WARMING^UP GOO
12 JUNE 2025

Warming^UP GOO
Geothermie & Opslag Opschaling

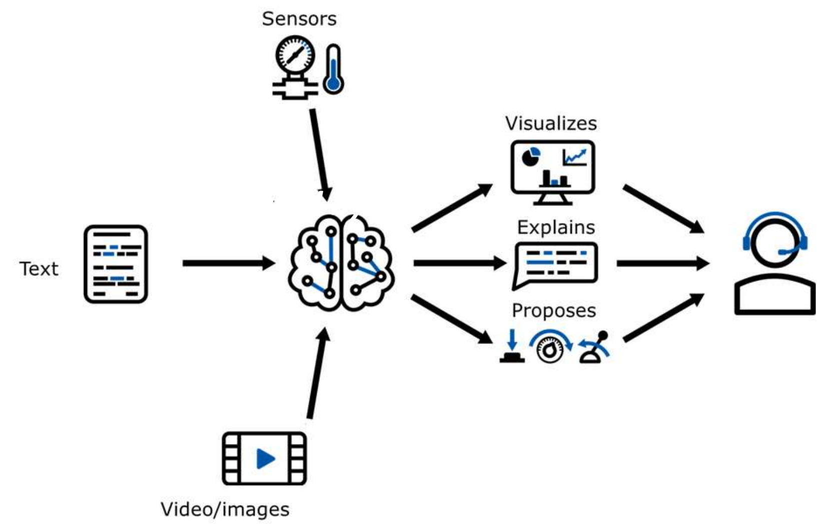
Gemini Digital Twin Development
-
Corrosion Prognosis

Floris Degener - Well Engineering Partners

TNO | WEP work well together | hvc. energie en hergebruik | Aardyn Geothermie ontwikkeling & beheer | GAIA ENERGY | Helin | geothermie nederland

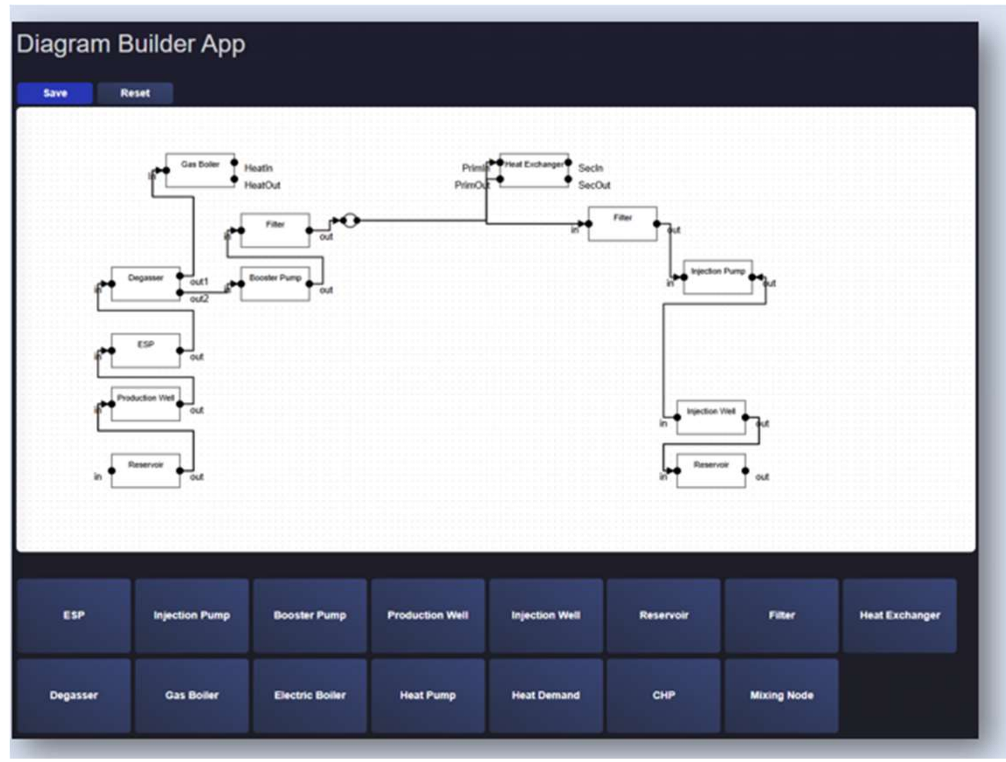
Digital Twin of Geothermal Systems

- Aim: **Improving the operation of geothermal production systems with digital technologies**
- How: by building a full Digital Twin of geothermal systems
  - Real-time model-based monitoring and calculations
  - Decision support systems
  - Early warnings for arriving problems; time to prepare or prevent
  - Help with diagnosing issues
- More info: poster exhibition Demetris Palochis - TNO

