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Case Study: Oilfield Completion Technology and Reservoir Analysis Optimizes Injectivity for Geothermal Water Production In the Netherlands

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Contents

REF: View from Rig Floor of Geothermal Heating District Infrastructure

Introduction

1. **Awarded ten-well TCP project for geothermal heating initiative.**
2. **Comprised five pairs of wells, i.e., doublets [Fig 1]**
    - Top zone: Delft- ~50 m thick, clean sandstones,
    - Gap: ~150m between them.
    - Bottom zone: Alblasserdam ~150m thick, less clean sandstone.
3. **The project faced several challenges: To be discussed.**
4. **Post-job Modeling: Evaluated results for future improvements**

Schematic of Doublet Wells and Target Reservoirs

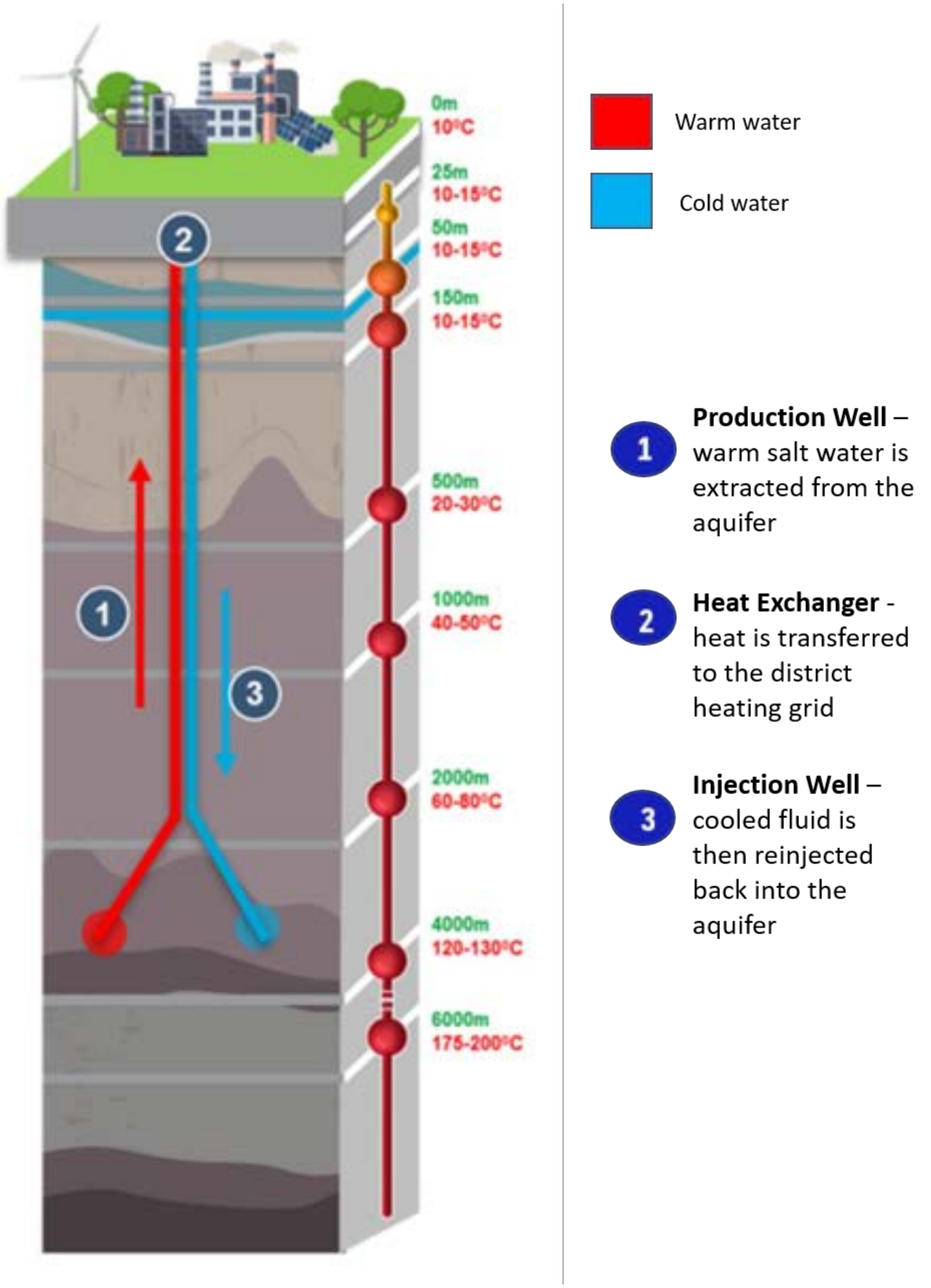


Fig 1- https://allesoveraardwarmte.nl

Project Parameters

1. The Greenport Westland-Oostkand area has geothermal production since 2007 (Van Leeuwen, 2019)[Fig 2]
2. The master plan includes 153 doublets covering 170 km2.
3. Objective is to provide heat to district for 30 years.
4. The spacing between production / injection wells is carefully planned, considers variations in reservoir thickness and temperature
5. Only 8 m spacing at surface, 1.5km at 9,000 ft depth

