connector failure, is **system reliability** being enhanced by adding redundant sensors to a single TEC?*

Ron's suggestion: where redundancy is warranted, consider <u>full redundancy</u> including redundant TEC and connectors, and not just the sensors.



What is an ICV?

- Most Interval Control Valves (ICVs) similar to slickline sliding sleeves, except there is a piston on the "insert" (orange) to allow it to be pumped open and closed.
- Most common are "annulus to tubing" (left).
- For "tubing to tubing" flow up tubing from below, a "diverter plug" is used to divert flow into a pressure-containing "shroud" and across the valve.



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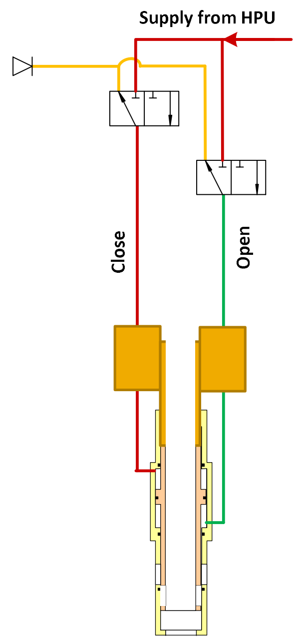
"On-Off" vs "Choking" ICV

- Simplest configuration is "on-off": one line pumps the ICV's "insert" open, the other pumps it closed.
- ICVs are typically equipped with erosion-resistant choke trim and can operate as chokes if partially opened.
- Virtually impossible to select a "choking" insert position by applying pressure pulses from surface, added downhole equipment required.
- Various solutions provided for choking: examples include "Stepper" that limits volume to valve from "open" line, "Accupulse" that limits volume from valve to "close" line, or lug & spring system similar to ballpoint pen.

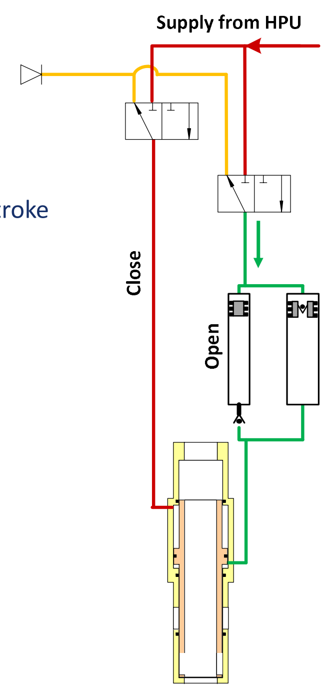


Choking ICV Operation

Example of one supplier's incrementing system at right.

Two pistons on "open" line immediately above ICV.

On first opening step, both pistons function and ICV sweeps about 50% of stroke and opens to #1 position.



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Choking ICV Operation

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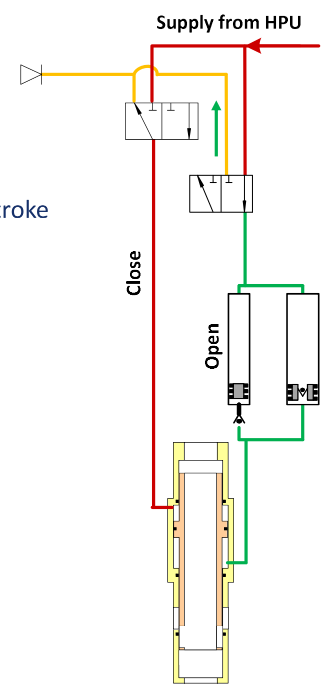
On first opening step, both pistons function and ICV sweeps about 50% of stroke and opens to #1 position.

Open line pressure is vented.

Only one piston is equipped with a spring (not shown) and once open line pressure is less than spring pressure, it re-sets (takes 15-30 minutes).



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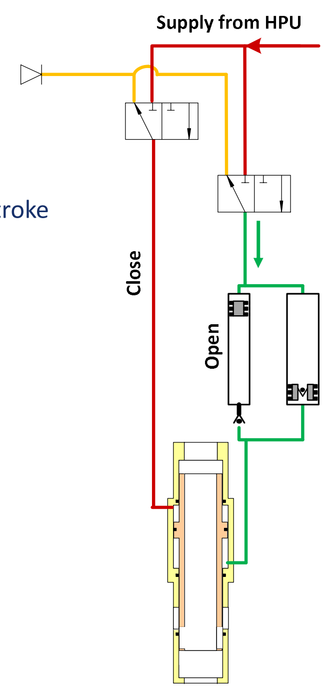
Next step only moves one piston and moves ~10% of remaining distance to Position #2.