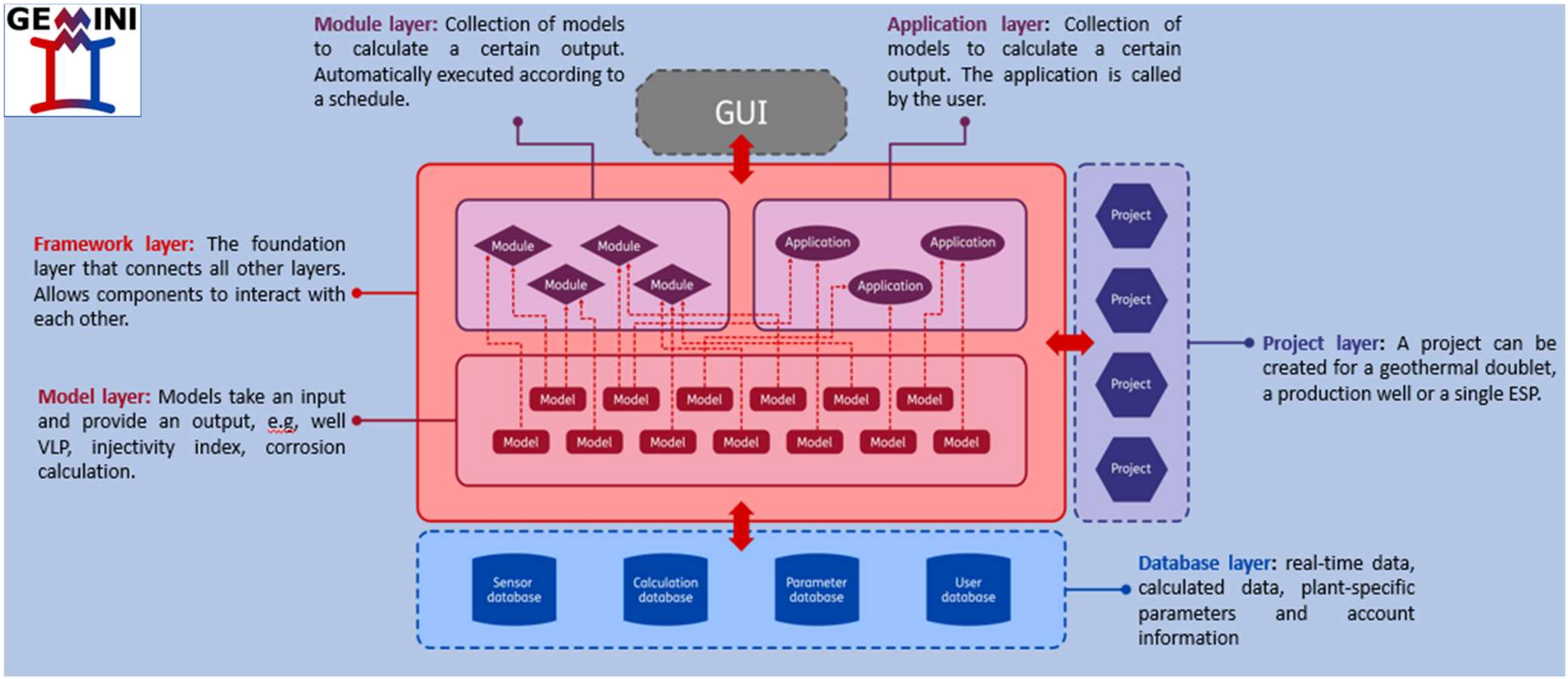


Digital Twin of Geothermal Systems

- Geothermal system components:
  - Production aquifer
  - Production well
  - ESP
  - Surface piping
  - Separator
  - Filters
  - Heat exchangers
  - Booster/Injection pumps
  - Injection well
  - Injection aquifer
- All components are connected
- User builds own system using diagram builder
- WIMS module, including corrosion