Map View of Netherland's Greenport Westland-Oostkand area

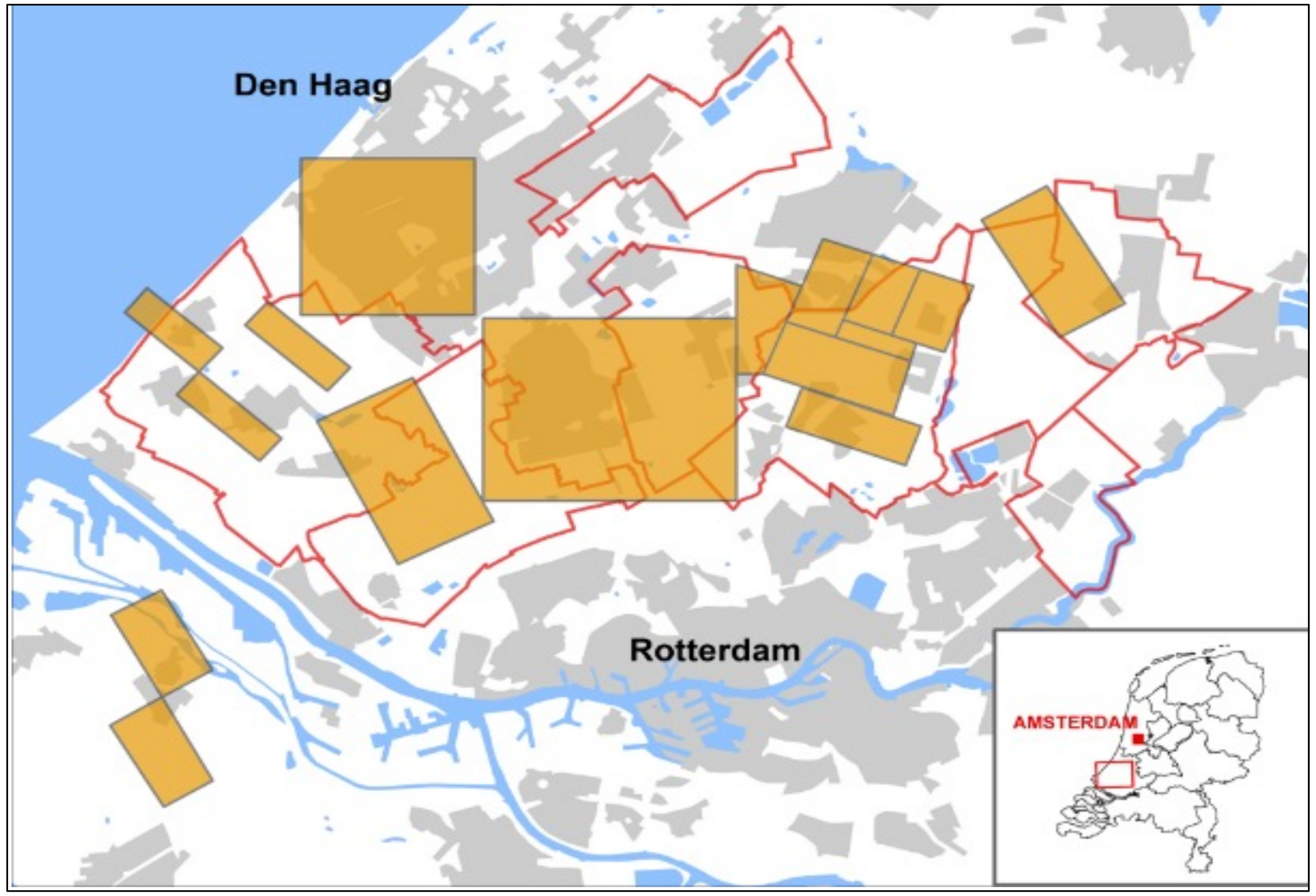


Fig 2- (Van Leeuwen, 2019)

Project Parameters

4. **The formation depths offer adequate temperatures, with a geothermal gradient of T=0.028*d+11 [Table 1]**
   - At 9,000 ft / 3,000m depth- 95°C/ 200°F
5. **Among the formations, Delft exhibits the highest potential for transmissivity (T)[Table 2]**
   - At 90%, the value of 6 for Delft ss is good.
6. **Well configuration ensures that Thermal Breakthrough (TB) occurs only after several years, optimizing heat extraction.**
   - TB- end of geothermal system's life, where extracted water's temperature from production falls below an acceptable threshold, target 30 years [Table 3]

Starting Points	KNNSB	SLDND
Flow rate (m^3/h)	150	150
Equivalent full load hours (h)	5,000	5,000
Initial temperature (° C)	45-70	70-75
Injection temperature (° C)	40	40
Porosity (-)	0.19	0.23
Thickness (m)	25-90	25-90
Volumertic heat capacity [$MJ/(m^3*K)$]	2.5	2.6
Desired lifetime of doublet	30	30
Thermal retardation factor [-]	3.3	2.8

Table 1: Delft Sandstone Properties (Van Leeuwen, 2019)

Member	p10	p50	p90
Berkel Sandstone	709	22	1
Delft Sandstone	211	37	6

Table 2: % Probabilities of transmissibility (Van Leeuwen, 2019)

TCP Parameters

1. **Previous wells completed encountered sand production/integrity challenges.**
2. **The plan was to use one continuous string of Tubing Conveyed Perforating (TCP) guns with the Static/Dynamic Underbalance (DUB) technique.**
3. **Running a long gun string (potentially 350m) on coiled tubing (CT) created risks associated with gun misfires and weight/shock load [Fig 3,4]**
   - Solution was to break into two runs, but this negated DUB on 2nd run, so it required innovative charge selection.
4. **Highest priority assigned to mitigate risks and ensure safe/efficient execution of the project.**