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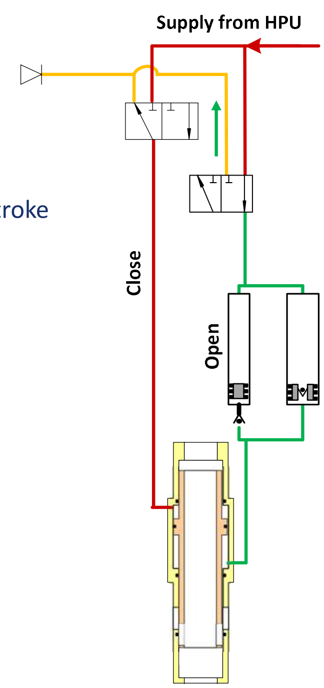

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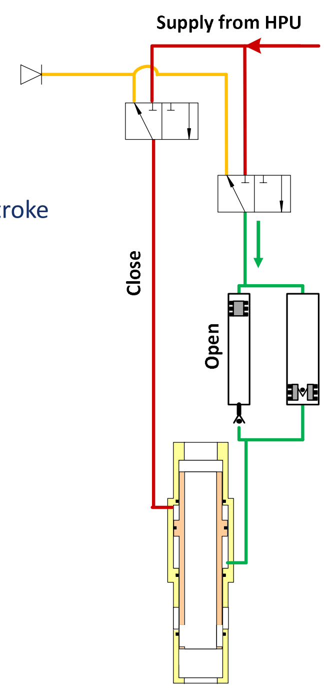
Step to Position #3.



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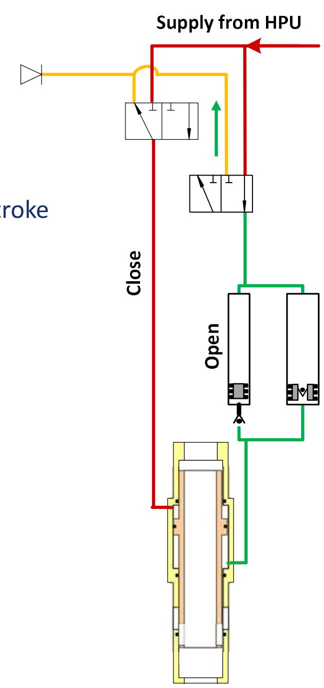

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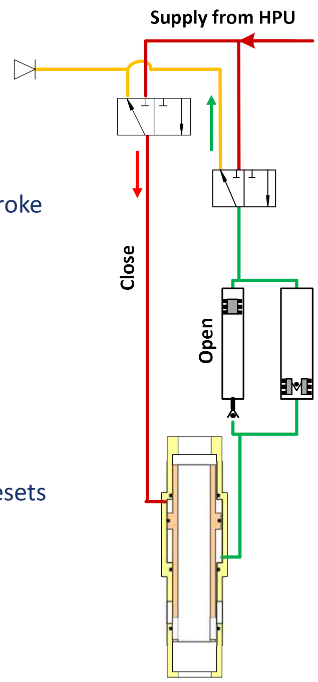
Step to Position #3. Vent open line pressure to reset the piston.

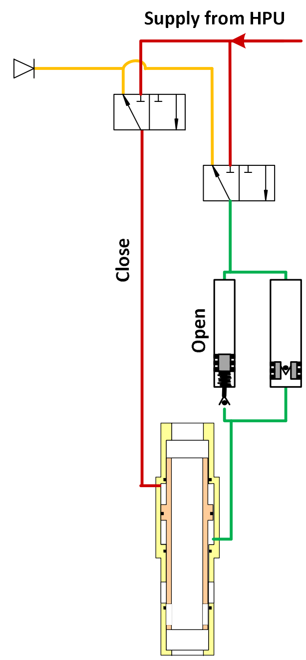
The ICV can be closed at any time. As the ICV shifts closed, displaced fluid resets the piston that lacks a spring and process is ready to be repeated.