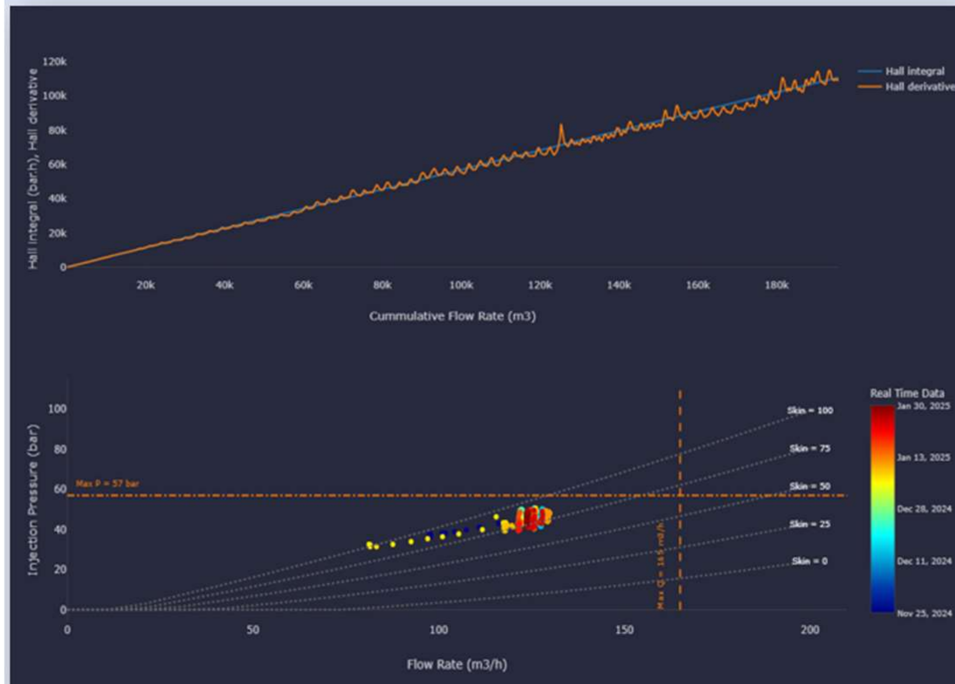


Gemini Digital Twin – Functional Achitecture

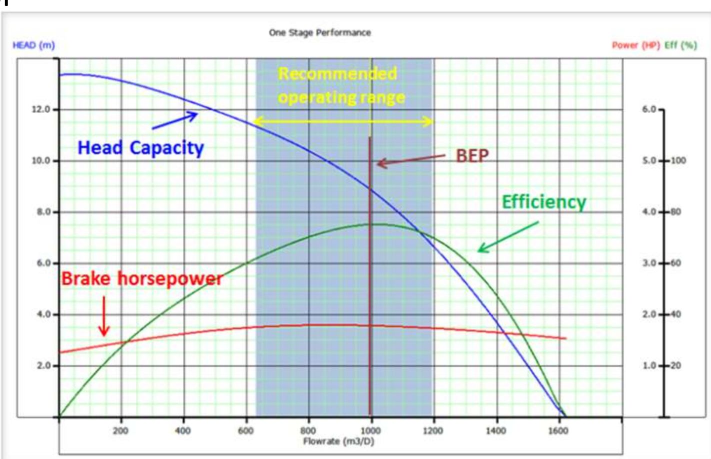


Real-time Data and Calculations

- Measured data
  - Sensor measurements (P, T, Q, A)
  - Plotting to visualize trends
- Calculated data
  - Local P, T, P CO_2, …
  - Hall plots, derivative of Hall, skin plot
  - Future: ESP pump curve
- Modules using calculated data
  - Injectivity monitoring
  - Productivity monitoring
  - WIMS
  - ESP



