Rittershoffen soft stimulations
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Outline

• Rittershoffen site overview
• Rittershoffen operation feedback after 2 years heat production
• Rittershoffen in Destress
  • Hydrothermal properties of the reservoir
  • Detailed GRT-1 stimulation analysis
  • Stress drops analysis
Rittershoffen site overview
Rittershoffen site location

- Industrial geothermal site located in the Upper Rhine Graben, 8km east of Soultz-sous-Forêts
- Target: regional fault zone in granite basement
Rittershoffen site overview: 100% heat direct use

26 MWth
Production Temp.: 168°C
Operation flowrate: 270m³/h
Wells GRT-1 and GRT-2: completion and well trajectories
Wells GRT-1 and GRT-2: temperatures

Temperature profiles at equilibrium
Operation feedback after ~2 years use
Rittershoffen operation feedback last 21 months

- In operation since April 2016
- No felt seismicity

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of induced events in 2017</td>
<td>734</td>
</tr>
<tr>
<td>Max Magnitude (Mlv)</td>
<td>1.3</td>
</tr>
<tr>
<td>Max PGV (mm/s)</td>
<td>0.24 mm/s</td>
</tr>
</tbody>
</table>

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Rittershoffen operation feedback last 21 months

- In operation since April 2016
- Availability > 90%
- Estimated avoided CO2 emissions in 2017: 35 kTo

<table>
<thead>
<tr>
<th>Mois</th>
<th>Nbr arrêt</th>
<th>Durée totale d'arrêt</th>
<th>Heures de marche</th>
<th>Disponibilité centrale</th>
<th>Énergie th centrale</th>
<th>Énergie th fournie</th>
<th>Efficacité réseau</th>
<th>Puissance th moyenne</th>
<th>Émission CO2 évitée</th>
</tr>
</thead>
<tbody>
<tr>
<td>2016</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Septembre</td>
<td>1</td>
<td>3 h</td>
<td>717 h</td>
<td>99.6 %</td>
<td>9 330 MWh&lt;sub&gt;n&lt;/sub&gt;</td>
<td>7 960 MWh&lt;sub&gt;n&lt;/sub&gt;</td>
<td>85.3 %</td>
<td>11.5 MWh&lt;sub&gt;n&lt;/sub&gt;</td>
<td>1 976 tCO₂</td>
</tr>
<tr>
<td>Octobre</td>
<td>2</td>
<td>8 h</td>
<td>736 h</td>
<td>98.9 %</td>
<td>10 652 MWh&lt;sub&gt;n&lt;/sub&gt;</td>
<td>9 080 MWh&lt;sub&gt;n&lt;/sub&gt;</td>
<td>85.2 %</td>
<td>12.7 MWh&lt;sub&gt;n&lt;/sub&gt;</td>
<td>2 254 tCO₂</td>
</tr>
<tr>
<td>Novembre</td>
<td>5</td>
<td>303 h</td>
<td>327 h</td>
<td>45.4 %</td>
<td>4 440 MWh&lt;sub&gt;n&lt;/sub&gt;</td>
<td>3 864 MWh&lt;sub&gt;n&lt;/sub&gt;</td>
<td>87.0 %</td>
<td>11.7 MWh&lt;sub&gt;n&lt;/sub&gt;</td>
<td>959 tCO₂</td>
</tr>
<tr>
<td>Décembre</td>
<td>2</td>
<td>132.5 h</td>
<td>611.5 h</td>
<td>82.2 %</td>
<td>9 271 MWh&lt;sub&gt;n&lt;/sub&gt;</td>
<td>8 181 MWh&lt;sub&gt;n&lt;/sub&gt;</td>
<td>88.2 %</td>
<td>13.6 MWh&lt;sub&gt;n&lt;/sub&gt;</td>
<td>2 031 tCO₂</td>
</tr>
<tr>
<td>Total 2016</td>
<td>10</td>
<td>536.5 h</td>
<td>2931.5 h</td>
<td>81.6 %</td>
<td>33 693 MWh&lt;sub&gt;n&lt;/sub&gt;</td>
<td>29 085 MWh&lt;sub&gt;n&lt;/sub&gt;</td>
<td>86.3 %</td>
<td>12.4 MWh&lt;sub&gt;n&lt;/sub&gt;</td>
<td>7 220 tCO₂</td>
</tr>
</tbody>
</table>