Choking ICV Considerations

- Choking capability is limited, usually <1500 PSIG for continuous service.
- Slow to open: often 10-12 positions and each opening step can take 30-45 minutes.
- Hydraulic incrementing systems used to position the insert add complexity and require specific well conditions to reset and allow further opening.
- **With complexity comes risk**:
  - *Choking ICVs will have lower reliability than "on-off"*
  - *Many examples of choking ICVs that are stuck in undesired positions (often in smallest choke setting)*

Ron's suggestion: make "on-off" your default, and run choking ICVs only if justified by a robust business case and supported by thorough risk assessment.



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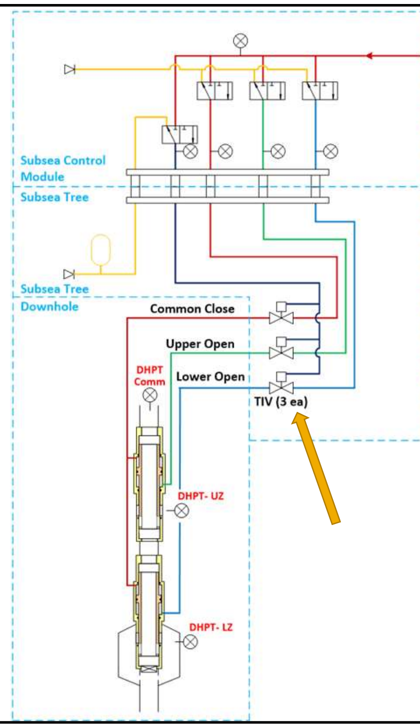
Thermally-Induced Pressure Changes

Important design consideration

- API Spec 17D (Specification for Subsea Wellhead and Tree Equipment) recommends that the Tree-mounted Isolation Valves (TIV) remain closed when not operating the ICV.
- With closed TIV, the **control lines are a closed system** and will behave similarly to casing annuli:

Line pressure will rise as the well warms and drop as the well cools.



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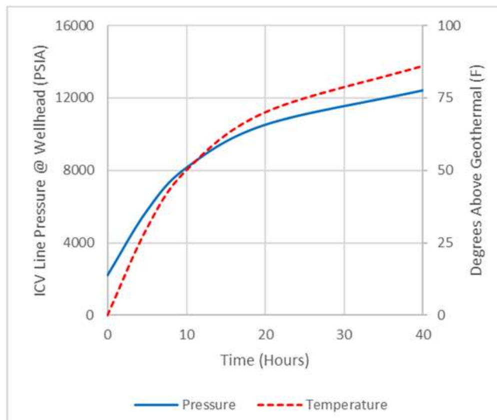
Thermally-Induced Pressure Changes

Well from US GoM:

- Well shut-in and cold, ICV lines in equilibrium with seawater hydrostatic (~2200 PSIA) when TIV are closed.
- Well started from cold and lines calculated to warm by ~94 deg F.
- If TIV remain closed from shut-in through warming, pressure in ICV control lines **will rise by over 10000 PSI** due to warming of the trapped line volume.
  - *Very similar to annular pressure build-up.*
- Pressure in lines may exceed tree rating and pose risk to controls components.
- Almost 22,000 PSIA in ICV control chamber (burst?)

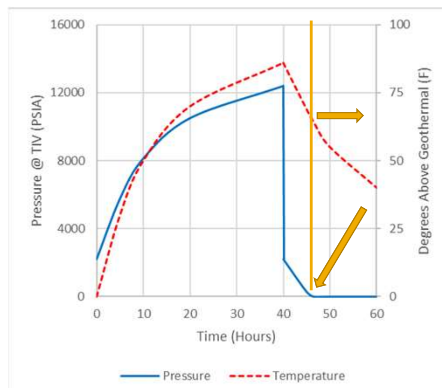


Thermally-Induced Pressure Changes

Well from US GoM (cont):

- If TIV are opened after heating, **pressure will vent and dump ~0.6 gal per line**. Lines again at seabed hydrostatic (2200 PSI) at the wellhead.
- TIV closed and well is shut-in. Well cools. Fluid in the lines will now contract.
- **Line pressure at the TIV drops** to the vapour pressure of the control fluid **(<1 PSIA)** and the fluid contact in the lines will drop several hundred feet below the wellhead.
- If the TIV are then opened, seawater will try to fill the void, entering and contaminating the control system and downhole lines.

