ConocoPhillips

Fitness for Service of Casing materials for sour service

Challenges when operating existing wells under souring conditions in mature fields.

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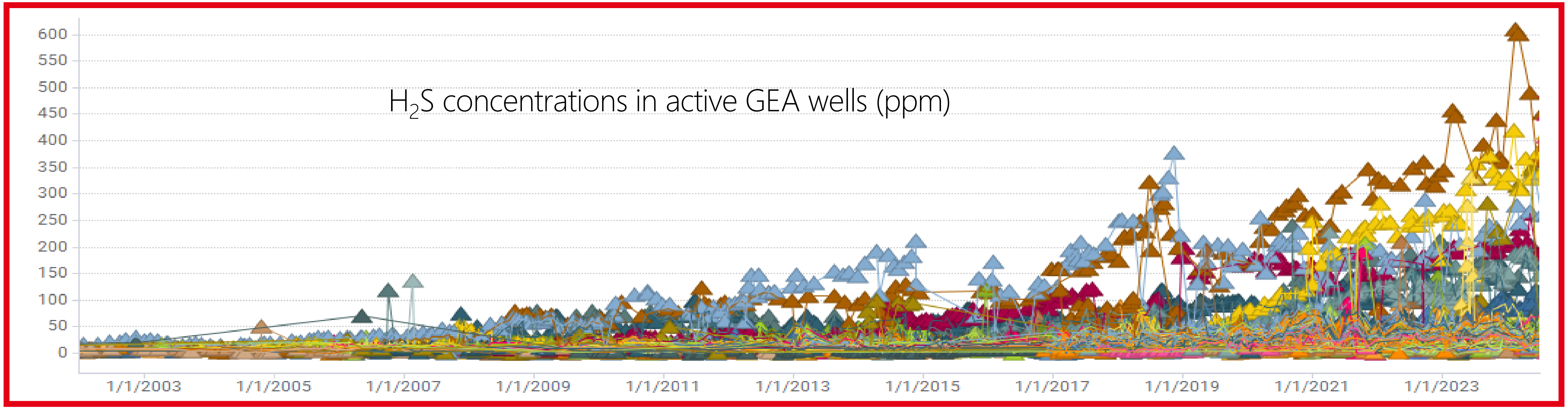
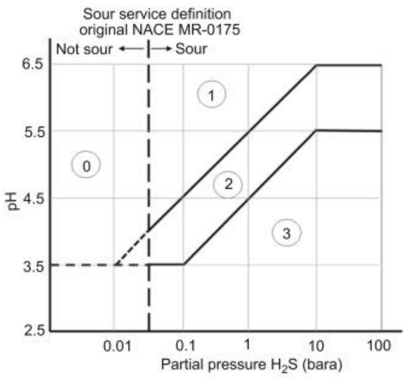
Mature Fields and H_2S

- ConocoPhillips has been operating in the Greater Ekofisk Area (GEA) since 1969
- H_2S was not an issue during early field life
- High H_2S levels was not expected, so early well design did not include sour-service requirements
- In-reservoir H_2S generation can be a very slow process
- Ekofisk seawater injection began in the late 1980s, H_2S concentrations became a challenge 25 years later

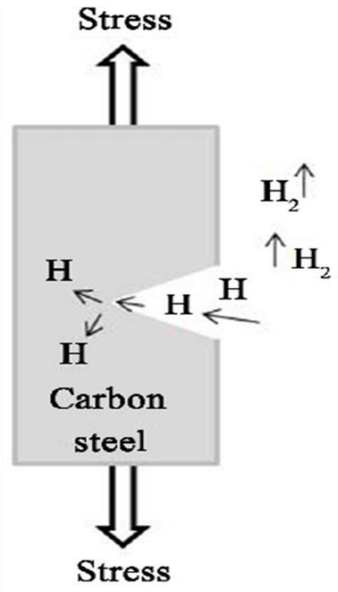


Recent H_2S Activity and Challenges in GEA

- An isolated case of highly-increased H_2S concentrations occurred during Eldfisk S operations in 2018. Downhole conditions (temperature, sulfate supply) were optimal for SRB activity. Mechanism was outside of the normal generation process.
- This incident prompted a significant emphasis on managing H2S.
- Discovered that even wells with relatively low H_2S concentrations could end up with elevated risk for equipment failure in several operational phases.



