Proceedings World Geothermal Congress 2000
Kyushu - Tohoku, Japan, May 28 - June 10, 2000

PRODUCTION CAPACITY AND SUSTAINABILITY OF GEOTHERMAL DOUBLETS

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Keywords: Geothermal doublet, thermal drawdown, recovery, sustainability

ABSTRACT

The reinjection of the cooled water in geothermal doublet operation causes thermal drawdown in an expanding volume which propagates to the production well, where the temperature will decrease after the breakthrough time. Corresponding long-term calculations with porous and fractured reservoir models for the doublet operation in Riehen near Basel, Switzerland show that only a moderate temperature drop is to be expected even after decades of production. The maximum value will be about -0.7 K in one decade.

After production stop the heat production capacity of the reservoir will recover. Corresponding calculations show that the recovery of the Riehen reservoir depends strongly on the circulation scheme. Shorter production-recovery cycles produce more thermal energy.
On the other hand the used reservoir model type showed only a small influence on the recovery which was 35%-40% after a 40 year production and a subsequent similar recovery time. The thermal drawdown as well as the recovery occurs in an asymptotic manner. Nevertheless sustainable heat production can be maintained over decades.

1. INTRODUCTION

The heat content of a deep aquifer can be utilised by producing the aquifer's fluid. The fluids heat is transferred through a heat exchanger to a district heating network, whereas the cooled water is reinjected into the aquifer by a second borehole at a sufficient distance to the production borehole (doublet operation). Due to this geothermal circuit the produced hot fluid is successively replaced by cooled injected water. This leads to an increasing volume of thermal drawdown propagating from the injection to the production well. After the thermal breakthrough time the temperature of the produced fluid will decrease with a rate depending on the production scheme and on the physical and geometric properties of the reservoir. The increasing thermal gradients in the reservoir cause a correspondingly increasing conductive thermal recovery. Hence a thermal steady state will be reached after a sufficient circulation time which yields a constant production temperature.

A central question often concerns the sustainability of a geothermal operation in general. At a regional scale geothermal resources are principally renewable in consequence of the heat flux from the earth's interior. However, the heat production of a specific geothermal operation can exceed the natural thermal re-supply considerably due to economic and technical constraints. Therefore considerations about the sustainability of a geothermal operation must be carried out at a local scale including also the recovery effect after a production stop.

2. THE GEOTHERMAL OPERATION IN RIEHEN

In the community of Riehen near the city of Basel a heating network has been installed in 1994, which supplies about 160 users. About 50% of the needed energy are covered by a geothermal doublet operation (production well 1547 m, reinjection well 1247 m in a distance of 1.0 km). The fluid is produced from a fractured aquifer (Triassic "Oberer Muschelkalk") at the border of the Rheingraben rift structure (Figure 1). The geothermal doublet operates with an annual average extraction/reinjection flowrate of 10 l/s. Reinjection temperature is 25 °C which yields a useable temperature drop of 37 K.

It is essential to provide the heat exchanger with a production temperature of 62°C without a considerable drawdown for about 30 years. It has been demonstrated by numerical simulations in (Mégel 1996) that these boundary conditions are fulfilled by the geothermal circuit for different reservoir types. Results of calculations for porous and fractured reservoir types are presented in this paper shortly.

Additional attention is focussed on the recovery effect of the geothermal doublet operation in Riehen. Results of numerical (finite element) calculations for porous and fractured reservoir models are presented.

3. RESERVOIR MODEL

The heat extraction from the rock mass, and consequently its thermal recovery, depends strongly on the structure of the flow-paths in the reservoir. Thus three different FE-models for the reservoir have been used for the calculations of the production temperature and thermal recovery:

1. homogeneous porous aquifer, thickness 20 m
2. fractured aquifer with a distance between the fracture zones of 50 m, height of the fracture zones 20 m
3. fractured aquifer with a distance between the fracture zones of 100 m, height of the fracture zones 20 m (Figure 2)

The two fractured reservoir models consist of a network of rectangular fracture zones with an hydraulic conductivity of about 10^5 times higher than that of the surrounding rock material (Figure 2). Thus the heat transport in the reservoir due to the injected cold water is governed in the fracture zones mainly by advection and by conduction in the surrounding rock respectively. The thermal conductivity was assumed as 2.5 W/m K, the heat capacity as 2.5 10^6 J/m^3 K. Corresponding to the hydraulic interpretation of the production tests the aquifer has two opposite impermeable boundaries (Figure 1).