Liquid continues to contract
Contact drops below wellhead



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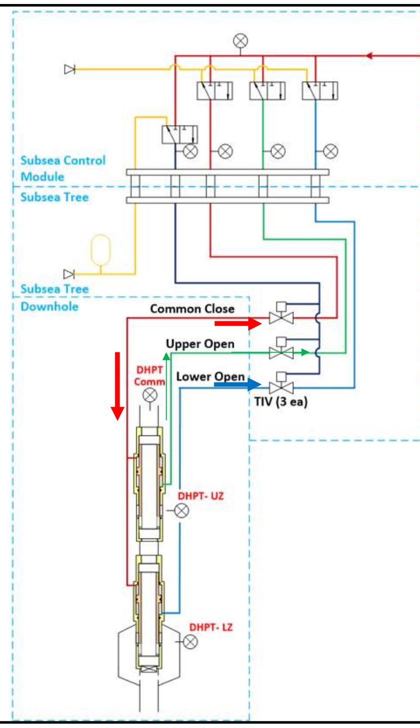
Uncommanded Shifts

Can impact well operations and interventions

- Uncommanded shifts, where ICVs move without applied control pressure, documented in many wells.
- Most due to temperature change and a single leaking TIV.
- Example:
  - *Well is flowed and warms.*
  - *Line pressures increase but TIV on Upper Open line leaks.*
  - *As well warms, Close pressure will exceed Upper Open pressure and Upper ICV will slowly close, as Close line volume is allowed to expand.*
- Uncommanded valve openings also occur and need to be considered in risk assessments.



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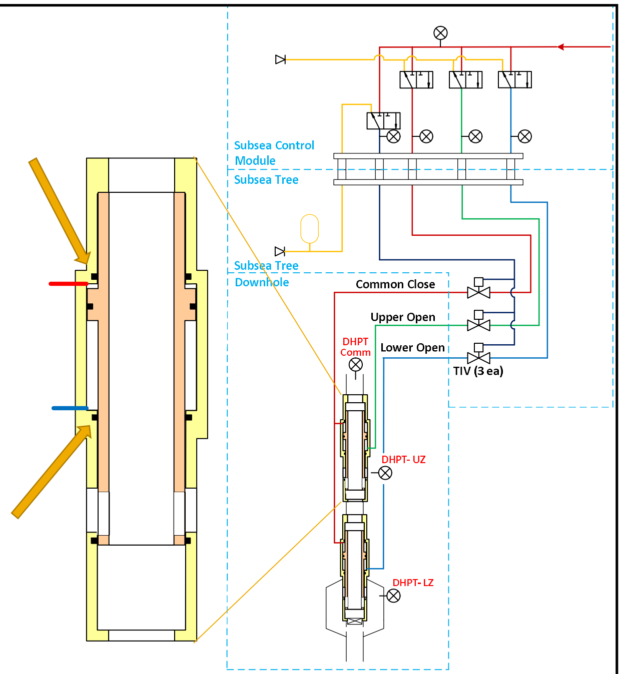
Control Chamber Seals

Another design consideration

- The control chamber seals isolate well fluids from the ICV hydraulic control fluid

  Are a primary barrier between well fluids and the environment (second barrier is TIV on tree).
- Few vendors have ever validated these seals to be bubble-tight: most validation had an acceptable pressure loss when gas testing.

  Not necessarily a leak, but an artifact of test fixture and method.
- Not all seals are equal: chevron vs metal spring energized (MSE), material types and hardness, surface finish, etc. *Some are more likely to seal than others.*



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Suggested Tree System Upgrades

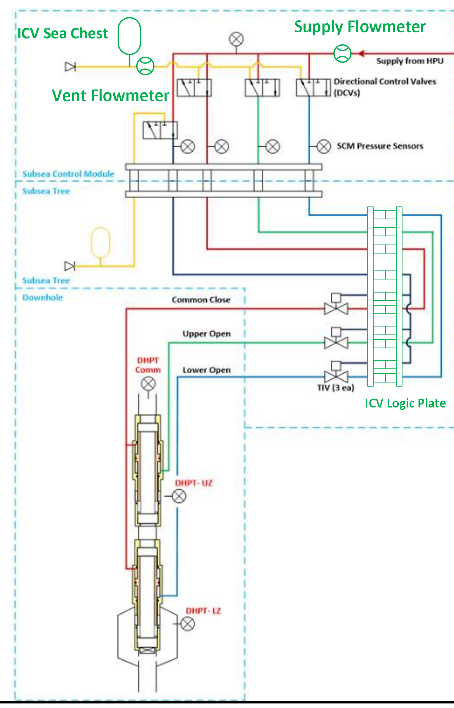
- Sea Chest (similar to accumulator with no pre-charge) on ICV vent line, to prevent seawater ingress after line cooling.

