INSIGHT INTO MODERN RESERVOIR ENGINEERING AND MANAGEMENT PRACTICE

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OUTLINE

- INTRODUCTION
- DEFINITIONS. EUROPEAN RESOURCE SETTINGS
- INSIGHT INTO MODERN RESERVOIR MANAGEMENT PRACTICE
  - HEAT EXTRACTION ISSUES
  - CASE STUDY – MADRID AREA ASSESSMENT OF GEOTHERMAL RESOURCES
  - WATER INJECTION
  - RESERVOIR SIMULATION
- SUSTAINABLE HEAT EXTRACTION. A RESERVOIR ENGINEERING APPROACH (CASE STUDY)
- CONCLUSIONS
INTRODUCTION

- **Geothermal Energy** is energy stored in the form of heat beneath the surface of the solid earth. This definition became official in Germany (VDI 4640) and it has been adopted by the European Geothermal Energy Council (EGEC).

- Geothermal energy can be reclaimed in two different ways:
  - in the form of electricity
  - the form of heat
    - each type of utilisation is distinguished by different technologies and applications.
GEODYNAMIC MAP OF EUROPE

EUROPEAN GEODYNAMIC SETTINGS
(after C. Sommaruga)
HEAT FLOW DENSITY MAP

from Cermak and Rybach (1979)
TEMPERATURE DISTRIBUTION @ 5000 m depth
RESOURCE ENVIRONMENTS

- high enthalpy (el. power)
- high temperature basins (el.power, district heating)
- medium temperature basins (district heating)
- everywhere: EGS, shallow geothermal
GEOTHERMAL ENERGY USES

www.geothermie-perspectives.fr
TENTATIVE GEOTHERMAL SYSTEM NOMENCLATURE
BASED ON SATURATED STEAM TEMPERATURES
(adapted from Subir Sanval. 2005)
SIMPLIFIED GEOTHERMAL UTILISATION DIAGRAM

Critical Point for pure water (@ 22,12 kPa)

Maximum saturated steam enthalpy (@ 3,48 kPa)

10 - 15 °C

100 - 110 °C

30°C

40°C

50°C

60°C

70°C

80°C

90°C

100°C

150°C

200°C

250°C

240°C

Direct Steam Expansion

Dual Flash Condensing

Single Flash (Condensing, Back-pressure)

Total Flow (Two phase expansion)

Binary (ORC, Kalina)

Freezing (Absorption)

Agro Industrial Uses

Process Heat

District Heating/Cooling

Space/Green house heating

Fish farming/Aquaculture

Balneology/Medicinal

Ground Source Heat Pump

10°C

20°C

30°C

40°C

50°C

60°C

70°C

80°C

90°C

100°C

150°C

200°C

250°C

300°C

350°C

374°C

CONVERSION CYCLE

ELECTRICITY GENERATION

GEOPOWER

GEOHEAT

DIRECT USES

THERMAL USES/PROCESSES (*)

(*) heat pump alone < 30 °C

combined heat pump/heat exchange > 30 °C

heat exchange alone > 50°C
Geothermal resource utilisation potential
A tentative assessment

![Diagram showing different temperature ranges for geothermal energy utilization: GEOPOWER and GEOHEAT, with categories for SuperCritical (SC), Conventional Steam Cycles (CSC), Organic Rankine Cycles (ORC), Enhanced Organic Rankine Cycles (EORC), and Low Enthalpy (LE).]
Geothermal continuum – The EGS issue

Low (≤1%)  Fluid Content \( \phi \), porosity  High (>20%)

Low Grade Conduction-Dominated EGS

Mid Grade EGS

High Grade Conduction-Dominated EGS

Conventional power generation boundary

Low Grade Hydrothermal

Mid Grade Hydrothermal

High Grade Hydrothermal

\( <T> \) °C/km

Average Geothermal Gradient

\(<K>\), permeability

Low (<1 md)  Natural Connectivity  High (>1000 md)