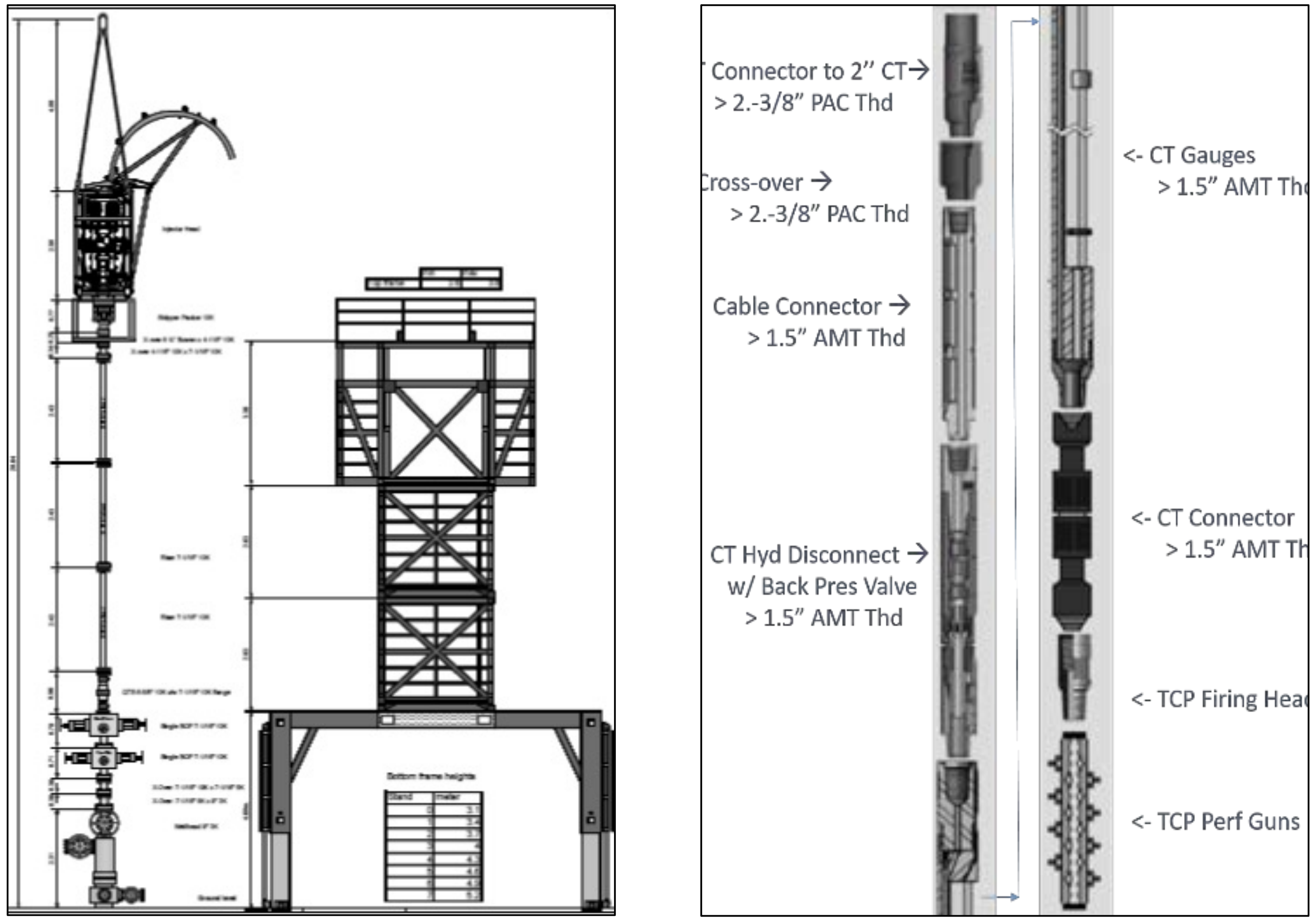


Fig 3- 3rd party Coiled Tubing Rig and BHA

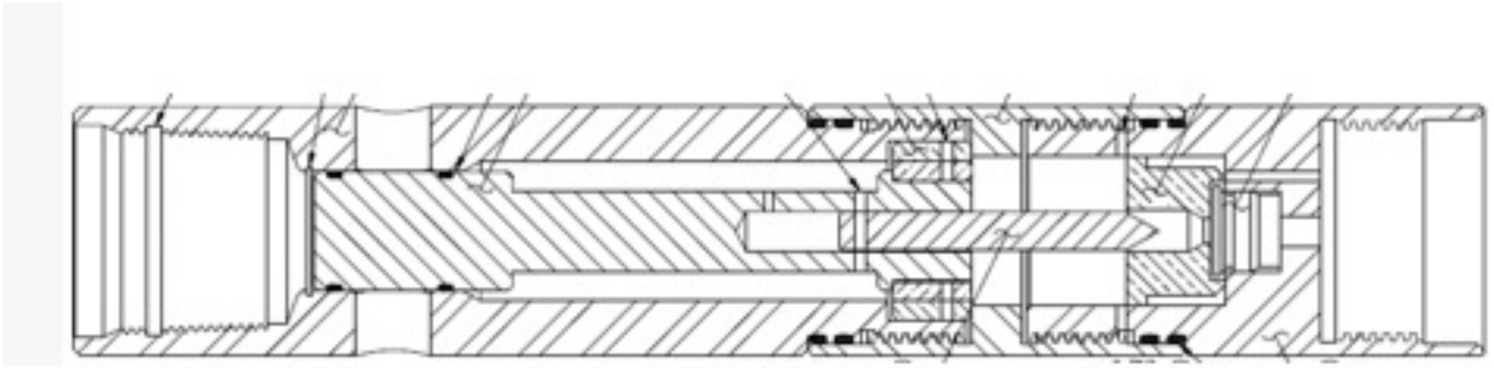


Fig 4- Proprietary Auto-Vent Firing Assembly

Challenges & Solutions

1. **Protection of Glass Reinforced Epoxy (GRE)-lined casing during intervention**
   - Highly corrosive environment- 1.08 Specific Gravity Salt Water with a salinity of approximately 10.8% (9.01 lb/gal).
   - Production water rate ~75,000 barrels per day,
   - Large 9 5/8" OD casing, designed for a completion life of 30 years.
   - The GRE lining is crucial for maintaining the wellbore's integrity over an extended period.

Solution:

- Implemented specially designed roller connectors to protect the GRE-lined casing **[Fig 5,6]**

Fig 5- Roller Sub Design

Fig 6- Drag Test Results

Challenges & Solutions

2. **Provide DUB at time of firing for optimal perforation tunnel cleaning across entire perforating interval [Fig 7]**
   - Used TCP since it simultaneously creates and cleans long sections of perforating interval.
   - Used explosive jet charges to create holes in the gun body, wellbore casing, and formation, thus forming perforation tunnels.
   - DUB created uniform cleaning, since higher pressure formation fluid surge-cleans the perforations into lower pressure evacuated guns, 0 psi.

Solution:

- Due to this, enhances overall operational efficiency.