| 2017    |           |                      |                  |                        |                     |                     |                   |                     |                     |
| Janvier | 1         | 10 h                 | 728 h            | 97.8 %                 | 13 654 MWh<sub>n</sub> | 12 583 MWh<sub>n</sub> | 92.2 %            | 17.3 MWh<sub>n</sub> | 3 124 tCO₂        |
| Février | 3         | 16.5 h               | 655.5 h          | 97.5 %                 | 12 813 MWh<sub>n</sub> | 11 822 MWh<sub>n</sub> | 92.3 %            | 18.0 MWh<sub>n</sub> | 2 935 tCO₂        |
| Mars    | 4         | 293.5 h              | 449.5 h          | 60.6 %                 | 8 317 MWh<sub>n</sub>  | 7 581 MWh<sub>n</sub>  | 90.9 %            | 17.5 MWh<sub>n</sub> | 1 877 tCO₂        |
| Avril   | 5         | 16 h                 | 704 h            | 97.8 %                 | 13 232 MWh<sub>n</sub> | 12 322 MWh<sub>n</sub> | 93.1 %            | 17.7 MWh<sub>n</sub> | 3 059 tCO₂        |
| Mai     | 4         | 13.5 h               | 730.5 h          | 68.2 %                 | 14 050 MWh<sub>n</sub> | 12 941 MWh<sub>n</sub> | 92.1 %            | 17.6 MWh<sub>n</sub> | 3 213 tCO₂        |
| Juin    | 1         | 1.5 h                | 718.5 h          | 99.8 %                 | 13 013 MWh<sub>n</sub> | 12 050 MWh<sub>n</sub> | 92.6 %            | 16.8 MWh<sub>n</sub> | 2 962 tCO₂        |
| Juillet | 2         | 223.5 h              | 520.5 h          | 70 %                   | 9 161 MWh<sub>n</sub>  | 8 233 MWh<sub>n</sub>  | 89.9 %            | 16.4 MWh<sub>n</sub> | 2 044 tCO₂        |
| Août    | 2         | 16 h                 | 728 h            | 97.8 %                 | 13 824 MWh<sub>n</sub> | 12 812 MWh<sub>n</sub> | 92.7 %            | 17.6 MWh<sub>n</sub> | 3 181 tCO₂        |
| Septembre | 2        | 4 h                  | 716 h            | 99.4 %                 | 15 345 MWh<sub>n</sub> | 14 030 MWh<sub>n</sub> | 91.4 %            | 19.6 MWh<sub>n</sub> | 3 484 tCO₂        |
| Octobre | 0         | 0 h                  | 745 h            | 100 %                  | 15 970 MWh<sub>n</sub> | 14 744 MWh<sub>n</sub> | 92.3 %            | 19.8 MWh<sub>n</sub> | 3 661 tCO₂        |
| Novembre | 4        | 19 h                 | 701 h            | 97.4 %                 | 12 456 MWh<sub>n</sub> | 11 230 MWh<sub>n</sub> | 90.2 %            | 16.6 MWh<sub>n</sub> | 2 788 tCO₂        |
| Décembre | 1        | 4 h                  | 740 h            | 99.5 %                 | 13 808 MWh<sub>n</sub> | 12 492 MWh<sub>n</sub> | 90.5 %            | 18.1 MWh<sub>n</sub> | 3 102 tCO₂        |
| Total 2017 | 29      | 623.5 h              | 8136.5 h         | 92.9 %                 | 155 642 MWh<sub>n</sub> | 142 820 MWh<sub>n</sub> | 91.7 %            | 17.8 MWh<sub>n</sub> | 35 461 tCO₂       |
Rittershoffen in Destress: reservoir characterization and detailed analysis of GRT-1 stimulation
GRT-1 stimulation sequence and injectivity index

- Initial injectivity x5
  - No felt events
  - Economic threshold reached
GRT-2 well testing sequence and injectivity index