(Adapted from J. Tester)
INSIGHT INTO MODERN RESERVOIR MANAGEMENT PRACTICE

RESERVOIR ENGINEERING VS. MANAGEMENT

- RESERVOIR ENGINEERING ADDRESSES
  - HEAT IN PLACE
  - RESERVOIR PERFORMANCE
  - WELL DELIVERABILITIES
  - HEAT RECOVERY
  - RESERVOIR LIFE

- RESERVOIR MANAGEMENT ADDRESSES
  - OPTIMUM EXPLOITATION STRATEGIES
    - TECHNICAL FEASIBILITY
    - ECONOMIC VIABILITY
    - ENVIRONMENTAL SAFETY

IN A SUSTAINABLE DEVELOPMENT PERSPECTIVE
KEY QUESTIONS:

- IS GE:
  - RENEWABLE?
  - EXHAUSTIBLE?
  - SUSTAINABLE?
DEFINITIONS

Renewability
« The energy extracted from a renewable energy source is always replaced in a natural way by an additional amount of energy and the replacement takes place on a similar time scale as that of the extraction » (Axelsson et al, 2001).

Sustainability
« ... the ability of a geothermal heat extraction system to sustain production over long times » (Rybach, 2003).
« ... for each geothermal system and for each mode of production there exists a certain level of maximum energy production, below which it will be possible to maintain a constant energy production from the system for a very long time (100 – 300 years)... » (Axelsson et al, 2004).
RESOURCE MANAGEMENT & SUSTAINABLE EXPLOITATION

- **IS GEOTHERMAL HEAT A RENEWABLE ENERGY SOURCE?**
  - **YES. BECAUSE OF EVIDENCE OF HEAT FLOW**

- **IS GEOTHERMAL HEAT EXHAUSTABLE?**
  - **YES AS IT CAN BE EXPLOITED ABOVE CONDUCTIVE HEAT RESUPPLY**

- **HOW TO RECONCILE HEAT MINING ISSUES WITH LONGEVITY OF RESERVOIR LIFE AND RISK ASSESSMENT**
  - THIS IS WHAT SUSTAINABLE MANAGEMENT OF GEOTHERMAL RESOURCES IS ALL ABOUT
RESERVOIR MANAGEMENT DIAGRAM

RESERVOIR ENGINEERING
- Offer: Recoverable Heat
- Production Technology

DEVELOPMENT/MANAGEMENT STRATEGY
- Risk Assessment
- Demand: Existing/potential heat loads
- Economic/Financial/Institutional/Environmental

SUSTAINABILITY
- Externalities
- Economic

RENEWABLE/ SYSTEM LIFE
CASE STUDY – MADRID AREA
ASSESSMENT OF GEOTHERMAL RESOURCES

MADRID GEOTHERMAL RESOURCE SETTING

Location of Target Assessment Areas

NO-SE CROSS SECTIONAL SKETCH

(Adapted from European Geothermal Atlas & Petratherm)
GEOTHERMAL RESOURCE CLASSIFICATION VS DEPTH, TEMPERATURE & AQUIFER OCCURRENCE

GEOTHERMAL HEAT FLOW (9 \times 10^4 \text{ Wm}^2)

Depth (m)

Temperature (°C)

Abbreviations
- CHP: combined heat and power
- EGS: enhanced geothermal system
- GCHP/GWHP: ground coupled/ground water heat pump
- GDHC: geothermal district heating & cooling
- HP: heat pump
- Hx: heat exchange

0

200

500

1000

1500

2500

3500

5000

SHALLOW GTH

15/20

Impervious Rock

MEDIUM DEPTH GTH

50

Impervious Rock

DEEP GTH

100

Impervious Rock

ULTRA-DEEP GTH

130/140

160/180

50 W/m - 1.16 kW/m^2/°C

1.16 kW/m^2/°C

1.16 kW/m^2/°C

1.16 kW/m^2/°C (heat)