SSC-induced failure in casing couplings



H_2S: Operational Issues and Well Integrity Challenges

- No special sour-service requirement for well components existed for wells prior to changes made in our "bases of design" in 2020-21.
- Most of our active wells were designed and built before this revision
- One of our field has lift gas that contains some H_2S, this gave us additional challenges
- Secondary barrier envelope identified to be the main concern
- Discovered that the most challenging condition was during pumping operations and longer "shut-in" periods, due to lower temperature
- Material H_2S tolerance tends to increase at higher temperatures (i.e. production) and in most cases is non existing above a certain temperature

Historic Well design

- Primary Barrier

0.5 psi	17/4 PH	0.5 psi partial pressure limit
	17/4 PH	0.5 psi partial pressure limit
	K-500 (Monel)	0.5 psi partial pressure limit
	K-500 (Monel)	0.5 psi partial pressure limit
	316SS	Below 60°C and below 50ppm chloride: H2S tolerance is 0.5 psi partial pressure. Not qualified above these values
1.5 psi	13Cr L80	1.5 psi partial pressure limit
	F6MN	1.5 psi partial pressure limit

- Secondary Barrier

0.05 psi	Q125	Below **107°C**: 0.05 psi partial pressure. Unlimited above this temperature.
	P110	Below **80°C**: 0.05 psi partial pressure. Unlimited above this temperature.
	D-95 HC	Below **80°C**: 0.05 psi partial pressure. Unlimited above this temperature.
	N80	Below **80°C**: 0.05 psi partial pressure. Unlimited above this temperature.
	N80 Type Q	Below **65°C**: 0.05 psi partial pressure. Unlimited above this temperature.

Strategy for improving H_2S operability

- Build an improved monitoring tool and update/make improved procedures
- Revise well design steering documentation
- Documentation of well equipment
- Deviations with compensating measures
- Increase safe operating window to eliminate deviations and restrictions

NORSOK D-010:2021+AC2:2021

5.2.3 Well barrier requirements

5.2.3.1 Minimum number of well barrier envelopes in well construction-, production / injection-phases and after permanent P&A

The general principle is to operate with two defined well barrier envelopes against over-pressure and/or flow potential. Table 1 below states the minimum number of well barriers required for the different life-cycle phases for a well.

5.2.3.2 Well barrier selection and construction principles

The well barrier envelope shall consist of qualified WBEs, and be designed and constructed with the capability to:

a) withstand the maximum differential pressure and temperature it can be exposed to (accounting for depletion or injection regimes in adjacent wells);

b) be leak tested, function tested or verified by other methods;

c) ensure that no single failure of a well barrier or WBE can lead to uncontrolled release of formation fluids and well fluids throughout the life cycle of a well;

d) re-establish a failed well barrier or establish another alternative well barrier;

e) operate competently and withstand the environment for which it can be exposed to for its intended service life;

f) be independent of other well barrier envelopes and avoid having common WBEs to the extent possible.

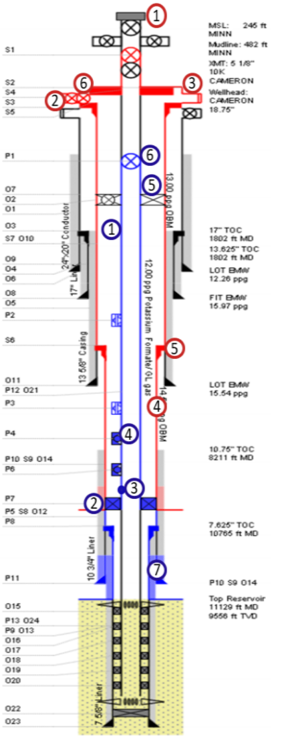
GEA H_2S Monitoring

- Multidisciplinary H_2S group established to create new procedures and tools
- Sour service dashboard created for scalable overview of H_2S picture, from field-wide to test-specific per well
- Detailed data and calculations are displayed and mapped in configurable monitoring system
- Produced H_2S levels measured by sampling at test separator
- Gas lift system has continuous H_2S monitoring

Revised well design to make new wells more robust.

- Updated our bases of design to meet the changed well conditions in our fields
  - New design criteria with respect to H2S tolerance:
    - Primary barrier envelope: 1,5 Partial pressure
    - Secondary barrier envelope : Unlimited Partial pressure

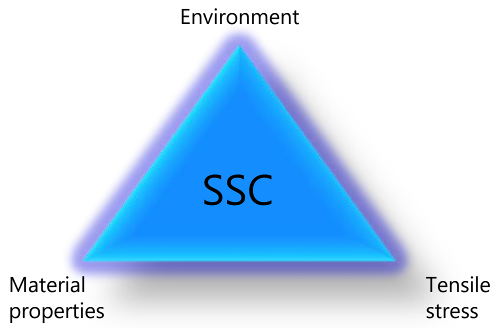
Primary elements	H_2S PP limit Old design	H_2S min. PP limit 6489 improved	Comment
1. Tubing	1.5 psi	1.5 psi	No change
2. Production Packer	1.5 psi	1.5 psi	No change (QAQC: 110 ksi)
3. DHPG/ mandrel	1.5 psi	1.5 psi	No change
4. SPM	1.5 psi	1.5 psi	No change
4. GLV, Dummies	0.5 psi	1.5 psi	17/4 PH/K-500 -> 13%Cr /Inc.718
5. ASV	1.5 psi	1.5 psi	No change
6. DHSV	3.0 psi	3.0 psi	No change
7. Deep Liners (barriers)	0.05 psi (stim)	Unlimited	Q-125 -> TN110SS / L-80
Secondary elements			
1. XMT/spool piece	1.5 psi	Unlimited	Body: F6NM replaced with low alloy CS + 625 full clad Valve internals: F6NM replaced with Nickel alloys
2. WH /valves	1.5 psi	Unlimited	Body: No change Pack off: F6NM-> Nickel alloys Valve internals: F6NM replaced with Nickel alloys
3. VR plug	Unlimited	Unlimited	No change
4. 10-¾ Liner	0.435 psi	Unlimited	TN125 SS connections-> 110SS connections
5. 10-¾ Liner Hanger (Vflex)	0.435 psi	Unlimited*	110 -> 80 ksi , * > 38 deg C
6. HASCV	0.5 psi	Unlimited	Monel K-500 -> Inc. 718