- Flow Meters (FMs) on supply and discharge, to confirm flow and quantify volumes.

  Discharge FM can be tricky and may not get good data at all flow rates. Suggest testing at SIT.

- Logic Plate to facilitate ROV intervention and troubleshooting without having to pull control module.

  Can also be used to install secondary barrier on line if ICV seals leak.



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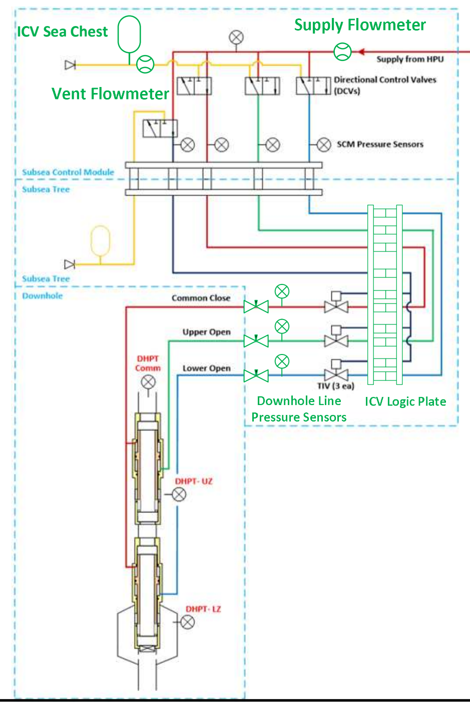
Suggested Tree System Upgrades

#1 Recommendation: pressure sensors between TIV and ICVs.

Previously not permitted by API Spec 17D but now allowed.

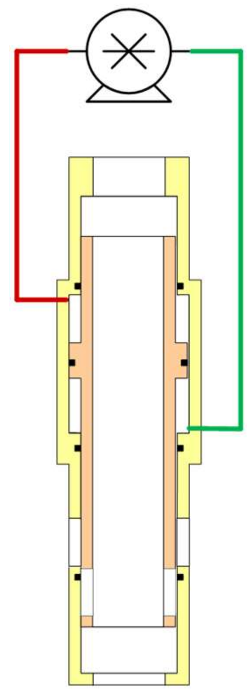
Placing outboard of tree-mounted needle valves enables easy compliance with API 17D and provides additional barrier if needed.

Powerful tool for monitoring system & barrier integrity and managing line pressures (not known without sensors).



Electro-Hydraulic & All-Electric ICVs

- Many suppliers developing (or have developed) electrically actuated ICVs.
  - *Can be a downhole pump(s) tied to the same field-proven hydraulic ICV (shown), or*
  - *A directly-linked motor that opens and closes the ICV.*
- Most designs use power and signal from TEC.
  - *Current draw may require a twisted pair TEC and non-standard wet-mates in subsea tree.*
  - *Some offerings use battery: limited life but eliminates need for cable contact.*
- Much complexity (not shown) with pressure compensation, electronics, etc.
- This technology has the potential to be transformative …



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Electric vs Hydraulic ICV

Benefits:

- *Eliminates control line leak paths;*
- *Eliminates thermal gain in control lines and associated burst loads and risk of uncommanded movement;*
- *No practical limit on number that can be run; 10-15 per TEC may be feasible;*
- *Easy enables highly accurate choking capability.*

Concerns:

- *Same concerns with electronics construction and reliability as gauges;*
- *Most examples of this technology not (yet) field proven;*
- *Far more complex than simple hydraulics;*
- *Wet-mates between subsea tree and tubing hanger have relatively high failure rate and are (at present) far less reliable than hydraulic couplers.*

Image courtesy of SLB

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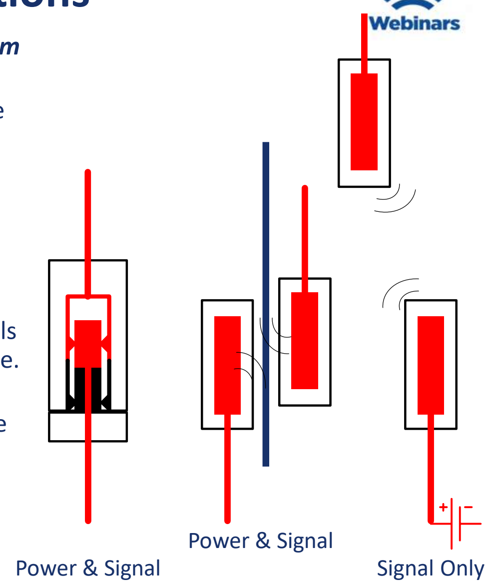
The Future of Intelligent Completions