\eta 1.16 kW/m^2/°C (power)
GEOTHERMAL EXPLORATION/RESOURCE/RESERVE INTERACTION

Source: Australian Geothermal Reporting Code (AGCC)
MINING SCHEMES

<table>
<thead>
<tr>
<th>a. Borehole heat exchanger (BHE)</th>
<th>b. Groundwater doublet (GWD)</th>
<th>c. Aquifer energy storage (ATES)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shallow geothermal (0-200m) GSHPs</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Shallow Geothermal Sources
## MINING SCHEMES

<table>
<thead>
<tr>
<th>a. Medium depth doublet (heat pump assisted)</th>
<th>e)</th>
<th>c. Multiwell arrays</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="Diagram of medium depth doublet" /></td>
<td><img src="image" alt="Diagram of multiwell arrays" /></td>
<td><img src="image" alt="Diagram of multiwell arrays" /></td>
</tr>
</tbody>
</table>

### Medium depth/deep geothermal (1000-2500m)

**Medium depths - Deep Geothermal Sources**
## MINING SCHEMES

<table>
<thead>
<tr>
<th>a. Organic Rankine Cycle</th>
<th>b. Unconventional (EGS) CHP</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Ultra deep geothermal (3500-5000 m)</strong></td>
<td></td>
</tr>
</tbody>
</table>

Deep - Ultradeep seated Sources EGS
GEOTHERMAL RESOURCE & RESERVE ASSESSMENTS

DEFINITIONS

- Heat in place HIP
  \[ HIP = \gamma_t * Ah(\theta_i - \theta_0) \]

- Recoverable heat RCH
  \[ RCH = \eta \gamma_t * Ah(\theta_i - \theta_r) = r * HIP \]

- Heat recovery factor \( r \)
  \[ r = RCH / HIP = \eta(\theta_i - \theta_r) / (\theta_i - \theta_0) \]

- Efficiency of the heat extraction scheme \( \eta \)
  \[ \eta = (q / Ah) * (\gamma_w / \gamma_t) * t^* \]

- EGS power (\( W \)) and energy supply (\( E \))
  \[ W = \eta' q' \gamma_w (\theta_i - \theta_c) / 3600 \]
  \[ E = W * t^* \]

NOMENCLATURE

\( A \) = area (m\(^2\))
\( h \) = effective thickness (m)
\( q, q' \) = flowrates (m\(^3\)/h)
\( r \) = recovery factor
\( t^*, t'^{**} \) = system life (hrs)
\( \gamma_t = \phi \gamma_w + (1 - \phi) \gamma_r \) = total (fluid + rock) heat capacity (kJm\(^{-3}\)K\(^{-1}\))
\( \gamma_t, \gamma_r \) = rock and water heat capacities (kJm\(^{-3}\)K\(^{-1}\))
\( \theta_i, \theta_0, \theta_r, \theta_c \) = reservoir, mean ground, rejection and condensing temperatures (°K)
\( \eta, \eta' \) = efficiencies
**MINING SCHEMES**

**INITIAL DOUBLET**  
0-25 yrs

- P
- WH
- I

Initial cased wells 9"5/8 casings

**INTERMEDIATE TRIPLET ARRAY**  
26-50 yrs

- I'
- WH
- I

Former doublet wells lined (7") as injector wells  
New anti-corrosion production well