The numerical simulations have been performed with the FE-code FRACTure (Kohl 1992; details about the site see in Mégel 1996).

4. RESULTS

4.1. Temperature development in the reservoir and at the production well

The development of the temperature in the aquifer is shown in Figure 3 for the porous model and for the model with a regular network of fracture zones with a spacing of 100 m (see also Figure 2). Since the thermal front (indicated as the isoline of a temperature decrease ΔT of 1 K) propagates faster to the production well in the fracture zone model than in the porous model, the corresponding thermal breakthrough time is shorter (Figure 6). Because of this fast propagation of the temperature front in the fractured aquifer most of the heat content in the rock between the fracture zones remains still unextracted at the time of the temperature fronts first arrival at the production well. Consequently the subsequent temperature drop is smoother in the fracture zone network models than in the porous ones.

The calculated drop of the production temperature for the doublet operation Riehen is very moderate for all reservoir models. The development of the production temperature depends strongly on the reservoir model type (Figure 6). For the model of a 100 m spaced fracture zone network the production temperature decreases by less than 2 K within the first 40 years. For a fracture zone network with 50 m spacing the corresponding value is less than 1 K, due to the larger heat exchange area available in the reservoir. The most favourable case is the porous aquifer with a drop of 0.3 K after the first 40 years.

4.2. Constant long-term production

For the Riehen doublet operation a long-term calculation has been carried out with the 100 m spaced fracture zone model. The steady state production temperature is not reached even after 300 years (Figure 4). The development of the temperature can be characterised by considering the temperature change ΔT over a given time period, e.g. 10 years. This curve indicates the asymptotic behaviour of the production temperature. The maximum value of -0.7 K/10 years is obtained after 20 years, afterwards the temperature drop decreases down to a value of -0.15 K/10 years after 300 years production. Thus practically constant heat production can be sustained.

4.3. Recovery of heat production capacity

For the doublet operation in Riehen the influence of the circulation scheme and the flowpath model to the recovery of the heat capacity of the reservoir have been investigated.

For a given reservoir model the circulation scheme leads to a specific production temperature development. For the 100 m spaced fracture zone network model the production temperature of a constant circulation rate of 5 l/s and production-recovery cycles with 10 l/s of 10, 20, 40 and 80 years have been calculated (Figure 5). A comparison of the production temperature shows that the temperature will remain on a level, which is the higher the shorter the production-recovery cycle period is. The maximum value E_{max} would be reached if the temperature stayed at its initial value (62ºC). This means that the reservoir has the ability to recover completely the extracted energy. Regarding an operation period of 160 years and a constant circulation of 10 l/s, one cycle of 80 years production with a subsequent 80 years recovery can be assumed to define the minimum energy production E_{min} (see Figure 5).
Relating the energy production E of different production schemes to E_{min} and E_{max} a circulation scheme dependent, relative recovery R_c of the reservoir can be defined as following:

$$R_c = \frac{E - E_{\min}}{E_{\max} - E_{\min}} \tag{1}$$

For the considered circulation schemes the maximum value for the relative recovery R_c of 48.7 % is obtained with a production-recovery-cycle of 10 years (Table 1). If the cycle period were shorten continuously a constant production rate of 5 l/s would be reached as a limiting value. The corresponding value for R_c is 70 % defining the maximum value of recovery for a given water extraction within a period of 160 years.