Injectivity index, Hall plot + derivative, skin plot

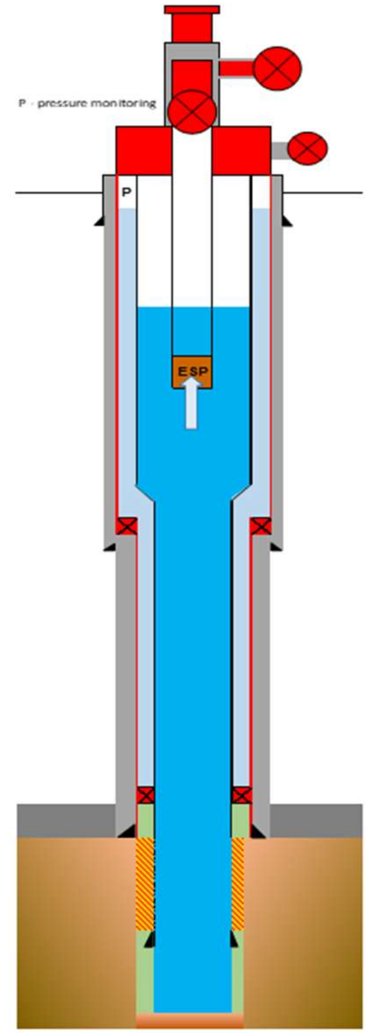


Typical Pump Curve

Warming UP GOO
Geothermie & Opslag Opschaling

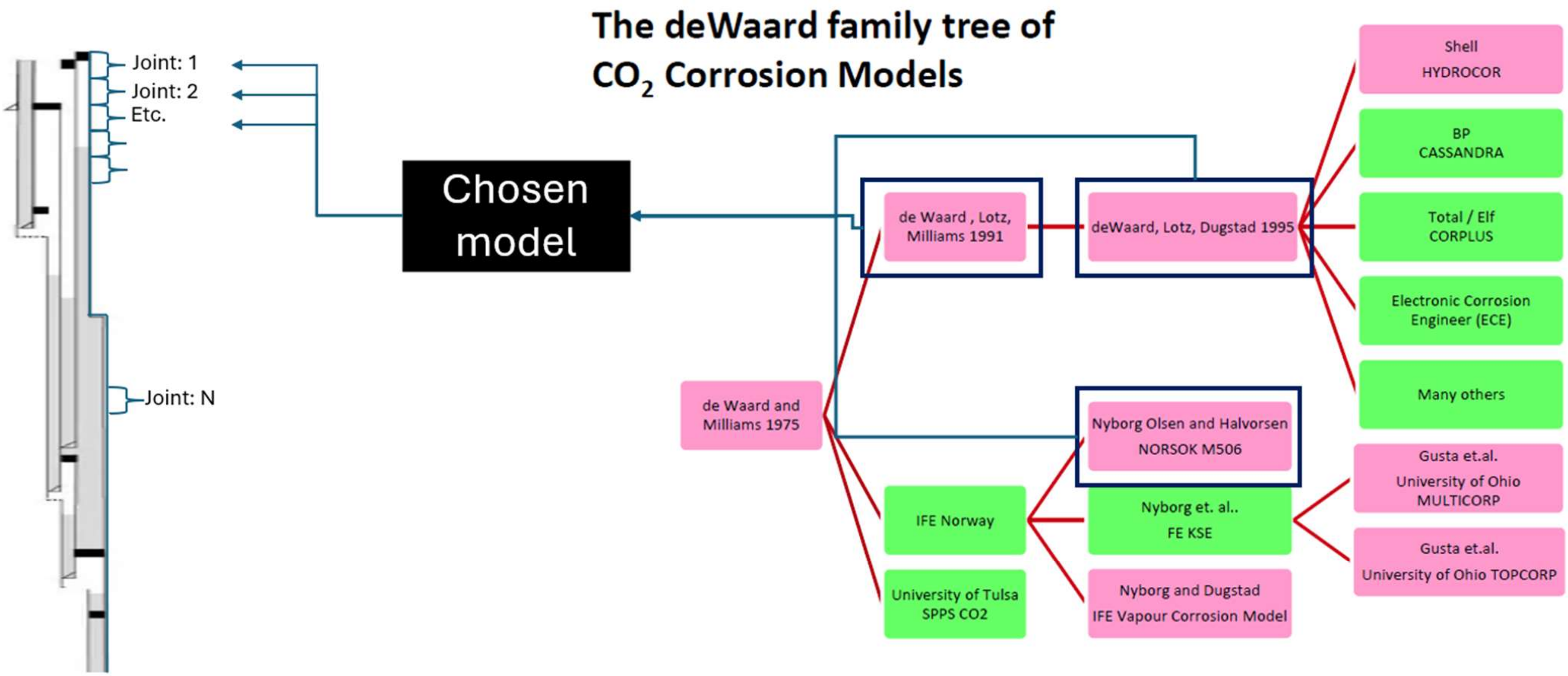
WIMS Module

- For producer/injector wells
- Goal: demonstrating WI compliance and highlighting potential WI issues
  - Current and future
- WIMS module includes:
  - Corrosion model: calculate actual corrosion status, interpolations and extrapolations
  - Erosion model: highlight areas in wells where high (cumulative) erosion occurs
    > may be used in future for erosion-corrosion, erosion of GRE (lining) or coated tubulars
  - Annulus pressure model for double skin wells
  - ‘Real time’ barrier scheme per well
- Real time production data is used as input for models
  - Actual production rates, temperatures, pressures over time
  - Future: Production scenarios can be used for predictions
- Local values relevant for corrosion are calculated:
  - Flow velocities, temperature, pressure, CO_2 fugacity