**NEW DOUBLET**  
51-75 yrs

- I'
- WH
- I

Former injector wells abandoned  
New anti-corrosion injection well

---

**Reservoir impacts**

- Red: Production well
- Blue: Injection well
- Black: Well heads

**Sustaining 75 yrs**  
**System life**
<table>
<thead>
<tr>
<th>ZONE</th>
<th>OVERALL (Grand Madrid)</th>
<th>SPECIFIC (NE Madrid)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AREA (km²)</td>
<td>1400</td>
<td>150</td>
</tr>
<tr>
<td>VOLUME 5 km depth (km³)</td>
<td>7000</td>
<td>750</td>
</tr>
<tr>
<td>HEAT FLOW DENSITY (Wm⁻²)</td>
<td>910⁻²</td>
<td>910⁻²</td>
</tr>
<tr>
<td>SUBSURFACE TEMPERATURES (°C)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>500 m</td>
<td>35</td>
<td>35</td>
</tr>
<tr>
<td>1500 m</td>
<td>60-70</td>
<td>60-70</td>
</tr>
<tr>
<td>2500 m</td>
<td>80-100</td>
<td>80-100</td>
</tr>
<tr>
<td>5000 m</td>
<td>160-180</td>
<td>160-180</td>
</tr>
<tr>
<td>ACCESSIBLE RESOURCE BASE (ARB) 5 km 10¹⁹ J</td>
<td>560</td>
<td>6.2</td>
</tr>
<tr>
<td>HEAT RESUPPLY</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Power (MWt)</td>
<td>126</td>
<td>13.5</td>
</tr>
<tr>
<td>Energy (GWht/yr)</td>
<td>1130</td>
<td>104</td>
</tr>
<tr>
<td>HEAT IN PLACE (HIP) (10¹⁸ J)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shallow GTH</td>
<td>21</td>
<td>2.2</td>
</tr>
<tr>
<td>Medium depth GTH</td>
<td>18</td>
<td>3.9</td>
</tr>
<tr>
<td>Deep GTH</td>
<td>27</td>
<td>3.1</td>
</tr>
<tr>
<td>Ultra-deep GTH</td>
<td>115</td>
<td>13.1</td>
</tr>
<tr>
<td>TOTAL</td>
<td><strong>181 10¹⁸ J</strong></td>
<td><strong>22.3 10¹⁸ J</strong></td>
</tr>
</tbody>
</table>
### RECOVERABLE HEAT (RCH) OVER 75 yrs

<table>
<thead>
<tr>
<th>Source</th>
<th>RCH J</th>
<th>Storage J</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shallow GTH (BHE/GWD) (10^18 J)</td>
<td>3.3/1</td>
<td>0.35/0.1</td>
</tr>
<tr>
<td>Medium depth GTH (10^18 J)</td>
<td>6.3</td>
<td>1.4</td>
</tr>
<tr>
<td>Deep GTH (10^18 J)</td>
<td>9.5</td>
<td>1.1</td>
</tr>
<tr>
<td>Ultra-deep GTH (10^18 J)</td>
<td>5.8</td>
<td>0.7</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td>24.9/22.6 10^18 J</td>
<td>3.6/3.3 10^18 J</td>
</tr>
</tbody>
</table>

### EXPLOITABLE HEAT (AND POWER) OVER 75 yrs

<table>
<thead>
<tr>
<th>Source</th>
<th>Exp J</th>
<th>Heat Exp J</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shallow GHT (BHE/GWD) (10^17 J)</td>
<td>0.36/0.07</td>
<td>0.04/0.007</td>
</tr>
<tr>
<td>Medium depth GTH (10^17 J)</td>
<td>1.3</td>
<td>0.3</td>
</tr>
<tr>
<td>Deep GTH (10^17 J)</td>
<td>4.4</td>
<td>1.1</td>
</tr>
<tr>
<td>Ultra-deep GTH CHP (10^17 J)</td>
<td>1.2</td>
<td>0.3</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td>7.3/7 10^17 J</td>
<td>1.7/1.7 10^17 J</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Source</th>
<th>Heat Exp J</th>
</tr>
</thead>
<tbody>
<tr>
<td>HEAT RESUPPLY (10^17 J)</td>
<td>3.09</td>
</tr>
<tr>
<td></td>
<td>0.33</td>
</tr>
</tbody>
</table>
CONCLUSION