The influence of the flowpath structure to the thermal recovery can be expressed as a relative recovery as used in (Pritchett 1998). It is defined by the relation between the difference of the second phase energy with and without a production break and the energy drop between the two continuous phases (see also Figure 6):

$$R_{40} = \frac{E_{2,R40} - E_2}{E_1 - E_2} \tag{2}$$

If the second phase energy $E_{2,R40}$ had reached the value of the first phase energy E_1 within the 40 year recovery break the relative recovery R_{40} would be 100 %.
As shown in Table 2 the relative recovery R_{40} of the heat production capacity of the reservoir due to a production break of 40 years is between 35% and 40%. The tendency of a higher recovery value from the 50 m to the 100 m spaced fracture zone network model can be explained by the higher production provoked temperature gradients in the reservoir which leads to a stronger temperature compensating heat influx. The unexpected higher relative recovery in the porous model may be due to the relatively late thermal breakthrough time in the first production phase.
Nevertheless it can be stated that at least for the three considered reservoir models the relative recovery of the heat

production capacity of the reservoir seems to be nearly independent from the reservoir model type. This may be due to the similarity between the thermal response of a reservoir to a heat extraction and to the subsequent recovery processes.

5. CONCLUSIONS

- The geothermal doublet Riehen will operate in a sustainable manner over decades without economically significant production temperature drop.

- With respect to a geothermal power of 1.5 MW the recovery of the heat production capacity of the Riehen reservoir of 35 % to 40% due to a production break of 40 years can be regarded as an average induced recovery heat flux of 525 kW to 600 kW. This exceeds a recovery value of about 100 kW derived from the regional terrestrial heat flow of 100 mW/m^2 and an approximate extension of the exploited reservoir of 1 km^2 by a factor of 5 to 6.

- Shorter production-recovery cycles produce more thermal energy. This may be significant for reservoir developments with multi-doublet patterns.

ACKNOWLEDGEMENTS

The authors thank Prof. Dr. L. Hauber (Geological Institute, University of Basel) for valuable advice and discussions.

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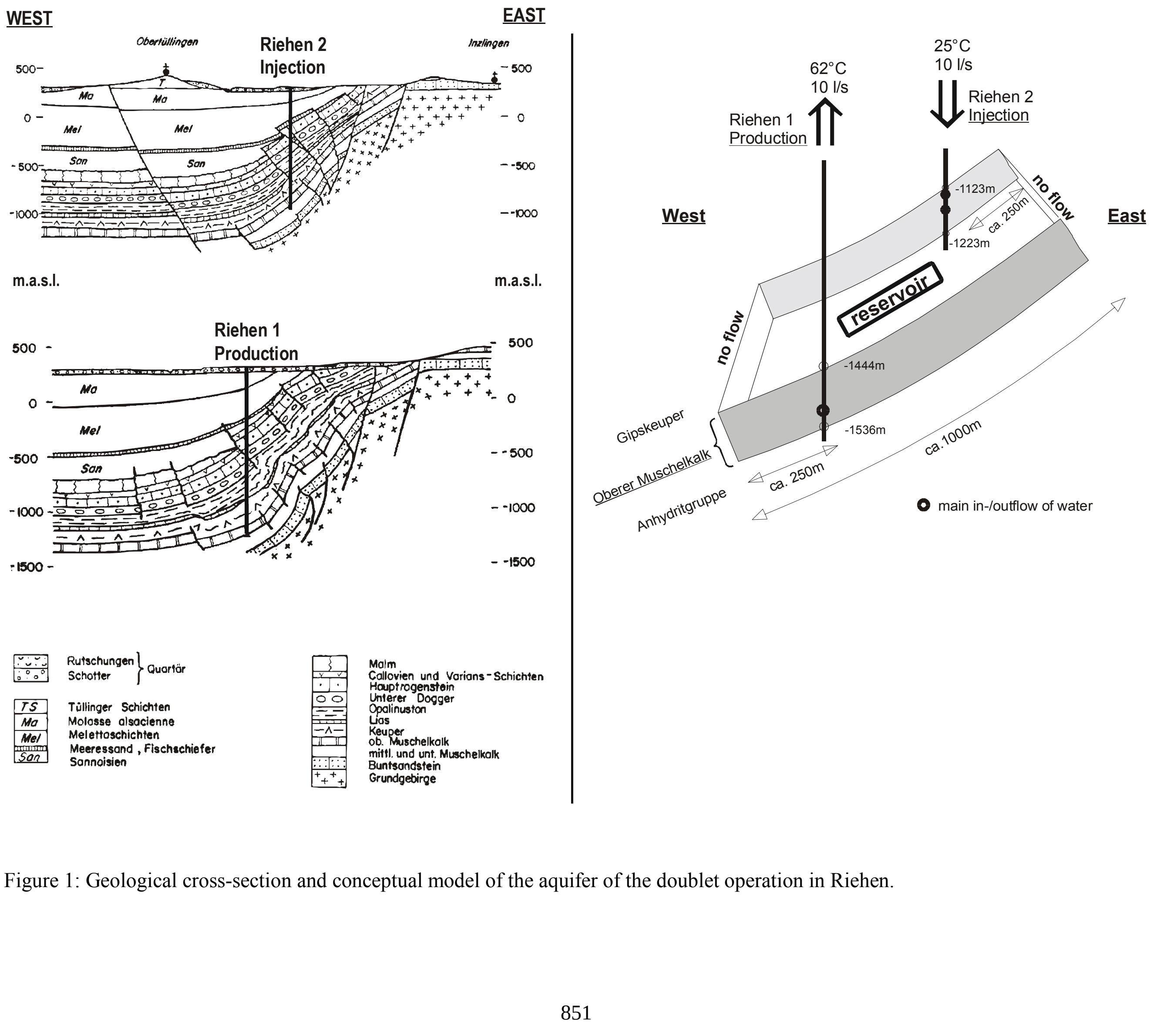