Figuur 3: Barrière schema geothermische put (productie)

Corrosion Model



Corrosion Model

Models & Requirements

1. DLM
   - Production data
   - Gas analysis

The deWaard Lotz, Milliams Equation

V_{corr} = Base corrosion rate (mm/yr)
- T = Temperature (K)
- f_{co2} = Fugacity of CO_2 (bara)

$$\log(V_{cor}) = 5.8 - \frac{1710}{T} + 0.68\log(f_{CO2})$$

2. DLD
   - Production data
   - *Gas analysis*

Equation 3.6 can be expressed as Equation 3.7, shown below. Equation 3.7 is the overall resistance model.

$$C_{CORR} = \frac{1}{C_R} + \frac{1}{C_{MT}} \quad (3.7)$$

Where:

C_R is the highest possible reaction rate, i.e. when mass transfer is infinitely fast

C_{MT} is the highest possible mass transfer rate of corrosive species

$$\log_{10}(C_R) = 4.93 - \frac{1119}{T_k} + 0.58\log_{10}(f_{co_2}) \quad (3.8)$$

Also, C_{MT} is given by: $C_{MT} = 2.45\frac{U^{0.8}}{d^{0.2}}$ (3.9)

Where:

U is liquid velocity (in m/s)

d is pipe diameter (in m)

f_{co_2} is Carbon dioxide fugacity (MPa)

3. NORSOK
   - Production data
   - *Water analysis*
   - *Gas analysis*

$$C_{NOR} = K_t f_{CO_2}^{0.62}\left(\frac{S}{19}\right)^{0.146+0.0324\log(f_{CO_2})} f(pH)_t \quad (3.10)$$

Where:

K_t is a constant dependent on temperature

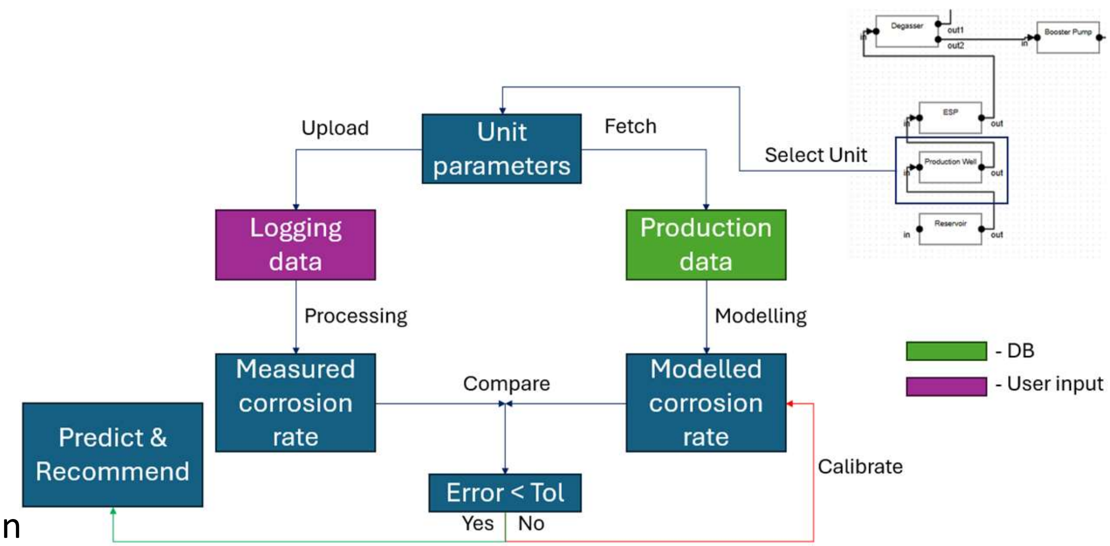
f_{co_2} is CO_2 fugacity

S is wall shear stress (Pa)