<table>
<thead>
<tr>
<th>Item</th>
<th>Grand Madrid</th>
<th>NE Madrid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat in place (HIP) $10^{18}$ J</td>
<td>181</td>
<td>22</td>
</tr>
<tr>
<td>Recoverable heat (RCH) 75 yrs $10^{18}$ J</td>
<td>25</td>
<td>3.5</td>
</tr>
<tr>
<td>Exploitable heat (and power) (EXH) 75 yrs $10^{17}$ J</td>
<td>7.3</td>
<td>1.7</td>
</tr>
<tr>
<td>Heat resupply (assuming 90mWm$^{-2}$ heat flow density) $10^{17}$ J</td>
<td>3.09</td>
<td>0.33</td>
</tr>
<tr>
<td>EXH / RCH ratio (%)</td>
<td>3</td>
<td>5</td>
</tr>
</tbody>
</table>

FINAL RESOURCE/RESERVE PROJECTED FIGURES
WATER INJECTION

- Water injection **PROS:**
  - optimum heat recovery
  - disposal of the waste, cooled, brine a major concern owing to, increasingly stringent, environmental regulations;
  - pressure maintenance as exemplified by the, mass conservative, doublet concept of heat mining;
  - land subsidence control.

- Water injection **CONS:**
  - well short-circuiting (fractured media)
  - premature cooling (thermal breakthrough) of production wells
WATER INJECTION

EFFECT OF SEGEP INJECTION ON SE GEYSERS GENERATION
Calpine Power Plant Units 13, 16, 18 and NCPA Plants 1 & 2

ANNUAL AVE. GENERATION RATE (MWG)

Exponential

Geothermal Energy and CO2 Storage: Synergy or Competition, GFZ Potsdam, 20100210
WATER INJECTION

PARTICLE INDUCED DAMAGE

ARGILLACEOUS SANDSTONE

Matrix

Internal particles

Temperature
Pressure
Velocity
Salinity
pH

External particles

Pore throat plugging

Permeability impairment

Corrosion of tubing

Bacteria

Gas bubbles

Suspended particles in the fluid

Precipitation of chemical species

Fluid
WATER INJECTION

PARTICLE INDUCED DAMAGE

Field test (Paris Basin Triassic Sandstone, 1983)
### Projected Well / Reservoir Performance

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top reservoir depth</td>
<td>1,500 m</td>
</tr>
<tr>
<td>Static WHP</td>
<td>5 bars</td>
</tr>
<tr>
<td>Total pay</td>
<td>400 m</td>
</tr>
<tr>
<td>Net pay (h)</td>
<td>110 m</td>
</tr>
<tr>
<td>Effective porosity (Ø)</td>
<td>0.2</td>
</tr>
<tr>
<td>Permeability (k)</td>
<td>100 mD</td>
</tr>
<tr>
<td>Transmissivity (kh)</td>
<td>11,000 mDm</td>
</tr>
<tr>
<td>Skin factor (S)</td>
<td>2</td>
</tr>
<tr>
<td>Formation temperature</td>
<td>90ºC</td>
</tr>
<tr>
<td>Average injection temperature</td>
<td>35ºC</td>
</tr>
<tr>
<td>Fluid (eq. NaCl) salinity</td>
<td>2.5 g/l</td>
</tr>
<tr>
<td>Fluid dynamic viscosity (production) (µp)</td>
<td>0.32 cp</td>
</tr>
<tr>
<td>Fluid dynamic viscosity (injection) (µi)</td>
<td>0.73 cp</td>
</tr>
<tr>
<td>Total compressibility factor (α)</td>
<td>$10^{-4}$ bars $^{-1}$</td>
</tr>
<tr>
<td>Fluid density (ρp) at 90ºC</td>
<td>965.34 kg/m$^3$</td>
</tr>
<tr>
<td>Fluid density (ρi) at 35ºC</td>
<td>994.06 kg/m$^3$</td>
</tr>
<tr>
<td>Target injection rate (Q)</td>
<td>150 m$^3$/hr</td>
</tr>
<tr>
<td>WHP (150 m$^3$/hr, 35ºC)</td>
<td>20.5 bars</td>
</tr>
<tr>
<td>Sandface velocity (v$_sf$)</td>
<td>0.23 cm/s</td>
</tr>
<tr>
<td>Velocity at completion outlet (v)</td>
<td>0.61 cm/s</td>
</tr>
</tbody>
</table>