Figure 1: Geological cross-section and conceptual model of the aquifer of the doublet operation in Riehen.

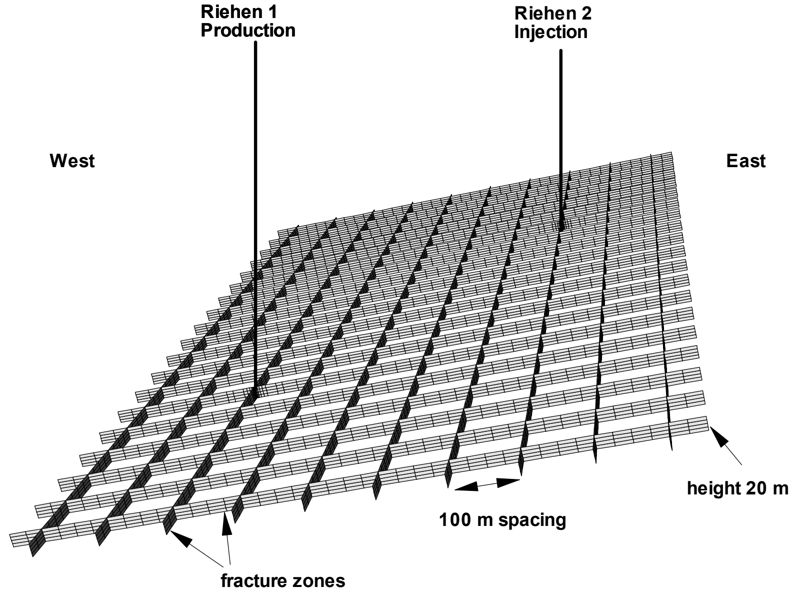

Figure 2: View to the FE-mesh of the 100 m spaced fracture zone model. These fracture zones are embedded within material with a permeability of at least 10^5 times lower.