Downhole power & communications "bridges" will transform our wells

- Downhole hydraulic and optical connectors will add value but are limited to either power or signal.
- Electrical connector technologies can do both power and signal and are likely to be transformative.
- Downhole conductive electrical connectors can allow sensors, arrays, and tools to be run in lower completions.
- Downhole inductive electrical connectors can allow the above, and also allow communication through casing walls and across lateral branches. Much better debris tolerance.
- Downhole acoustic electrical connectors can allow the above and can span great distances. They cannot provide power and their tools rely on batteries or another power source.



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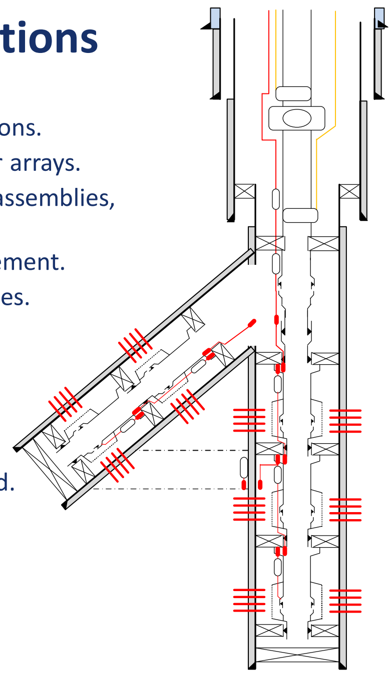
Possible Future(s) of Intelligent Completions

The Good

- Installation of sensors in new locations within (and outside) completions.
- Availability of highly granular data thru fibre & high-resolution sensor arrays.
- Electric ICVs will allow incorporation into lower completions, screen assemblies, and across multi-lateral branches.
- More sensors and ICVs can be run, providing better reservoir management.
- Potential elimination of downhole hydraulics and associated challenges.
- Possible to further reduce well counts and/or improve recovery.

The Challenges

- Greater consequence of single-point electrical failure.
- Subsea tree to tubing hanger interface remains a weak link.
- Massive data transfer, processing, interpretation and storage required.
- Complexity and reliability (?)



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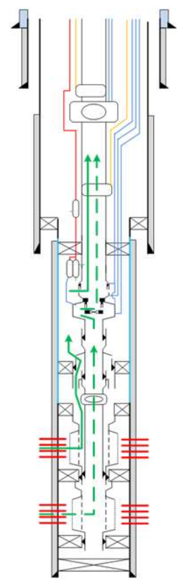
Intelligent Completion Design Recommendations

- Engineer a system, not a bunch of components.

  Recognize that the operating company is probably the only entity that understands the system as a whole.
- The subsea tree & control fluids are rarely optimized for an intelligent completion and require time to change; work these interfaces ASAP.
- Calculate thermally-induced line pressures and use these to help guide component selection and well operability.
- Follow the KISS principle.
- Document your wells' design limits and operating expectations / assumptions.
- Pre-plan and facilitate your contingency operations: where to anchor shifters, how to achieve depth control, how to cut mandrels, diverter plug recovery, etc.



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Intelligent Completion Execution

- Conduct SIT(s) with controls or any interface you're not 100% certain of.
- QA, QA, QA
- Cleanliness, Cleanliness, Cleanliness
- Employ best practices when handling, especially to minimize bending.
- Develop and employ detailed procedures thru which you can capture and apply learnings. Document in detail every step that's performed.
- Validate and document proper system function (sensors and ICVs) throughout the installation.