### Diagram

- Drilling
  - Ø 24
  - 60
  - Ø 17 1/2
  - 650
  - Ø 12 1/4
  - 1,420
  - Ø 12
  - 1,450
  - Ø 8 1/2
  - 1,815
  - Ø 6
  - 1,820
  - Ø 4
  - 1,816

- Casing / completion
  - Ø 18 5/8
  - 58
  - Ø 13 3/8
  - 648
  - DV 660
  - Ø 9 5/8
  - 1,448
  - Wire wrapped screen/blank liner assembly
  - Ø 6 3/8
  - 1,448
  - Gravel pack
  - 1,816
**RESERVOIR SIMULATION**

1. **Phase**
   - **Main exploration**
     - Identification of prospect, hydrological, geological setting, surface manifestations
   - **Assessment of structure and volume of reservoir**
     - Fluid characteristics
     - Classification of system
   - **Net heat loss (renewable resource estimate)**
   - **Conceptual model** (completion of at least one deep well)

2. **Phase**
   - **Reservoir modelling** (natural state)
     - (P, T data of wells)
   - **Interference tests** (multiple wells)
   - **Pump tests flow tests** (single well)

3. **Phase**
   - **Reservoir modelling** to match some significant transients
   - **Reservoir characteristics established from analysis of production wells**
   - **Reservoir modelling (matching most observed data)**

**Exploration stage**
- Exploration drilling

**Prefeasibility stage**
- Exploration drilling

**Feasibility stage**
- Production drilling (Production history)

**Production stage**
- Production drilling (Production history)
RESERVOIR SIMULATION

- All successful geothermal simulation techniques are based on two common ideas:
  - Difference equations are fully implicit with all mass and energy fluxes evaluated at the new time level.
  - Upstream weighting is used to calculate interface quantities.
RESERVOIR SIMULATION

In summary a successful reservoir modelling program has three fundamental components:

- The collection of meaningful and reliable geoscientific, production, and reinjection data, and the interpretation and analysis of this data.
- The construction of a conceptual reservoir model.
- The development of a computer model of the reservoir, to allow the simulation of behaviour patterns and response to exploitation.
RESERVOIR SIMULATION

Data collection and analysis

Conceptual model

Preliminary models

Natural state models (full or partial)

Simple production models (possibly several)

Full-scale production models (usually 3-D)
CASE STUDY - SOUTHAMPTON

- 1820 m deep well
- Triassic sandstone reservoir
- 70 m$^3$/h, 
- 74°C well head temperature,
- 300 m water level drawdown
- #3.5 Darcy meter transmissivity
SOUTHAMPTON RESERVOIR MODEL
Model calibration

a. Water level drawdowns

- Dashed line: Recharged reservoir (R)
- Solid line: Impervious closed reservoir (C)
- Dotted line: Weighted (3R + C)/4
- Red squares: Measured drawdown

b. Production history

- Black line: Q (L/s)
Predicted drawdown patterns
SUSTAINABLE HEAT EXTRACTION. A RESERVOIR ENGINEERING APPROACH. (CASE STUDY)
BACKGROUND AND SCOPE

RESOURCE SETTING

I Test area (single doublet, homogeneous reservoir)
II Development area (multidoublet, heterogeneous reservoir)
BACKGROUND AND SCOPE

RESOURCE SETTING
PROCEDURE

STUDY OBJECTIVES

1. early reservoir conceptual models and related production well thermal breakthrough predictions;
2. matching forecasted vs. actual breakthrough times and redesigning/calibrating modelling features by:
   i. comparing 2D (single layer) and 3D (multilayered) reservoir structures;
   ii. assessing relevant bedrock/caprock thermal boundary conditions;
   iii. quantifying (analytically and numerically) interbedded impervious layer heat transfers and subsequent impacts on production well cooling kinetics;
3. enhancement of well and reservoir life via appropriate production/injection multiwell arrays and novel, long lasting, well completions;
4. relevant future heat demand and offer scenarios meeting sustainability requirements.
BACKGROUND AND SCOPE