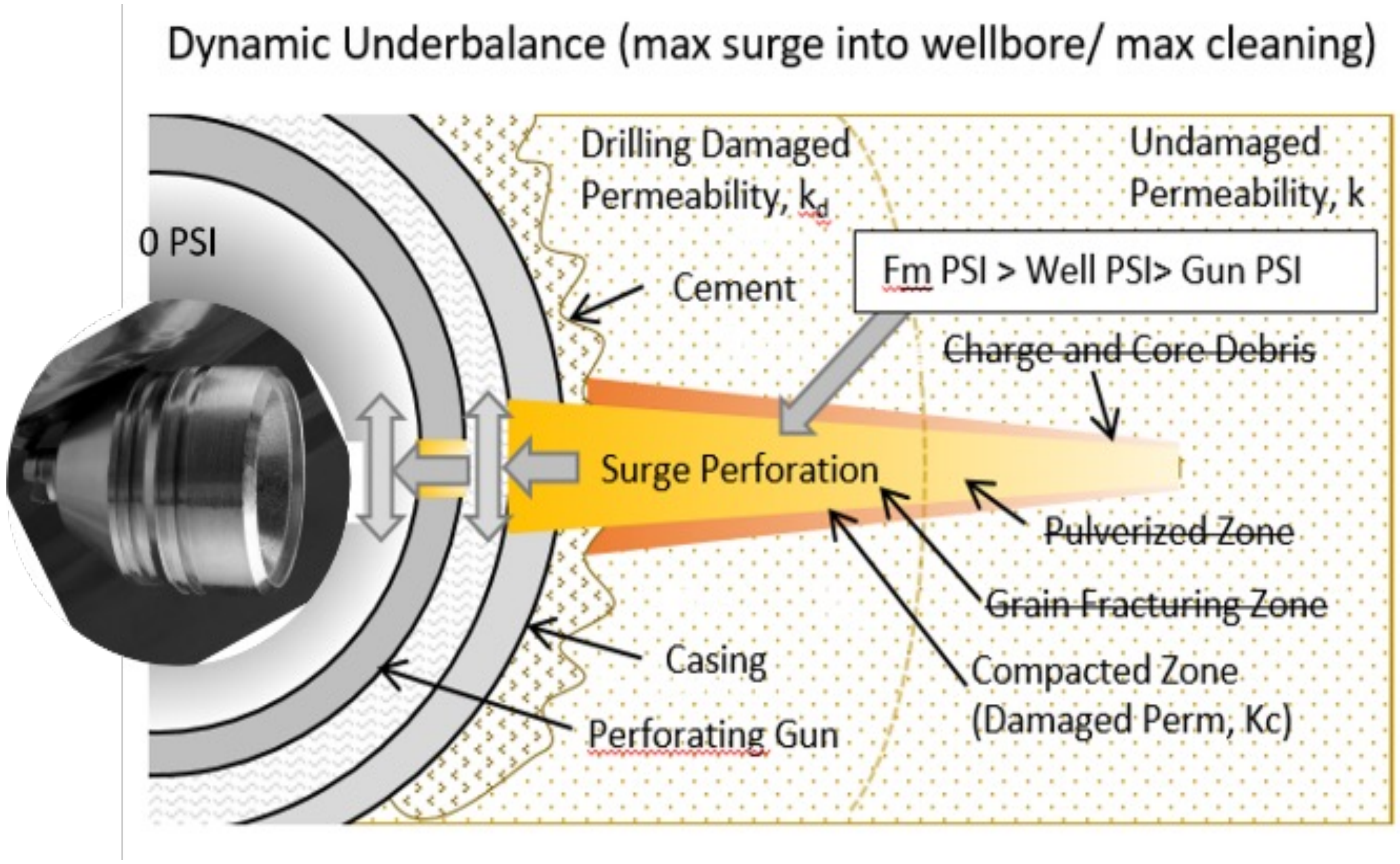


Fig 7- Dynamic Underbalance, Fadzil et al (2021)