- New requirements for documentation (DFO) on equipment to be implemented to ensure “in house” availability of key information an all our barrier elements during the well's lifetime.

H_2S: Operational Issues and Well Integrity Challenges

- Each well has hundreds of components which may be exposed to H_2S
- Identifying and classifying these components is a major task
- Components in barrier envelopes have the highest priority
- Operating limits are set in place for production (e.g. H_2S partial pressures in gas lift)
- Deviations with mitigating measures are in place where barrier elements are at risk
- Wells are individually re-assessed before interventions

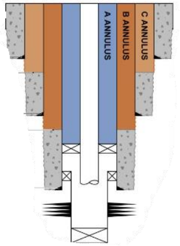


Costly compensating measures

- Plug setting to protect tubulars during shut in e.g., periodically maintenance shutdowns

- Reduced gaslift pressure

- GLV replacements before pumping operations and shut-in



- Liquid filling of annulus before pumping operations

- Use of scavenger to protect tubulars and other equipment during shut in and pumping

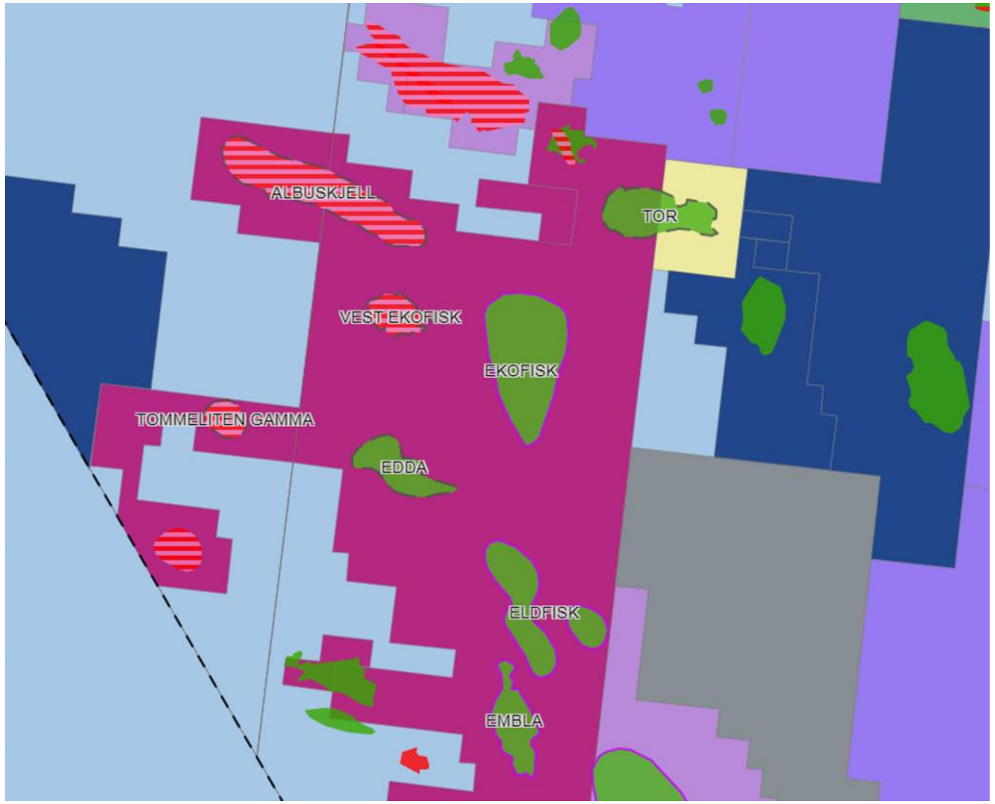
- Interventions needed for several of the compensating measures
  - Drives risk by itself
  - Costly
  - less value-added interventions

Material testing

- Increase safe operating window to be able to understand risk and minimize need for deviations and restrictions

  - Requalification of materials by laboratory testing is an effective way to raise limits

    - GEA is especially well-suited for material-testing technique
    - Consistent materials and field conditions
    - Straightforward method and application
    - Rapid results and implementation (2-4 months)
    - Very low cost compared to benefits