$f(pH)_t$ is a complex function of pH and temperature

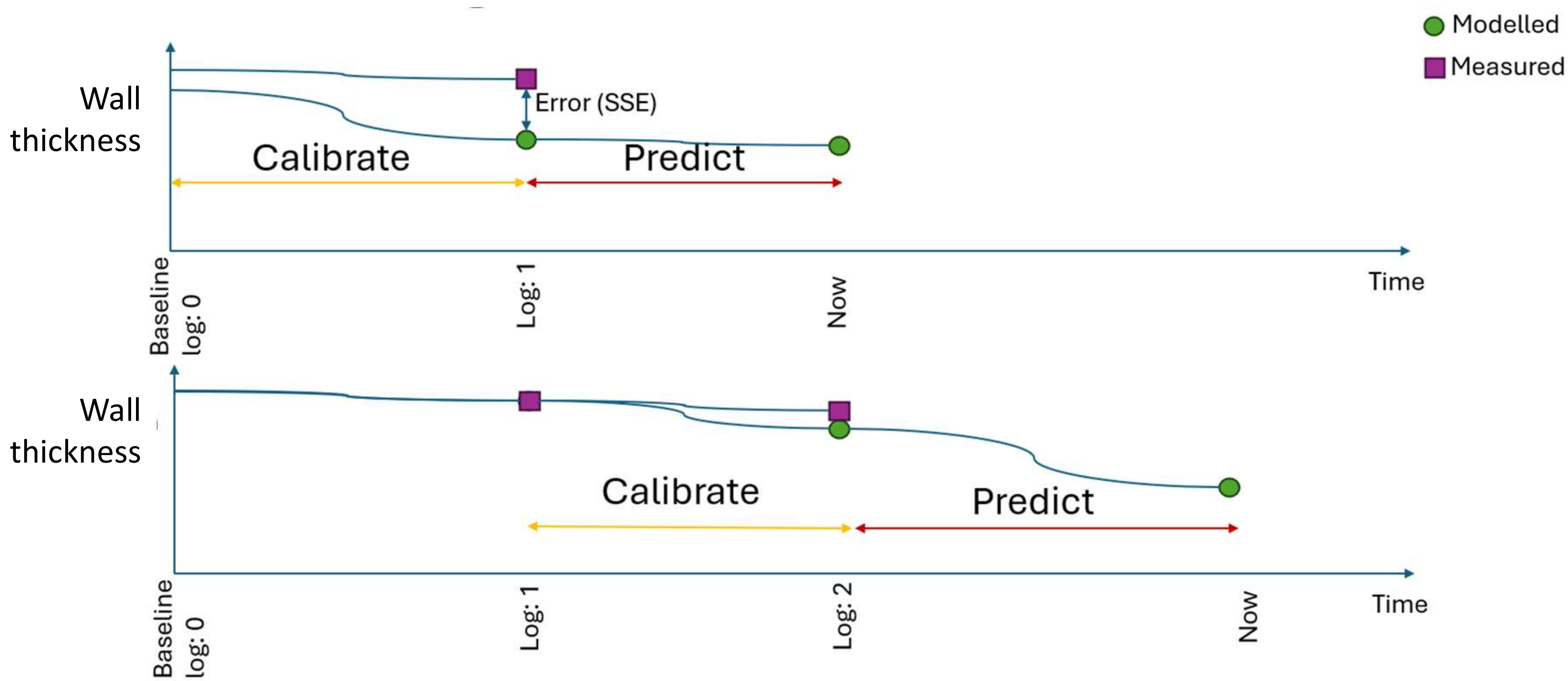
Corrosion Model

- Model input: CO_2 concentration, real time production parameters, flowrate, temperature, pressure
- Wall thickness loss modelled per joint and per timestep
- Compare modelled corrosion with actual corrosion through MFC logs
  - Ability to upload LAS files (application)
- Adjust model coefficients
- Predict future corrosion
  - Based on production scenarios
  - Early warning for reaching WI limits
  - Can be used to optimize logging frequency