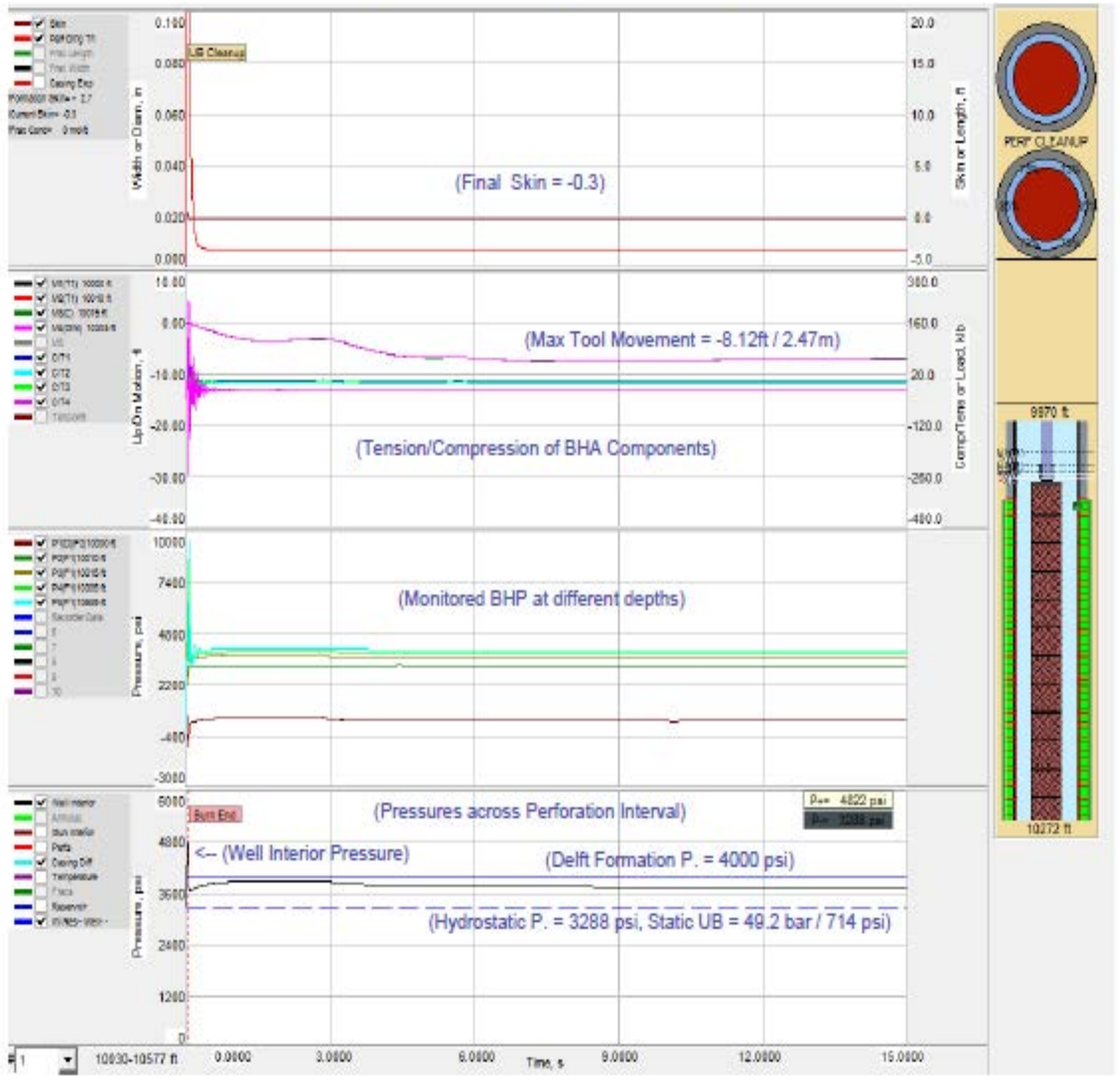
Challenges & Solutions

2. **Required successful deployment of long bottom hole assembly (BHA)**
   - Long intervals of large OD perforating guns with high-shot density were required on small-diameter Coiled Tubing.
   - The perforating guns: 114 mm (4.5 in) OD with density of 39 shots per meter (12 shots per foot).
   - The Coiled Tubing: 50.8 mm (2.00 in) OD, with AMT threads of 38.1 mm (1.50 in) OD, and low tensile strength of 42,000 lbs.

Solution:

- Expro performed modeling to ensure successful deployment, firing, and retrieval of the long BHA on Coiled Tubing **[Fig 8, Table 3]**.
- Also, split perforation intervals into two separate runs.

Fig 8-: Shock Model showing no failure points



Alblasserdam Sand: Wellbore fluid level at 735m, Hydrostatic static Pressure = 226.7 bar (3,288 psi), static underbalance (UB) = 49.2 bar (714 psi)

Blank Guns: 3,054m – 3,057m = 3m (MD)
Alblasserdam Sand Perforation Interval: 3,057m – 3,224m = 167m (MD)

Static UB (psi)	DUB Created (psi)	Final Skin Factor	Max Tool Movement (ft)	Max. Pressure (psi)	Min. Press. (psi)
714	406	-0.3	-8.12	4,822	3,288

Table 3- Shock model showing Tool Movement

Challenges & Solutions

3. Required successful deployment of long bottom hole assembly (BHA)

- By splitting interval, no DUB available on 2nd run

Solution:

- Standard DP or GH charges used on 1st run when DUB cleaning was available **[Fig 9]**
- Reactive liner charges used on 2nd guns- these provide cleaning/ opening of the perforation tunnel similar to DUB **[Fig 10]**

Fig 9-
Run 1- Injector Well: Standard Deep Penetrating (DP) charges
Run 1- Production Well: Standard Good Hole (GH) charges
(Third party Perforating gun system)

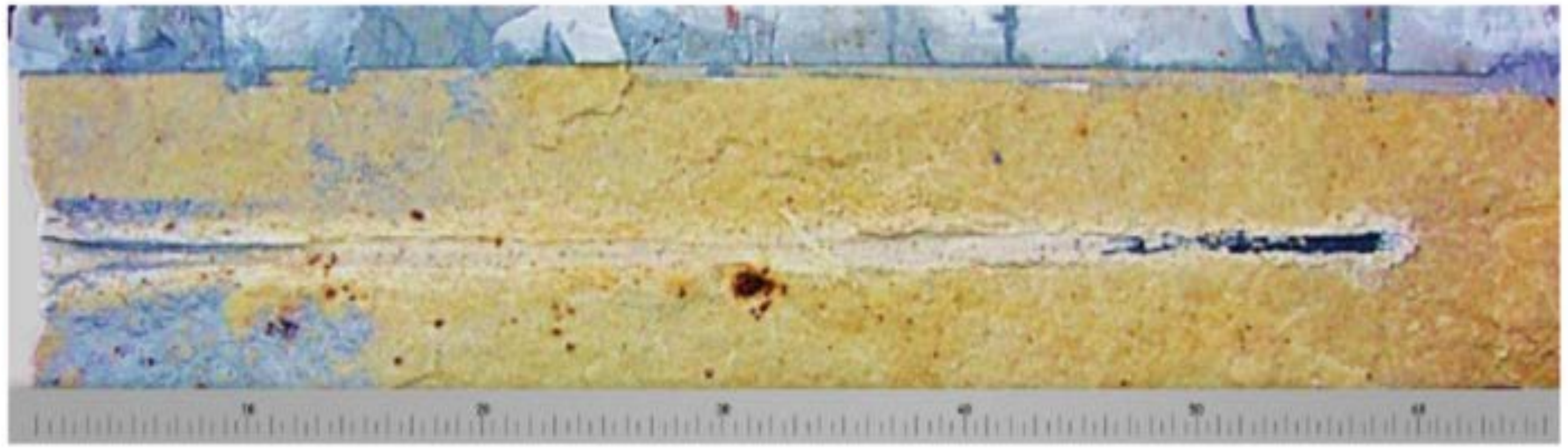


Fig 10-
Run 2- Both Injector and Producer: Reactive liner charges
(Third party Perforating gun system)

Reservoir Analysis

1. Injector Well Flow Performance Results

Run 1: Upper Delft Formation - shot 50 psi static underbalanced, so formation surge-cleaning probable (Formation P > Wellbore P) with DP charges **[Table 4]**

Well Fluid	Depth/Layer	Permeability	Injection Pressure	Gun System	Gun Casing Data	Shot Phasing	Shot Density	Casing Entrance Hole Diameter	Total Penetration Depth	Perforation Flow Performance
	(m) MD	(mD)	BARa	-	(Inches)	(degrees)	Shots/ft	(inches)	(inches)	(m3/hour)
Case 1:	2XXXX -2XXX	700	20	DP Chg	4-1/2	45	12	0.38	7.06	142
	2XXX.X – 2XXX.X	700	20		4-1/2	45	12	0.38	7.02	39
	2XXX.X– 2XXX.X	700	20		4-1/2	45	12	0.38	6.90	258

Table 4- Modeling Analysis for Injector Run 1

Best= 258 m3/hr

Note1: 3 loaded intervals within the larger zone, all with varying rock parameters

Run 2: Lower Alblasserdam Formation- shot balanced conditions, so no formation surge-cleaning possible (Formation P= Wellbore P), so shot with Reactive Liner charges **[Table 5]**