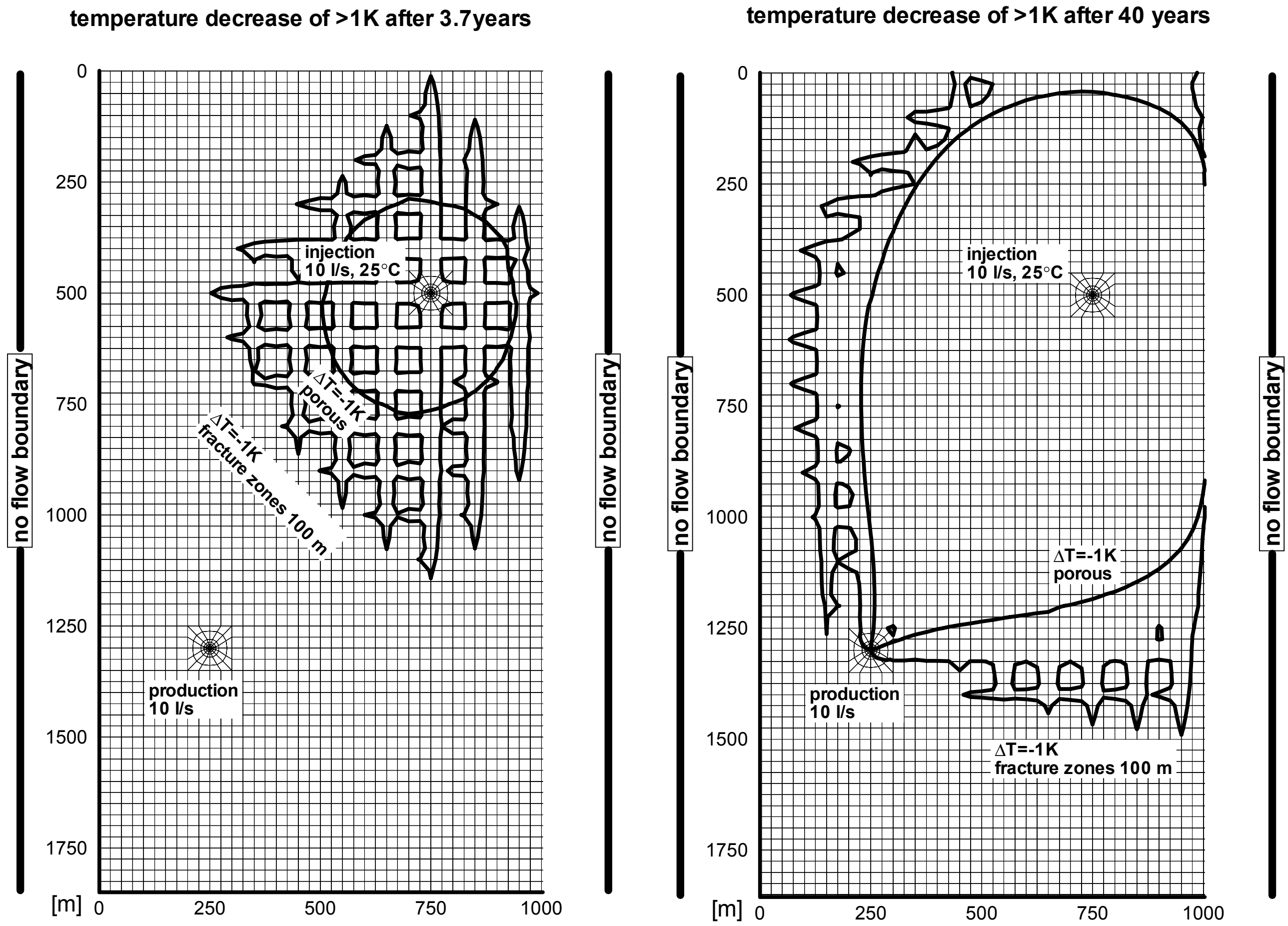

Figure 3: Propagation of the contour line of a temperature drop of 1 K for the porous and the 100 m fracture zone model in a horizontal plane. Indicated is also the 25 m FE-grid.