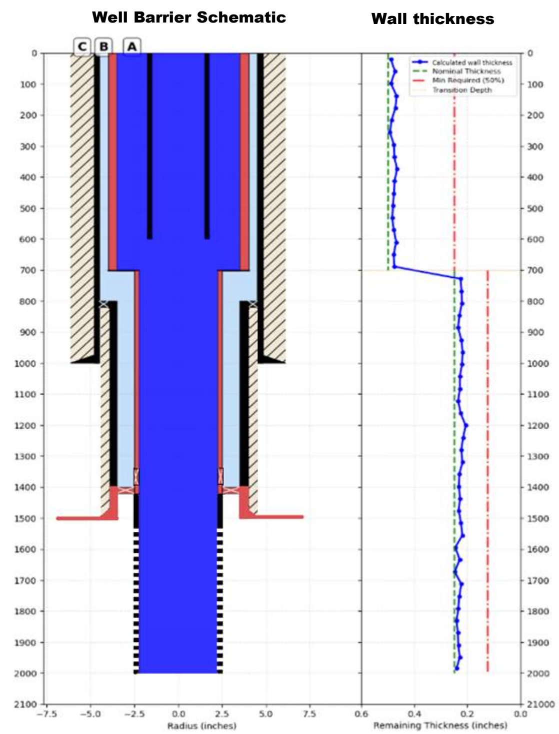
Joint No.	Max. Pen. [%]	Max. Loss [%]	Max. Pen. Depth [m]	Min. Pen. Depth [m]	Max. ID [inch]	Min. ID [inch]	Mean. ID [inch]
1	18.8	8.2	3.4213	10.7113	12.595	12.359	12.497
2	16.6	6.4	14.0063	11.2513	12.574	12.351	12.478
3	19.3	7.9	26.8063	26.6863	12.6	12.359	12.493
4	17.7	7	44.9963	42.6663	12.585	12.365	12.485
5	17.9	7.1	49.4113	46.2813	12.587	12.343	12.486
6	18.9	7.9	59.8663	58.0213	12.596	12.345	12.493
7	18.4	7.3	72.3713	69.7663	12.592	12.328	12.488
8	18.6	8.9	84.3663	81.4263	12.594	12.356	12.503
9	19.1	7.9	94.4913	103.7713	12.598	12.367	12.494
10	20.8	9.2	108.7113	113.8363	12.615	12.375	12.507
11	20	7.8	123.3163	121.9413	12.607	12.346	12.493

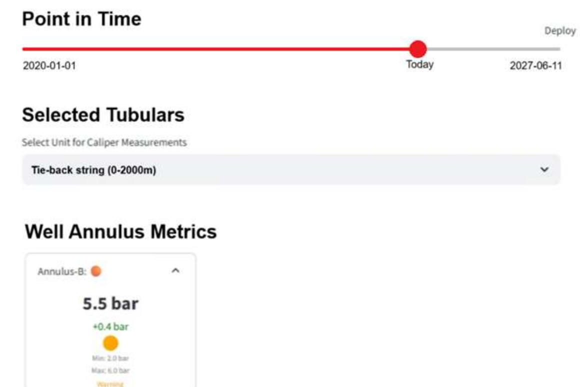
Calibrating Model and Forecasting



Graphical User Interface

- Well Barrier Schematic builder
  - Define well layout
  - Define WBE and their correlation
  - Graphical representation of well barrier envelope
- Graph with wall thickness of tubulars
  - Calculated W/T per joint
  - Includes minimum allowed W/T
  - For any tubular string
- Ability to look back in time and forecast wall thickness
- What will be added (future):
  - Wellhead WBE
  - Forecast based on user provided production scenarios
  - Estimate when min. W/T is reached
  - WBE status table



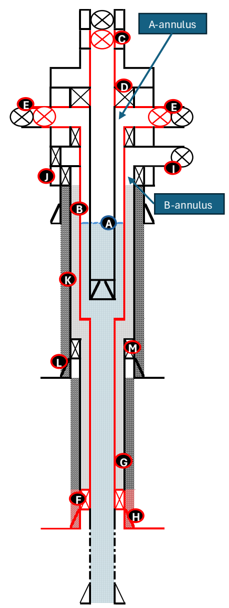


WarmingUPGOO
Geothermie & Opslag Opschaling

Graphical user interface

- WBE status table (work in progress)

Put barrières (actueel)



Algemene informatie

Well:	
Location:	
Prepared/Changed by:	
Verified by:	
Date latest update:	

Overall Integrity status:		Type well:	Production well
Integrity status description:		Well Status:	Producing
Failed			
Not verified or other issues		Boordatum:	
Verified and in good state		Laatste interventie:	