Well Fluid	Depth/Layer	Permeability	Injection Pressure	Gun System	Gun Casing Data	Shot Phasing	Shot Density	Casing Entrance Hole Diameter	Total Penetration Depth	Perforation Flow Performance
	(m) MD	(mD)	BARa	-	(Inches)	(degrees)	Shots/ft	(inches)	(inches)	(m3/hour)
Case 2:	3XXX.X - 3XXX.X	700	20	Reactive Liner Chg	4-1/2	45	12	0.31	9.28	86
	3XXX.X - 3XXX.X	700	20		4-1/2	45	12	0.31	9.25	89
	3XXX.X - 3XXX.X	700	20		4-1/2	45	12	0.31	9.16	198
	3XXX.X – 3XXX.X	700	20		4-1/2	45	12	0.31	9.10	70
	3XXX.X – 3XXX.X	700	20		4-1/2	45	12	0.31	9.06	80
	3XXX.X – 3XXX.X	700	20		4-1/2	45	12	0.31	9.00	80
	3XXX.X– 3XXX.X	700	20		4-1/2	45	12	0.31	8.89	263

Table 5- Modeling Analysis for Injector Run 2

Best= 263 m3/hr

Note 2: 7 loaded intervals within the larger zone, all with varying rock parameters

Note: Perforation analysis was performed with Commercial Modeling Software. This includes a calculation too used to estimate the penetration length and entrance hole diameter. The Darcy IPR model and the System IPR/VLP model were employed to generate the perforation flow potential. In this model, MacLeod was used to calculate the mechanical/geometric skin, while the Cinco and Martin-Bronz Skin models were employed to calculate the partial penetration skin.

Reservoir Analysis

1. Injector Well Flow Performance Results

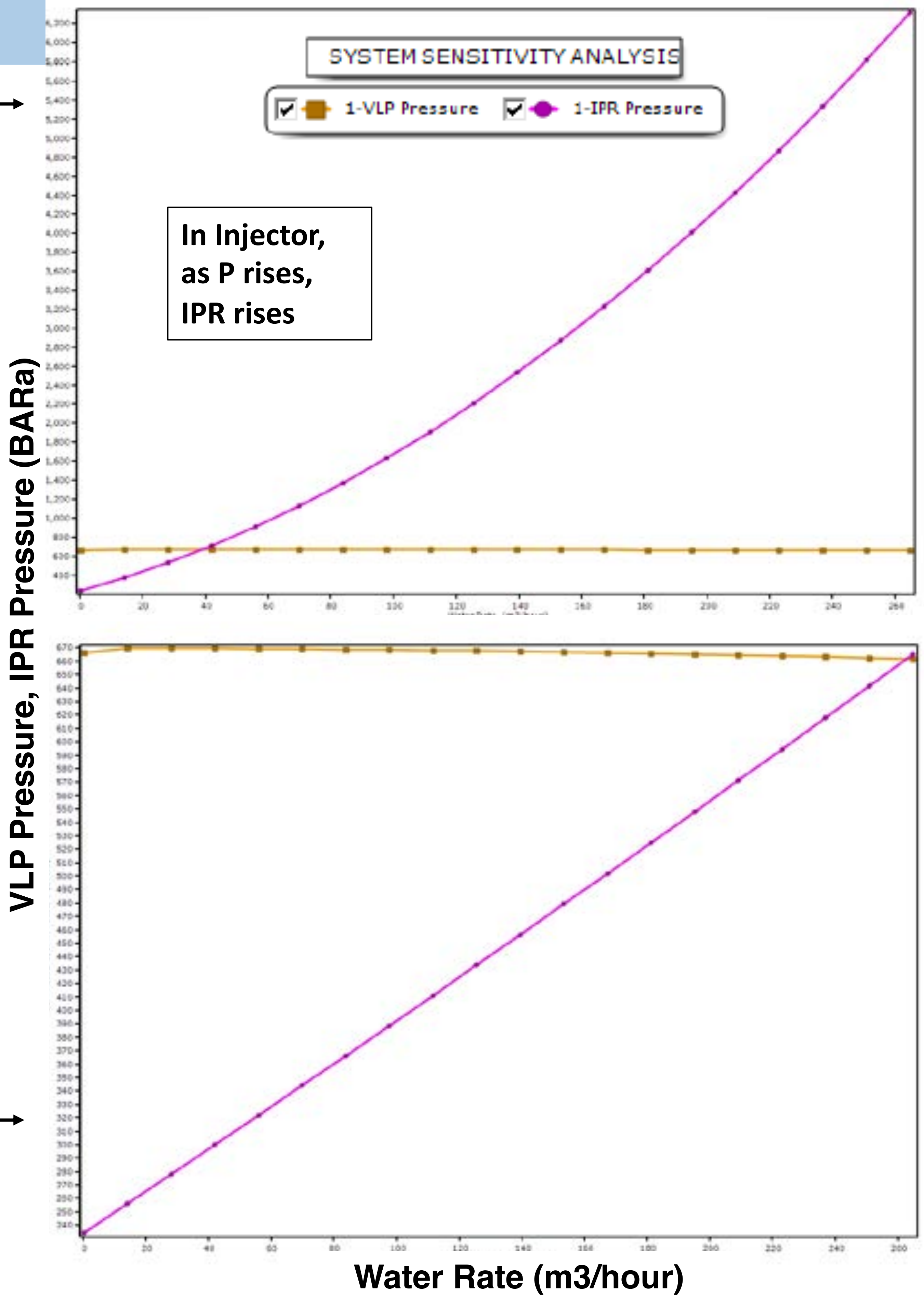
Run 1 with DUB: Best= 258 m3/hr

Post-Job Analysis: [Fig 11]

Compare modeling data to Client flow test results:

- Injector- ran PLT, but spinner stopped, so, unfortunately, no good data.
- However, promising results from injection test
  - Top perforations took 70% vs. 30% for the bottom

In Injector, as P rises, IPR rises



SUMMARY DATA

Fluid	Water
PVT Method	Black oil
Separator	Single-Stage
Emulsions	No
Hydrates	Disable Warning
Water Viscosity	Use Default Correlation
Water Vapour	No Calculations
Viscosity Model	Newtonian Fluid
Steam Option	No Steam Calculations
Flow Type	Tubing
Well Type	Water Injector
Artificial Lift	None
Predicting	Pressure and Temperature (offsho
Temperature Model	Rough Approximation
Range	Full System
Completion	Cased Hole
Sand Control	None
Inflow Type	Single Branch
Gas Coning	No
Company	HVC Groep
Field	Maasdijk Field
Location	Maasdijk, Netherlands
Well	MSD-GT-03
Platform	Onshore
Analyst	AO
Date	06/02/2023