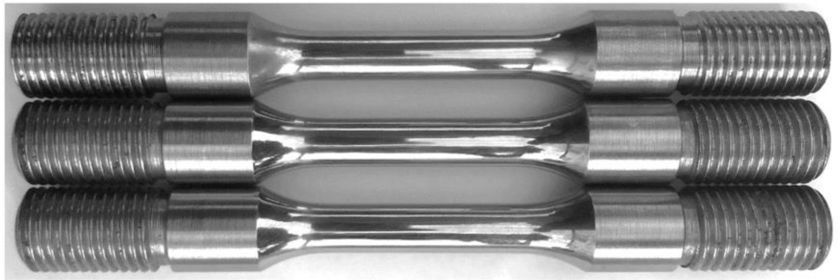


Re-certification of materials for sour service

- Current pH_2S limits assume lowest material quality and least-favourable operating conditions
- Material-specific pH_2S limits may be increased by method defined in ISO-15156, Annex B
- Minimum of 9 tests required to recertify each material and condition (3 heats x 3 samples) Samples must represent the upper end of hardness range for each grad
- A single tensile failure on any sample/heat disqualifies a given condition
- Results apply to all casing, liner and tubing materials in each grade
- Higher material hardness = Lower H_2S tolerance

Pre-testing pH_2S limits for carbon steels

Material	Default limit: H_2S partial pressure	Conditions
Q-125	0.05 psi (Temp-dependent)	Unlimited above **107°C,** 0.05 psi below
P-110		Unlimited above **80°C,** 0.05 psi below
D-95 HC		Unlimited above **80°C,** 0.05 psi below
N-80		Unlimited above **80°C,** 0.05 psi below
C-95		Unlimited above **65°C,** 0.05 psi below
N-80 Type Q		Unlimited above **65°C,** 0.05 psi below



Standard NACE TM0177-A tensiles

Background: Material Testing

- Review available material certificates and identify most susceptible materials based on hardness/strength
- Start test program with most susceptible material, test three parallels and expand to two more materials if a pass is obtained.
- Increase or reduce severity to identify safe operational envelope for the subject materials based on test result outcome.

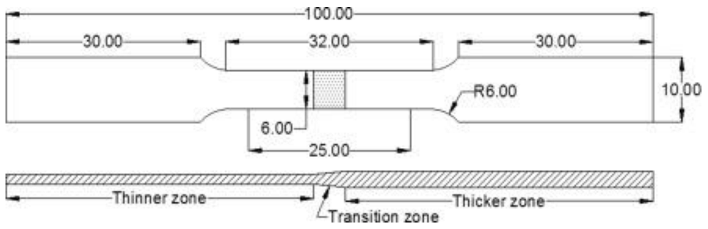
- Testing method is defined in ISO 15156-2 standard for use of carbon steels in H2S-containing environments

Annex B
(normative)

Qualification of carbon and low-alloy steels for H_2S service by laboratory testing

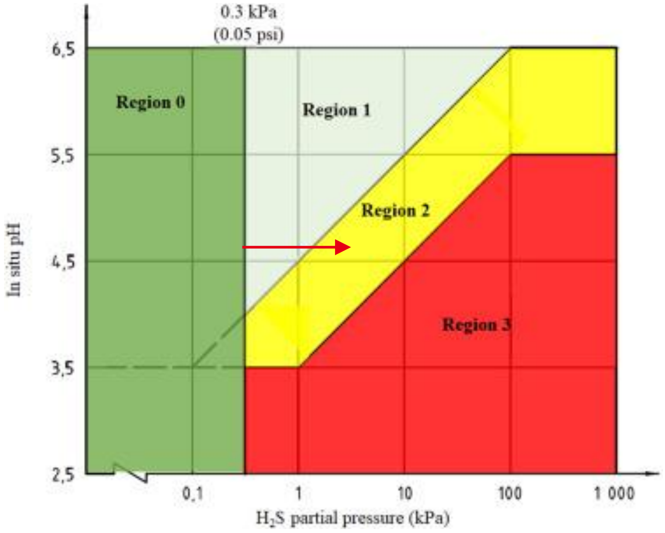
B.1 Requirements

This annex specifies requirements for qualifying carbon and low-alloy steels for H_2S service by laboratory testing. Requirements are given for qualifying resistance to the following cracking mechanisms.



SSC testing using
NACE TM0177 Method A specification

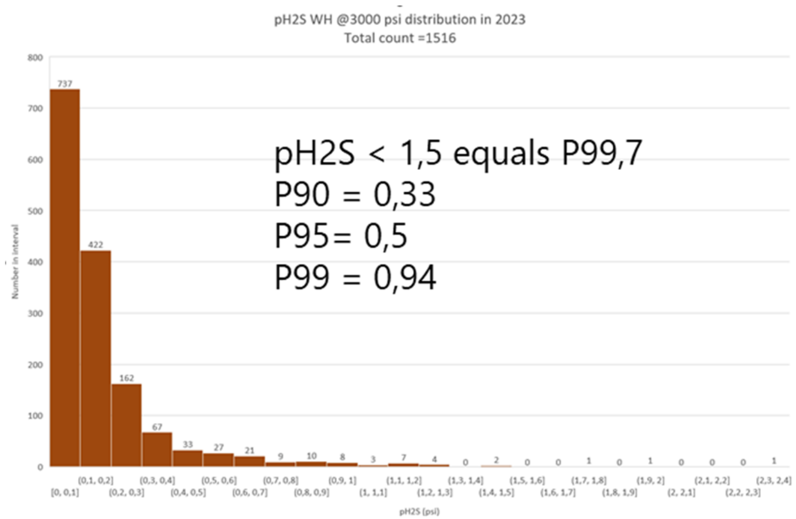
Goal to move current limit given by ISO 15156-2 diagram to the right for a given pH (red arrow)