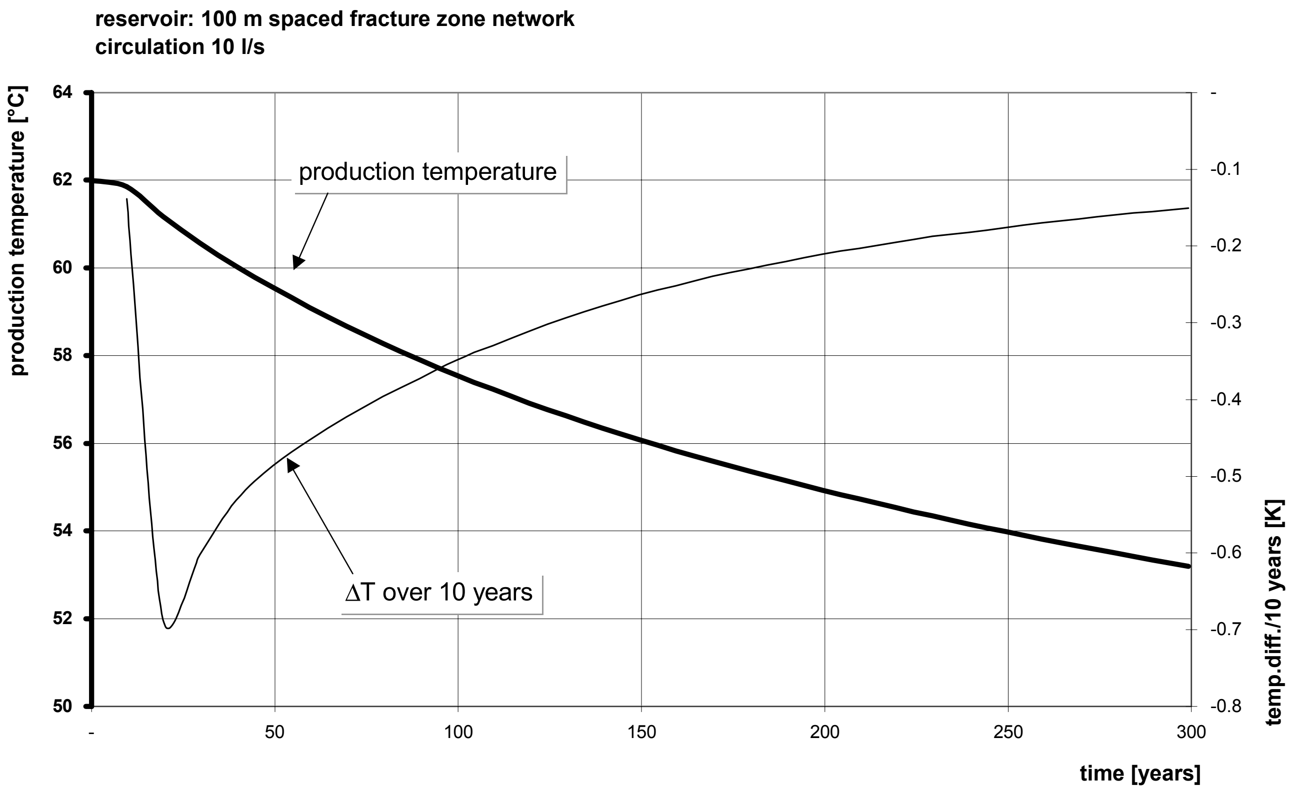

Figure 4: Development of the production temperature for a 100 m spaced fracture zone reservoir model (see also Figure 2 and Figure 3)