SYSTEM SENSITIVITY ANALYSIS - INPUT DATA

Top Node Pressure	20.00 (BARa)
Surface Equipment Correlation	Hydro-2P
Vertical Lift Correlation	Petroleum Experts 2
Solution Node	Bottom Node
Rate Method	Automatic - Linear
Left-Hand Intersection	DisAllow
PES Stability Flag	Yes
Bottom Measured Depth	3259.0 (m)
Bottom True Vertical Depth	2936.0 (m)

Fig 11- All Images Here

INFLOW PERFORMANCE DATA (OIL WELL)

Inflow Type	Single Branch
Completion	Cased Hole
Sand Control	None
Gas Coning	No
Reservoir Model	Darcy
M&G Skin Model	MacLeod
D&PP Skin Model	Cinco / Marting-Brons
Perm(k) Reduction Model	No
Reservoir Pressure	234.00 (BARa)
Reservoir Temperature	35.00 (deg C)
Reservoir Permeability	700.00 (md)
Reservoir Thickness	182.2 (m)
Drainage Area	966.9 (acres)
Dietz Shape Factor	30.9972
Wellbore Radius	6.13 (inches)
Reservoir Permeability	700.00 (md)
Perforation Diameter	0.30698 (inches)
Shot Density	12.00 (1/ft)
Perforation Length	8.89 (inches)
Perforation Interval	30.20 (m)
Perforation Efficiency	0.9 (fraction)
Wellbore Radius	6.13 (inches)
Perforation Technique	Underbalanced
Deviation	8.00 (degrees)
Penetration	0.0477 (fraction)
Vertical Permeability	650.00 (md)

REF: INPUT & SUMMARY

Run 2 with Reactive: Best= 263 m3/hr

Reservoir Analysis

1. Producer Well Flow Performance Results

Run 1: Lower Alblasserdam Formation- shot 30 psi static underbalanced with GH charges **[Table 6]**

RUN 1	Depth/Layer	Permeability	Pressure	Gun System	Gun Casing Data	Shot Phasing	Shot Density	Casing Entrance Hole Diameter	Total Penetration Depth	Perforation Flow Performance
	(m) MD	(mD)	BARa	-	(Inches)	(degrees)	Shots/ft	(inches)	(inches)	(m3/hour)
Case 1a:	2XXX.X – 3XXX.X	700	20	DYNA 4.5" 23g GH RDX	4-1/2	45	12	0.51	4.40	216
Case 1b:	3XXX.X– 3XXX.X	700	20	RDX	4-1/2	45	12	0.51	4.39	71
Case 1c:	3XXX.X– 3XXX.X	700	20	GH Chg RDX	4-1/2	45	12	0.51	4.37	109
Case 1d:	3XXX.X – 3XXX.X	700	20	RDX	4-1/2	45	12	0.51	4.35	73
Case 1e:	3XXX.X– 3XXX.X	700	20	RDX	4-1/2	45	12	0.51	4.34	77
Case 1f:	3XXX.X – 3XXX.X	700	20	DYNA 4.5" 23g GH RDX	4-1/2	45	12	0.51	4.32	101
Case 1g:	3XXX.X– 3XXX.X	700	20	DYNA 4.5" 23g GH RDX	4-1/2	45	12	0.51	4.31	64
Case 1h:	3XXX.X – 3XXX.X	700	20	DYNA 4.5" 23g GH RDX	4-1/2	45	12	0.51	4.29	124
Case 1i:	3XXX.X– 3XXX.X	700	20	DYNA 4.5" 23g GH RDX	4-1/2	45	12	0.51	4.27	116
Case 1j:	3XXX.X– 3XXX.X	700	20	DYNA 4.5" 23g GH RDX	4-1/2	45	12	0.51	4.25	144
Case 1k:	3XXX.X– 3XXX.X	700	20	DYNA 4.5" 23g GH RDX	4-1/2	45	12	0.51	4.22	108
Case 1l:	3XXX.X– 3XXX.X	700	20	DYNA 4.5" 23g GH RDX	4-1/2	45	12	0.51	4.19	91

Table 6- Modeling Analysis for Producer Run 1

Best= 216 m3/hr

Note 1: 12 loaded intervals within the larger zone, all with varying rock parameters

Run 2: Upper Delft Formation- shot balanced conditions with GH charges, so no automatic formation surge-cleaning possible (Formation P= Wellbore P), so shot with Reactive Liner charges **[Table 7]**

RUN 2	Depth/Layer	Permeability	Pressure	Gun System	Gun Casing Data	Shot Phasing	Shot Density	Casing Entrance Hole Diameter	Total Penetration Depth	Perforation Flow Performance
	(m) MD	(mD)	BARa	-	(Inches)	(degrees)	Shots/ft	(inches)	(inches)	(m3/hour)
Case 2a:	2XXX.X – 2XXX.X	700	20	Reactive Liner Chg	4-1/2	45	12	0.51	4.77	38
Case 2b:	2XXX.X – 2XXX.X	700	20		4-1/2	45	12	0.51	4.74	99
Case 2c:	2XXX.X– 2XXX.X	700	20		4-1/2	45	12	0.51	4.70	184
Case 2d:	2XXX.X– 2XXX.X	700	20		4-1/2	45	12	0.51	4.69	44
Case 2e:	2XXX.X– 2XXX.X	700	20		4-1/2	45	12	0.51	4.68	48
Case 2f:	2XXX.X – 2XXX.X	700	20		4-1/2	45	12	0.51	4.66	83

Table 7- Modeling Analysis for Producer Run 2

Best= 184 m3/hr

Note 2: 6 loaded intervals within the larger zone, all with varying rock parameters

Reservoir Analysis

Run 1 with DUB:
Best= 216 m3/hr

2. Producer Well Flow Performance Results

Post-Job Analysis: [Fig 12]

Compare modeling data to Client flow test results

- Producer using GH charges- ran PLT, but spinner stopped, so no data
- Client Calculated Final Skin= - 0.75
- Compare that to the original model, which calculated Final Skin= -0.3, so close match.