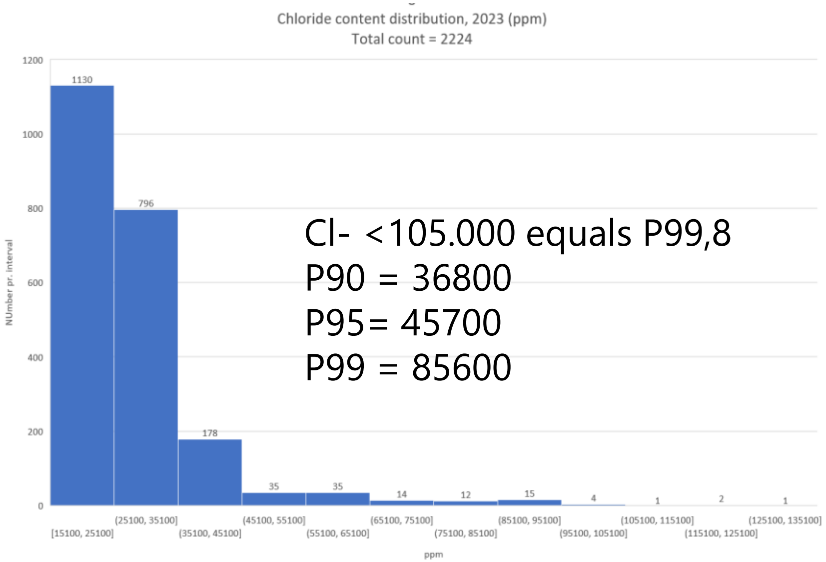


SSC Testing: P110 and Q125

Begin testing with most-vulnerable materials under worst-case conditions for GEA

- Demonstrate that GEA downhole environment is consistent and well-monitored
- Set testing conditions to cover entire field (P99.7+)





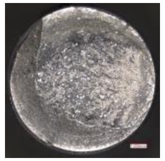
SSC testing results

Phase 1, intial conditions

Material	Material details	Axial (%SMYS)	pH2S (psi)	pH2S (kPa)	Time to failure (days)	Final pH	Days on test
P110	10.3/4" x 55.5 PPF Heat No. 81362 P110-PSL3	50	0,5	3,45	NA	4,1	Satisfactory
					NA	4,14	Satisfactory
					NA	3,98	Satisfactory
		76,5	0,5	3,45	NA	4,54	Satisfactory
					NA	4,59	Satisfactory
					NA	4,51	Satisfactory
		50	1	6,9	NA	4,34	Satisfactory
					NA	4,04	Satisfactory
					NA	3,91	Satisfactory
		76,5	1	6,9	NA	4,34	Satisfactory
					NA	4,46	Satisfactory
					NA	4,58	Satisfactory
Q125	5" x 23.2 PPF Heat No. 234444 Q125-Type 1	50	0,5	3,45	NA	4,37	Satisfactory
					NA	4,36	Satisfactory
					13	3,98	
		76,5	0,5	3,45	7	4,08	
					20	4,58	
					8	4,24	
		50	1	6,9	28	4,55	
					NA	4,28	Satisfactory
					13	4,13	
		76,5	1	6,9	8	4,12	
					6	3,94	
					6	4,1	

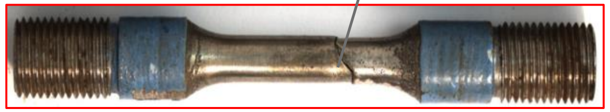
Phase 2, two more P110 at 1 psi and redo Q125 at reduced pH2S

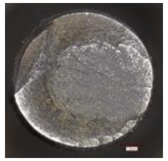
Material	Material details	Axial (%SMYS)	pH2S (psi)	Time to failure (days)	Final pH	Days on test
P110	10.3/4" x 55.5 PPF Heat No. 81362 P110-PSL3	50	1,5	NA	4,48	PASS
				NA	4,5	PASS
				NA	4,41	PASS
		76,5	1,5	NA	4,49	PASS
				NA	4,48	PASS
				13	4,27	Failed
	9.7/8" x 68.38 PPF Heat No. 97819 P110-PSL3	76,5	1	NA	4,57	PASS
				NA	4,51	PASS
				NA	4,49	PASS
	10.3/4" x 55.5 PPF Heat No. 18310 P110-PSL3	76,5	1	NA	4,59	PASS
				NA	4,6	PASS
				NA	4,6	PASS
Q125	5" x 23.2 PPF Heat No. 23444 Q125-PSL3	50	0,1	NA	4,41	PASS
				NA	4,51	PASS
				NA	4,46	PASS
		76,5	0,1	NA	4,52	PASS
				NA	4,57	PASS
				NA	4,6	PASS
		50	0,25	NA	4,56	PASS
				NA	4,58	PASS
				NA	4,55	PASS
		76,5	0,25	15	4,3	Failed
				NA	4,58	PASS
				NA	4,55	PASS