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GRT-1 and GRT-2 hydraulic analysis

-> See details in Baujard et al. (2017), Geothermics

• No clear boundary effect to be seen on the hydraulic tests

• Circulation test performed:
  • Tracer breakthrough in 14 days
  • Pressure connection in 30 minutes
  • Downhole distance between open sections: 1200m

<table>
<thead>
<tr>
<th>Well</th>
<th>Dimensionless skin factor [-]</th>
<th>GRT-1</th>
<th>GRT-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fault</td>
<td>Hydraulic cond. [m·s⁻¹]</td>
<td>21.3</td>
<td>1.8</td>
</tr>
<tr>
<td></td>
<td>Specific storage [m⁻¹]</td>
<td>-</td>
<td>2.9 · 10⁻⁶ (40m)</td>
</tr>
<tr>
<td>Matrix</td>
<td>Hydraulic cond. [m·s⁻¹]</td>
<td>6.1 · 10⁻⁸ (500m)</td>
<td>5.3 · 10⁻⁷ (500m)</td>
</tr>
<tr>
<td></td>
<td>Specific storage [m⁻¹]</td>
<td>7.2 · 10⁻⁷ (500m)</td>
<td>5.2 · 10⁻⁷ (500m)</td>
</tr>
</tbody>
</table>
Acoustic Image Logs comparison before and after stimulations in well GRT-1

-> See details in Vidal et al. (2016), Geophysical Journal International

- Quantification of the impact of different stimulations (thermal, chemical and hydraulic) on the different sections of well GRT-1
Pressure drop analysis

-> See details in Meyer et al. (2017) Stanford Geothermal Workshop

- Detailed analysis of hydraulic stimulation performances applied to fractured hard rocks in GRT-1 and pressure drops mechanism investigations

- Correlation of pressure drops and induced seismicity

- Proposition of a pressure drop mechanism and modelling of the process using CFRAC (McClure)
Lesson’s learned

• At a reservoir scale
  - Regional faults are flow zone in the Rhine Graben
  - Convection between to Muschelkalk and weathered granite
  - In-fault convection?

• Successful stimulation of GRT-1
  - Chemical stimulation impacted Triassic sandstones and basement permeability
  - Hydraulic stimulation impacted mostly basement permeability
  - Great injectivity increase of GRT-1
  - There is a link between pressure drops and seismicity (seismic clusters)
  - No relation between pressure drop amplitude and seismic magnitude could be highlighted
  - The CFRAC model seems to confirm the inferred mechanism
  - In any case, pressure drops are related with near-well phenomena (50-100m max)

• Operation
  - Continuous injectivity increase of injection well
  - LSP (Line shaft pumps) show good results for high temperature and high salinity fluids
  - Induced seismicity can be handled
  - High temperature corrosion and scaling inhibitors available

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On-going work

• Contribution to GRC 2018 submitted: “Experience learnt from a successful soft stimulation and operational feedback after 2 years geothermal power and heat production plants in Rittershoffen and Soultz-sous-Forêts (France)”, by Baujard et al.

• Contribution to EAGE 2018 submitted by Sosio et al. (SCHLUMBERGER)

• Paper preparation on GRT-1 induced seismicity catalogues, by Maurer et al.
Related publications

• Peer reviewed journals

• Reports
  - MEYER, G. (2016) Advanced analysis of the stimulation of GRT-1 geothermal well (Rittershoffen, France), ESG Report 16-0186, 78pp - Confidential

• EGC Conference

• Other Conference
  - VIDAL J., GENTER A., SCHMITTBUHL J., BAUJARD C., (2016). Hydraulic stimulation or low water injection in fractured reservoir of the geothermal well GRT-1 at Rittershoffen (France)?AGU Fall meeting, 12-16 December 2016, San Francisco, California, USA.
  - MEYER et al. (2017), “Analysis and numerical modelling of pressure drops observed during hydraulic stimulation of GRT-1 geothermal well (Rittershoffen, France)”, Stanford geothermal workshop, California

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Thank you very much for your attention

Acknowledgements

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