Intelligent Completion Assembly - Lift Rigging SIT

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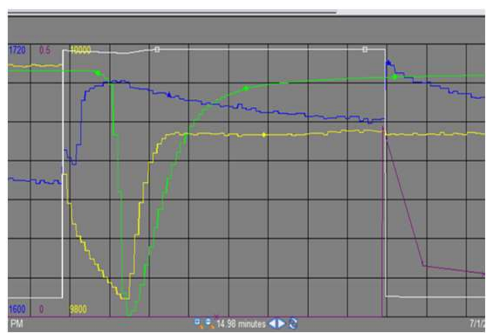
Intelligent Completion Operation

- Develop an operating manual. Use the operating manual.
- Train offshore operators prior to well start-up and ensure that training continues for new operators.
- Understand the well's design limits and operate within them (see above bullets).
- Make the controls interface as simple and intuitive as possible.
- Set-up protocols that limit how often the ICVs are functioned, and under what conditions.
- Store all applicable shifting data from well gauges and controls in high resolution (~1 second frequency) and use the data proactively.



Recorded data from controls and downhole sensors during ICV shift

Intelligent Completion Operation

#1 recommendation: ensure that ICVs are periodically functioned as recommended by suppliers.

- Usually same requirement as SCSSVs (function every 6 months) for same reason.
- Fear of operating an ICV "in case it gets stuck" often self-fulfilling if left static for years.

Image courtesy of Halliburton

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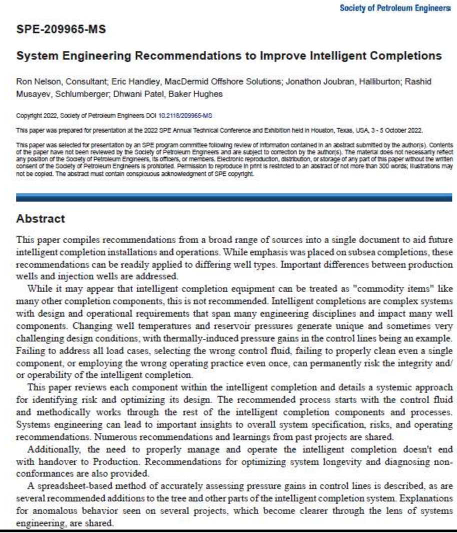
Additional Reading

- API Spec 19 ICV (to be released), Interval Control Valves
- AWES 3362-36, Recommended Practice For the Qualification of Downhole Instrumentation / Sensors
- SPE-209965-MS, System Engineering Recommendations to Improve Intelligent Completions
- SPE-196231-MS, Application of Multizone Water Injection Downhole Flow Control Completions with Fibre-Optic Surveillance in Soft Sand Reservoirs



SPE-209965-MS

System Engineering Recommendations to Improve Intelligent Completions

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This paper was prepared for presentation at the 2022 SPE Annual Technical Conference and Exhibition held in Houston, Texas, USA, 3 - 5 October 2022.

Abstract

This paper compiles recommendations from a broad range of sources into a single document to aid future intelligent completion installations and operations. While emphasis was placed on subsea completions, these recommendations can be readily applied to differing well types. Important differences between production wells and injection wells are addressed.

While it may appear that intelligent completion equipment can be treated as "commodity items" like many other completion components, this is not recommended. Intelligent completions are complex systems with design and operational requirements that span many engineering disciplines and impact many well components. Changing well temperatures and reservoir pressures generate unique and sometimes very challenging design conditions, with thermally-induced pressure gains in the control lines being an example. Failing to address all load cases, selecting the wrong control fluid, failing to properly clean even a single component, or employing the wrong operating practice even once, can permanently risk the integrity and/or operability of the intelligent completion.

This paper reviews each component within the intelligent completion and details a systemic approach for identifying risk and optimizing its design. The recommended process starts with the control fluid and methodically works through the rest of the intelligent completion components and processes. Systems engineering can lead to important insights to overall system specification, risks, and operating recommendations. Numerous recommendations and learnings from past projects are shared.

Additionally, the need to properly manage and operate the intelligent completion doesn't end with handover to Production. Recommendations for optimizing system longevity and diagnosing non-conformances are also provided.

A spreadsheet-based method of accurately assessing pressure gains in control lines is described, as are several recommended additions to the tree and other parts of the intelligent completion system. Explanations for anomalous behavior seen on several projects, which become clearer through the lens of systems engineering, are shared.

Final Slide – Wrap-up

Webinars

Biggest lesson from past projects:

Success requires **systems-wide understanding** and cross-discipline **communication**

My sincere thanks to employers and colleagues on current and past projects, and to the intelligent completion equipment suppliers who've so freely shared their time and knowledge

Questions, concerns, or comments?

You're welcome to contact me at

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