HEAT EXTRACTION

\[ t_B = \frac{\pi \gamma_t d^2 e}{3 \gamma_f q} \]

where:
- \( t_B \) = thermal breakthrough time (h)
- \( d \) = bottomhole (top reservoir) well spacing (m)
- \( q \) = production (-)/injection (+) flowrate (m\(^3\)/h)
- \( \gamma_t \) = reservoir heat capacity (J/m\(^3\) K)
  \( = \phi \gamma_f + (1 - \phi) \gamma_r \)
- \( \gamma_f \) = fluid heat capacity (J/m\(^3\) K)
- \( \gamma_r \) = rock heat capacity (J/m\(^3\) K)
- \( \phi \) = porosity
PROCEDURE

ASSESSMENT OF RESERVOIR STRUCTURE

b. Three layered reservoir

a. Flowmeter logging

100

Production well

%FLOW

100

Injection well

%FLOW

1. 34.5%
2. 10%
3. 30.5%
4. 18%
5. 5%

1. 40%
2. 15%
3. 23.5%
4. 4%
5. 4%

a. Flowmeter logging

RESERVOIR
IMPERVIOUS LAYER

CR  CAPROCK
BR  BEDROCK

b. Three layered reservoir

c. Sandwiched reservoir

Geothermal Energy and CO2 Storage: Synergy or Competition, GFZ Potsdam, 20100210
II Development area (multidoublet, heterogeneous reservoir)

I Test area (single doublet, homogeneous reservoir)
TEST AREA

TEMPERATURE DEPLETION AT PRODUCTION WELL
2D AND SINGLE LAYER EQUIVALENT MODELS

[Graph showing temperature depletion over time for single layer equivalent reservoir and 2D reservoir.]
TEST AREA

TEMPERATURE DEPLETION AT PRODUCTION WELL
THREE LAYERED RESERVOIR MODEL

Temperature depletion, °C

Time, years

Reservoir 1 (top)
Reservoir 2 (int.)
Reservoir 3 (bot)
TEST AREA
TEMPERATURE DEPLETION AT PRODUCTION WELL
SANDWICHED RESERVOIR MODEL

Time, years

Temperature depletion, °C

Top reservoir
Bottom reservoir
Test area (single doublet, homogeneous reservoir)

Development area (multidoublet, heterogeneous reservoir)

- Doublet in operation
- Abandoned doublet

Geothermal Energy and CO2 Storage: Synergy or Competition, GFZ Potsdam, 20100210
DEVELOPMENT AREA
LAYER STACK
## DEVELOPMENT AREA

### PRODUCTION/INJECTION SCHEDULE

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### DOUBLET

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### DOUBLET

- Initial doublet: 2 deviated wells (steel cased 9”5/8)
- Intermediate triplet: 2 injection wells (initial reconditioned doublet, 7” steel lining), 1 new anticorrosion (steel/fiberglass lined), large diameter deviated well
- Final doublet: 3 anticorrosion (steel/fiberglass lined), large diameter deviated (existing producer and newly completed injector) wells.
DEVELOPMENT AREA

SIMULATION PERIOD: 2010-2035

[Diagram with temperature distribution and location markers]
CONCLUSIONS

- Sustainable extraction of exhaustible geothermal resources aims at increased reservoir and well longevities targeted at lifetimes nearing one hundred years.

- It requires:
  - Dependable reservoir properties
  - Appropriate assessment of reservoir structure
  - Reliable heat extraction concepts, well completion/maintenance technologies and monitoring protocols
  - Databases and reservoir simulation tools
Geothermal Energy:
renewable-sustainable-proven-achievable-realistic

Thank you!

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