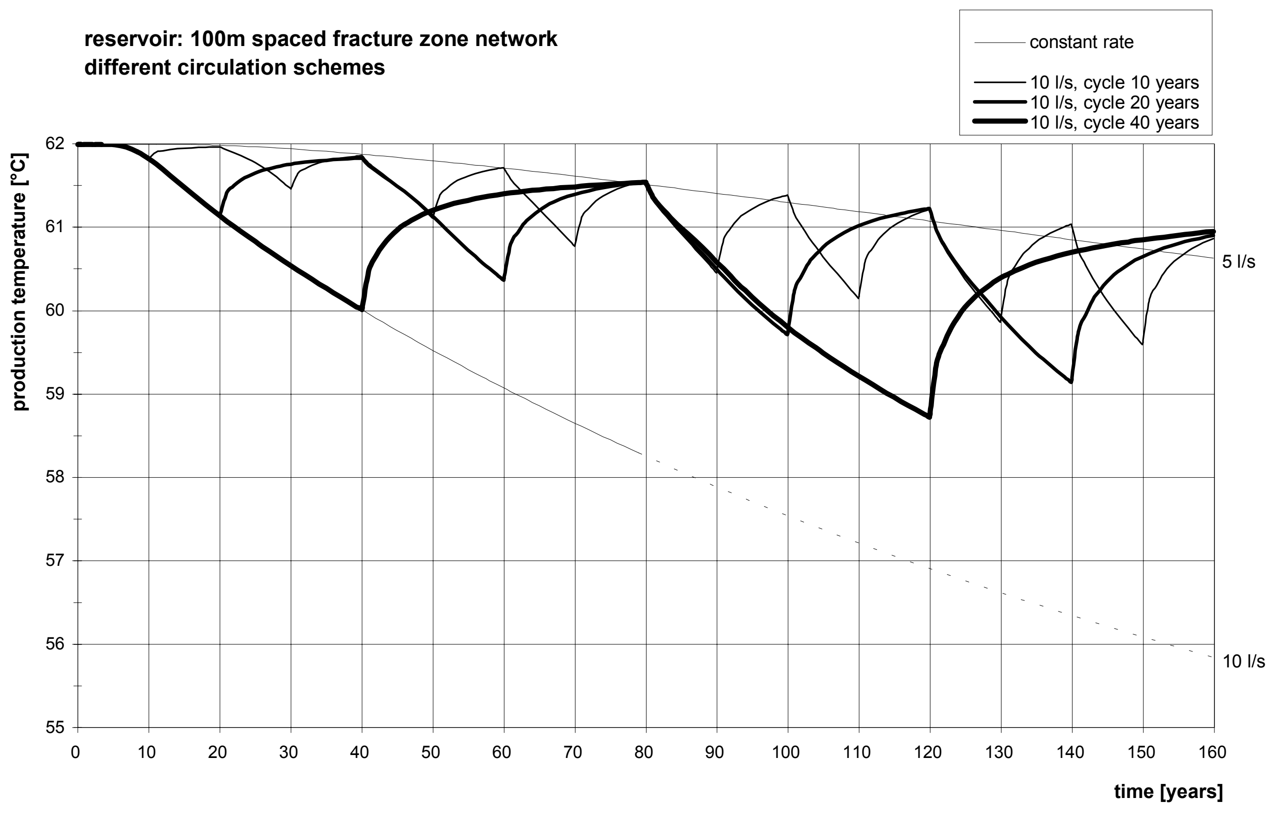

Figure 5: Production temperature for production-recovery cycles of different duration for a 100 m spaced fracture zone reservoir model (see also Figure 2 and Figure 3)

Table 1: Circulation scheme dependent recovery of the reservoir (see Figure 5)

circulation scheme	circulation rate [l/s]	considered time period [years]	energy production E [MWh]	energy production [%]	reservoir recovery R [%]
1x80 year prod.-rec. cycle, no thermal drawdown	10	160	1'089'043	105.5	100
no production breaks	5	160	1'071'908	103.8	70
8x10 year prod.-rec. cycles	10	160	1'059'875	102.7	48.7
4x20 year prod.-rec. cycles	10	160	1'052'908	102.0	36.5
2x40 year prod.-rec. cycles	10	160	1'043'995	101.1	20.8
1x80 year prod.-rec. cycle	10	160	1'032'164	100	0