Phase 3, two more P110 at 1,5 psi and two more Q125 at 0,1 psi

Material	Material details	Axial (%SMYS)	pH2S (psi)	Time to failure (days)	Final pH	Days on test
P110	10.3/4" x 55.5 PPF Heat No. 81362 P110-PSL3	50	1,5	NA	4,48	PASS
				NA	4,50	PASS
				NA	4,41	PASS
		76,5	1,5	NA	4,49	PASS
				NA	4,48	PASS
				13	4,27	Failed
	9.7/8" x 68.38 PPF Heat No. 97819 P110-PSL3	76,5	1	NA	4,57	PASS
				NA	4,51	PASS
				NA	4,49	PASS
	10.3/4" x 55.5 PPF Heat No. 18310 P110-PSL3	76,5	1	NA	4,59	PASS
				NA	4,60	PASS
				NA	4,60	PASS
Q125	5" x 23.2 PPF Heat No. 23444 Q125-PSL3	50	0,1	NA	4,41	PASS
				NA	4,51	PASS
				NA	4,46	PASS
		76,5	0,1	NA	4,52	PASS
				NA	4,57	PASS
				NA	4,60	PASS
		50	0,25	NA	4,56	PASS
				NA	4,58	PASS
				NA	4,55	PASS
		76,5	0,25	15	4,30	Failed
				NA	4,58	PASS
				NA	4,55	PASS
	5" x 23.2 PPF Heat No. 39265 Q125-PSL3	76,5	0,1	NA	4,67	PASS
				NA	4,64	PASS
				NA	4,74	PASS
	5-4.3/4" x 23.2 PPF Heat No. 79103	76,5	0,1	NA	4,64	PASS
				NA	4,56	PASS
				NA	4,72	PASS





Increased H2S partial-pressure limits for casing materials

Results

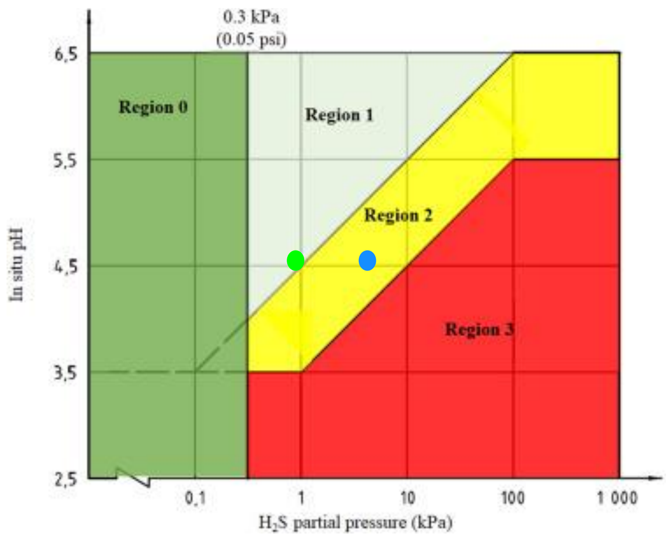
- P110 certified to 1.0 psi pH_2S at all temperatures to maximum design stress
  - *20X increase from pre-test limit*
- Q125 passed testing to 0.1 psi pH_2S at all temperatures to maximum design stress

Current testing activity

- Q125 final certification
- Elevated-temperature testing (Q125 at 50 °C)