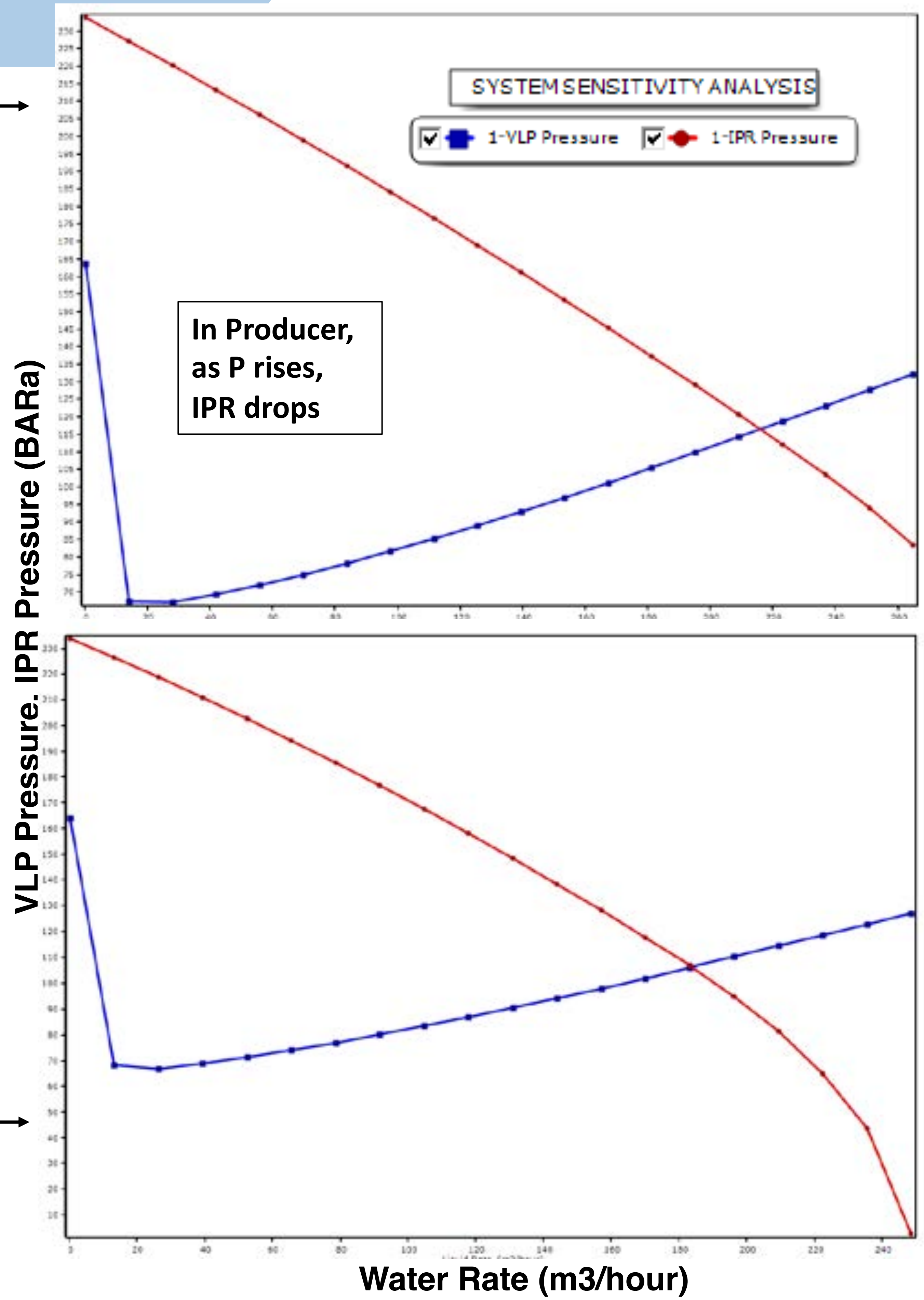


Fig 12- All Images Here

Run 2 with Reactive:
Best= 184 m3/hr

IPR/VLP injection flow potential in m3/hr calculated from the IPR of the layers of interest.

Recommendation

- **Given acceptable results in Producer well when using Good Hole (GH) charges,**
  - Next Injection well will use GH charges to compare against first well, which used DP and DP reactive charges.
- **This downhole result comparison will allow optimization of further completion designs.**

REF: Company personnel inspecting firing head assemblies during in-country training

Conclusion

- To date, two wells (4 runs total) completed, with several challenges addressed (discussed here).
- Provided value to geothermal projet through proven technology and oil and gas industry expertise.
- Provided enhanced productivity, bolstering energy security and supporting energy transition initiatives.
- Provided solutions encompassing technical expertise, supply chain coordination, and operational excellence.
- Further analysis is ongoing to evaluate the effectiveness of gun systems and to optimize bottom-hole assembly (BHA) for future use.

REF: Personnel inspecting GRE casing during the Rig Visit

Acknowledgment

- **Expressing our sincere gratitude to the International Perforating Symposium (IPS) for selecting us.**
- **Recognizing the invaluable contributions of our suppliers and personnel who contributed to the success of this project.**
- **Thanks to our company management for allowing us to be here today.**

Ref: Personnel inspecting GRE casing during the Rig Visit

References

- **Van Leeuwen, W., Buik, N., Gutierrez-Neri, M. Lokhorst, A., Willemsen, G., (2019, April 25-29), Proceedings World Geothermal Congress 2010, Bali, Indonesia: Subsurface Spatial Planning for Geothermal Heat Production in Greenport Westland-Oostland, the Netherlands, IF Technology, Postbus 605, 6800 AP Arnhem, the Netherlands.**
- **https://allesoveraardwarmte.nl/**
- **Stichting Platform Geothermie (2018, May). Master Plan Geothermal Energy in the Netherlands: A broad foundation for sustainable heat supply: www.geothermie.nl**
- **Nurul Fadzil et al., "Maximizing Injection Performance Through Fit-for-Purpose Dynamic Underbalance Perforation Using Unconventional Gun System in Offshore Well, Sarawak, Malaysia." Paper presented at the IADC/SPE Asia Pacific Drilling Conference and Exhibition, virtual, 8 June 2021. DOI: 10.2118/201061-MS**
- **Third-party provider information- Coiled Tubing BOP/ Lubricator/ Work Platform**
- **Third-party provider information- Perforating Gun Systems**

QUESTIONS?

MAY 13-15 IPS 2024

Case Study: Oilfield Completion Technology and Reservoir Analysis Optimizes Injectivity for Geothermal Water Production In the Netherlands

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