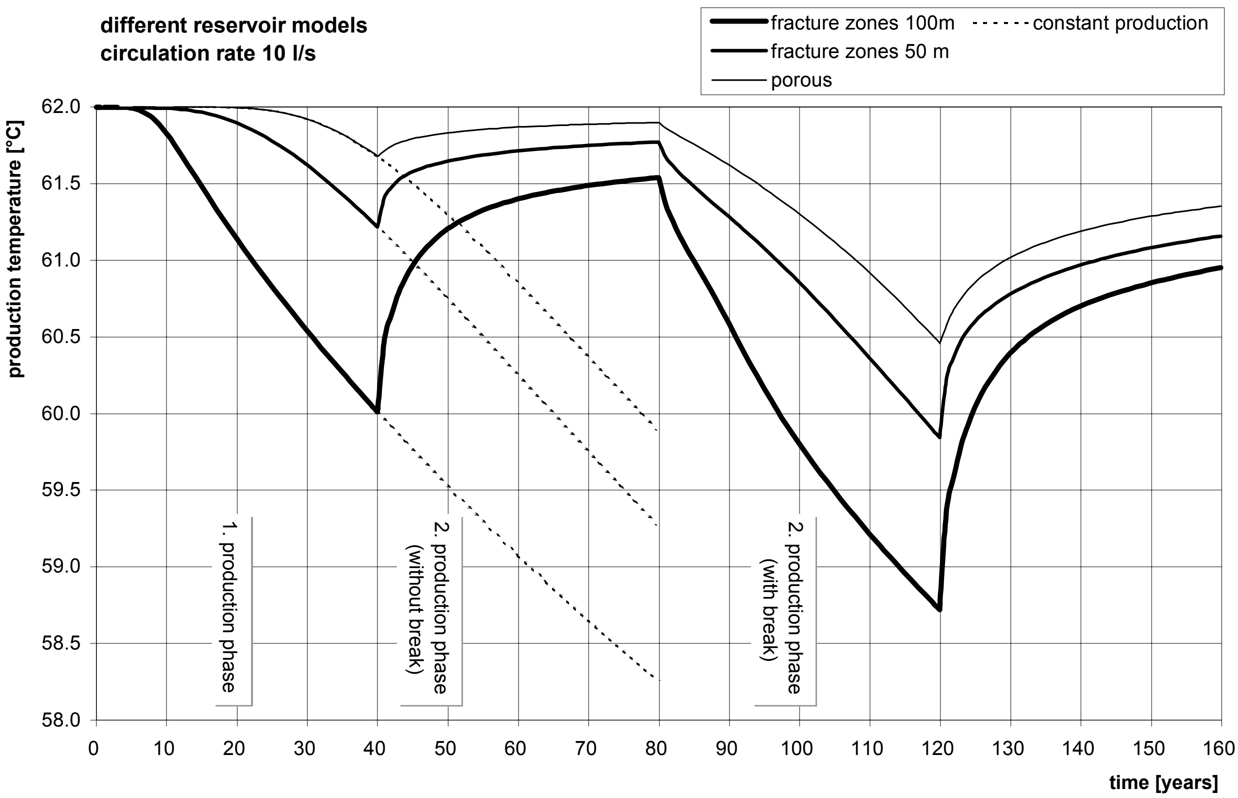

Figure 6: Calculated production temperatures for reservoir models of a porous, a 50 m and 100 m spaced fracture zone network type, two production phases of 40 years with and without a production break of 40 years.

Table 2: Relative recovery of the heat production capacity, 40 years production break between the first and second production phases of 40 years each, different reservoir models (see Figure 6)

Reservoir model	break between phase 1 and 2	1. phase energy E_1 [MWh]	2. phase energy E_2 [MWh]	relative recovery R_{40} [%]
porous	0	543'514	526'568	0
	40	543'514	532'749	36.5
fracture zones 50 m	0	541'095	518'017	0
	40	541'095	526'225	35.6
fracture zones 100 m	0	531'296	500'867	0
	40	531'296	512'698	38.9