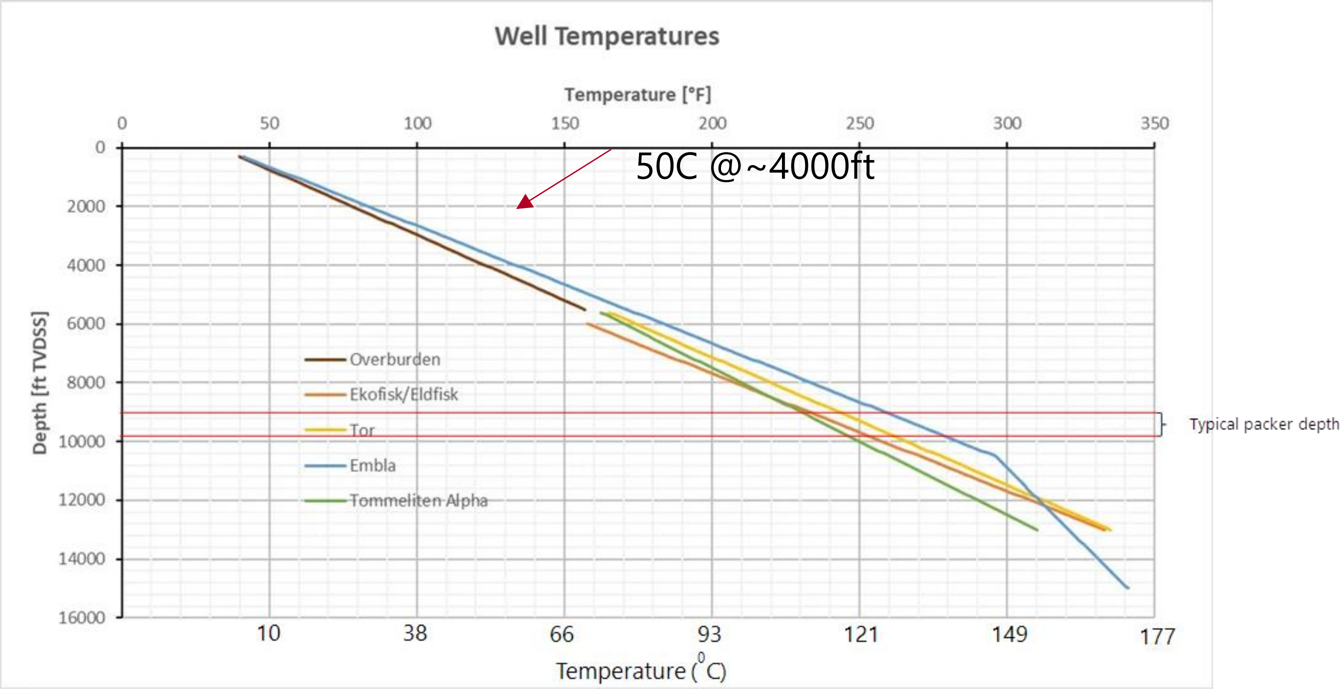
Qualified limit, H_2S partial pressure	Material Grade	Pre-Testing Limit (ISO 15156-2, Table A.3)	Post-Testing Limit (Annex B procedure)	Ongoing and Potential Further Testing
0.05 psi	Q125	0.05 psi below **107°C**	**0.1 psi @ all temps**	In progress: 0.25 / 0.5 psi @ >50 °C
	P110	Below **80°C**	**1.0 psi @ all temps**	1.5+ psi @ elevated temp
	D95-HC	Below **80°C**	Pending	Material is out of production May require P&A retrieval
	N80	Below **80°C**	Pending	Sourcing from P&A and supplier's global operations
	N80 Type Q	Below **65°C**	Pending	Available for testing

New limits in ISO 15156-2 diagram for P110 and Q125



Ongoing and Potential Further Testing Work

- Elevated-temperature tests (ongoing for Q-125)
- Requalification tests for more materials (e.g. N80, proprietary material grades)
- High-pressure SSC testing to certify EPP factor



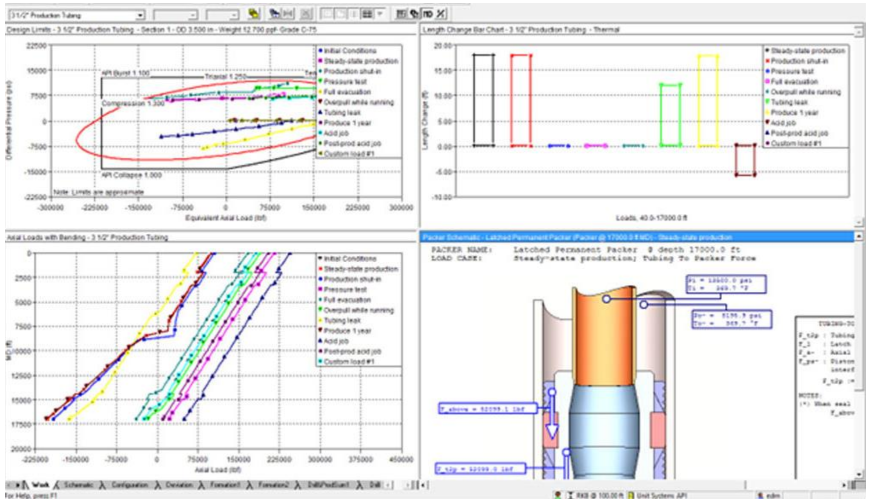
Q125 Casings
(Excluding liner elements isolated below packer depth)