Primaire Barriere Elementen

Element	Qualification	Monitoring		Remarks
A) Formation Brine	Fluid gradient overbalanced with respect to formation. Produced 12x well volume.	Static fluid level with ESP gauge		

Secondaire Barriere Elementen

Element	Qualification	Monitoring		Remarks
B) Tieback + seal stem	Pressure test annulus to 75 bar	Annulus pressure monitoring		Annulus pressure below threshold
C) XMT, Master Valve	Pressure test to 75 bar	Visual checks, periodical function test, periodical pressure test		
D) Casing hangers	Pressure test to 75 bar	Visual checks		
E) A-ann. SOV's	Pressure test to 75 bar	Visual checks, periodical function test		
F) 9-5/8x7" liner hanger packer	Pressure test to 75 bar	Annulus pressure monitoring		Annulus pressure below threshold
G) 9-5/8" Liner	Pressure test to 75 bar	Annulus pressure monitoring		Annulus pressure below threshold
H) 9-5/8" cement	Job performance record	No monitoring		
Redundant secondary WBE				
I) B-ann. SOV's	Pressure test to 75 bar	Visual checks, periodical function test		
J) Wellhead, spools	Pressure test to 75 bar	Visual checks		
K) 13-3/8" casing	Pressure test to 75 bar	Annulus pressure monitoring / MFC		Annulus pressure below threshold
L) 13-3/8" cement	Job performance record	No monitoring		
M) 9-5/8x7" liner hanger + tie-back packer	Pressure test to 75 bar	No monitoring		

Opmerkingen

Actieve MOC's:

1	
2	
3	

Acties:

1	
2	
3	

WEP work well together

Development Status

- Ongoing:
  - Back-end programming
  - Design user interface
  - Integrating in Gemini
  - Validating model + MFC calcs

- Challenges
  - Practical: getting good data to validate models
  - Pitting corrosion – notoriously difficult – indirect modelling after MFC
  - Inhibitor usage – assumed Y or N – could be added in future if enough data or model is available
  - Ensuring uniformity of MFC log data and depth correction

- Future developments
  - ESP failure forecasting (TNO)
  - Erosion model evolvement to predict erosion-corrosion of CRA, erosion of GRE, coating erosion
  - Matching coupon data, LPR probe data
  - Early warning for reaching WI limits

Outlook

- Release to Gaia/HVC in steps for testing and obtaining feedback
- Open-access toolbox for Operators
  - Part developed under Warming Up GOO

MVP date (internal)	MVP contents
April 2024	GEMINI framework + basic flow modelling capabilities
July/August 2024	Injection monitoring
First external release January 2025 (basic functionalities + injection monitoring)	
Februari/March 2025	Corrosion WIMS
May 2025	ESP monitoring, Text data processing
Second external release July 2025 (ESP monitoring + corrosion WIMS + text processing and generation)	
August 2025	DTS data functionality + “advanced” ESP
October 2025	Extension of WIMS (erosion, maintenance planning, well history tracking)
Final external release November 2025	
December 2025 / January 2026	Streamlining, bug fixes, leftovers, etc.

Conclusion

- Digital Twin provides:
  - Real-time model-based monitoring and calculations
  - Decision support systems
  - Early warnings for arriving problems; time to prepare or prevent
  - Help with diagnosing issues
    - ESP (real time and historic pump graphs, future: failure prediction)
    - Aquifer (Hall plots + derivative)
  - Ideal platform for continuing development

- WIMS module:
  - Demonstrating WI compliance in line with ISO 16530-1
  - Calculate corrosion based on actual operating parameters and tuned to measured corrosion rates
  - Improved corrosion forecasting may reduce logging and workover intervals

- Partly available as open access toolset

Conclusion

- Digital Twin provides:
  - Real-time model-based monitoring and calculations
  - Decision support systems
  - Early warnings for arriving problems; time to prepare or prevent
  - Help with diagnosing issues
    - ESP (real time and historic pump graphs, future: failure prediction)
    - Aquifer (Hall plots + derivative)
  - Ideal platform for continuing development

- WIMS module:
  - Demonstrating WI compliance in line with ISO 16530-1
  - Calculate corrosion based on actual operating parameters and tuned to measured corrosion rates
  - Improved corrosion forecasting may reduce logging and workover intervals

- Partly available as open access toolset

- **What is sought in WIMS module / Digital Twin?**

Thank you!

Digital Twin Architecture