	Installation	Casing Size	Grade	Csg Top (ft)	Top Temp (°C)	
1		11 3/4"	Q125	55	2	DEVIATION
2		11 3/4"	Q125	55	2	
3		11 3/4"	Q125	59	2	
4		11 3/4"	Q125	61	2	
5		11 3/4"	Q125	152	2	
6		13 5/8"	Q125	163	2	
7		13 5/8"	Q125	190	2	
8		11 3/4"	Q125	2462	21	
9		11 3/4"	Q125	3236	32	
10		7 3/4"	Q125	4852	54	NO DEVIATION
11		10 3/4"	Q125	4892	55	
12		10 3/4"	Q125	5446	62	
13		11 3/4"	Q125	5634	65	
14		9 5/8" x 9 7/8"	Q125	5920	69	
15		9 5/8" x 9 7/8"	Q125	6613	79	
16		9 5/8"	Q125	6743	80	
17		9 5/8" x 9 7/8"	Q125	6806	81	
18		9 5/8"	Q125	7027	84	
19		9 5/8" x 9 7/8"	Q125	7066	85	
20		9 5/8" x 9 7/8"	Q125	7751	94	
21		9 7/8"	Q125	7817	95	
23		9 5/8" x 9 7/8" x 10 3/4"	Q125	7934	97	
24		9 5/8" x 9 7/8"	Q125	8048	98	
25		9 5/8" x 10 3/4"	Q125	8075	99	
26		9 5/8" x 9 7/8" x 10 3/4"	Q125	8267	101	
27		9 5/8" x 9 7/8"	Q125	8300	102	
28		9 5/8"	Q125	8302	102	
29		9 5/8" x 9 7/8"	Q125	8861	110	
30		9 5/8" x 9 7/8" x 10 3/4"	Q125	8949	111	
31		9 7/8"	Q125	9204	115	
32		9 5/8"	Q125	9310	116	
33		9 5/8" x 9 7/8" x 10 3/4"	Q125	9405	117	
34		9 7/8" x 10 3/4"	Q125	9425	118	
35		9 5/8" x 9 7/8" x 10 3/4"	Q125	9725	122	
36		9 5/8" x 9 7/8"	Q125	9842	123	
37		9 5/8" x 9 7/8"	Q125	9870	124	
38		9 5/8" x 9 7/8"	Q125	9981	125	
39		9 5/8" x 9 7/8" x 10 3/4"	Q125	10031	126	
40		10"	Q125	10191	128	
41		9 5/8" x 9 7/8"	Q125	10480	132	
42		9 5/8" x 9 7/8" x 10 3/4"	Q125	10771	136	
43		10"	Q125	10815	137	
44		9 5/8" x 9 7/8" x 10"	Q125	11068	140	
45		9 5/8" x 9 7/8"	Q125	11406	145	
46		9 5/8" x 9 7/8" x 10"	Q125	11434	145	
47		9 5/8" x 9 7/8"	Q125	11892	152	
48		9 5/8" x 9 7/8"	Q125	12713	163	

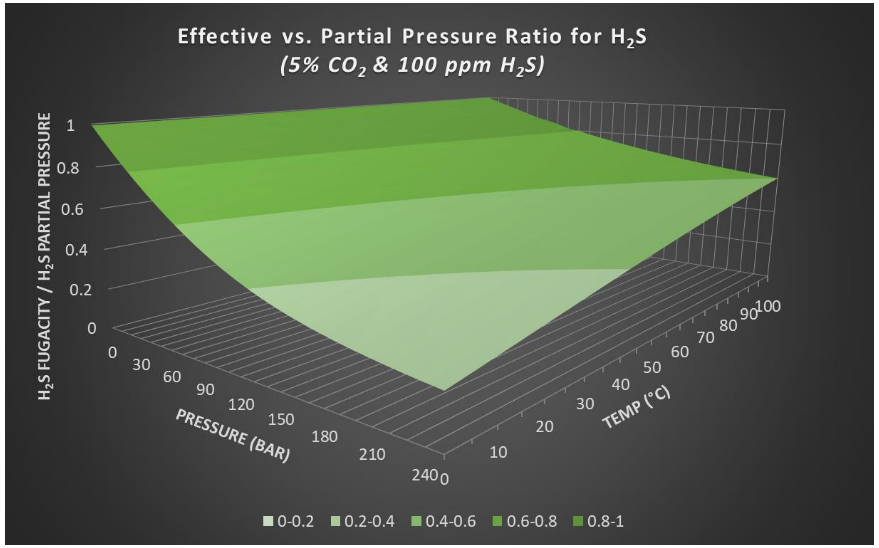
SSC testing continued to improve conditions for ~50 Q125 wells :
Test at 0,25 psi pH_2S at 50C

Going forward: Increased H_2S operational limits for wells

- Stress-modelling analysis
  - Operating conditions where components may be exposed to unacceptable SSC risk can be predicted by accurate simulation techniques (e.g. WellCat).

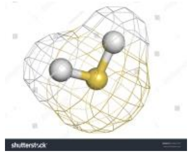


- Qualify a GEA-specific effective partial pressure (EPP) factor for reduced downhole H_2S reactivity (e.g. fugacity)



Summary

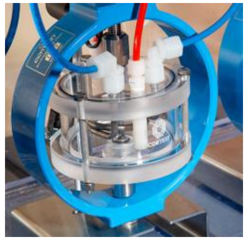
- Even relative low concentration of H2S can be a challenge in some operational phases/operations in wells that is not build for sour service



- Surveillance and sampling processes on all relevant wells is important

- Documentation on barrier elements (material spec etc.) is key

- Compensating measures can be very costly



- Material testing is a good way of setting/expanding the operational envelope and better understanding the risk.

- Stress modeling and Effective partial pressure methods is important tools to further understand risk and your real operational envelope