Basic characteristics of hydraulic model for the Velika Ciglena geothermal reservoir

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ORIGINAL SCIENTIFIC PAPER

The large potential of the Velika Ciglena geothermal reservoir has not been utilized in the last 20 years. During the review of predictive values, possible inflow of 7 200 m^3/d (170 °C; 28 bar) has been viewed as fairly possible. In that respect the designers are very convincing, since the flow path of fluids through the well is clear and well known. However, with respect to utilization life at constant temperature (20-24 years), they are not credible enough, since it was not easy to prove the flow path of fluids from the injection to the production well. The course of data collection about reservoir characteristics, which were the basis for construction of the reservoir's hydraulic model, is shown. The role of super-permeable fractured zones cooling with loss of drilling mud was stressed. These zones are actually reverse faults. They were identified by temperature measurements following the drilling operations and injection tests. These measurements, together with well logging data, seismic prospecting and interference test were used for the construction of reservoir's hydraulic model. The paper discusses reliability of such a model. Possibilities to increase the hydraulic model reliability were also reviewed.

Key words: fractured geothermal reservoir, cooling effect, interference test, hydraulic model

1. Introduction

The aim of the paper is to indicate the dilemmas in valuation of the Velika Ciglena geothermal reservoir. One of the largest dilemmas is the hydrogeological (hydraulic) reservoir model. Investment decision on starting of utilization has been pending for almost 20 years, mainly due to this dilemma, although the fact has never been put into words.

The reservoir was discovered in 1990 by the VC-1 well within the scope of exploration for oil, conducted by INA-Naftaplin. Oil was not found, but a promising geothermal potential was established. After penetration of Tertiary basement, i.e. carbonate breccias, intermediate 244.5 mm casing was lowered into the well at the depth of 2 574.4 m. An unusually high temperature (172 °C) was registered at the depth of 2 585 m and the first circulation losses were recorded. Further drilling through Triassic carbonate complex (up to 3 835 m) was continued with total circulation losses. Only a part of the well bore was drilled with circulation using the water-nitrogen mixture. In that manner some reservoir rock cuttings were obtained. A shorter hot water and CO$_2$ blow-out occurred at the depth of 3 200 m. Multiple fracture zones were identified by logging. Two of them at depths of 3 210 - 3 220 m and at 3 590 - 3 630 m respectively, swallowed the largest part of the drilling mud, as confirmed by temperature measurements[1,2] (Fig. 1). Later on these zones were interpreted as intersections of the well bore with reverse faults. Temperature anomaly in the very base of Triassic carbonate complex at the depth of 3 821-3 831 m is also interesting. In that interval the well bore diameter exceeds 26 in. (66.04 cm).

A 177.8 mm diameter liner was set at the depth of 4 043 m when the well bore passed through the fractured Triassic complex. The liner was cemented only in the lower part in order to prevent cement losses into the super-permeable zones. Drilling continued through the impermeable or poorly permeable carbonate deposits of Permian age. Drilling was suspended at the depth of 4 790 m due to breakdown of drill pipes. The well did not fulfil the expectations and no oil reservoir was discov-

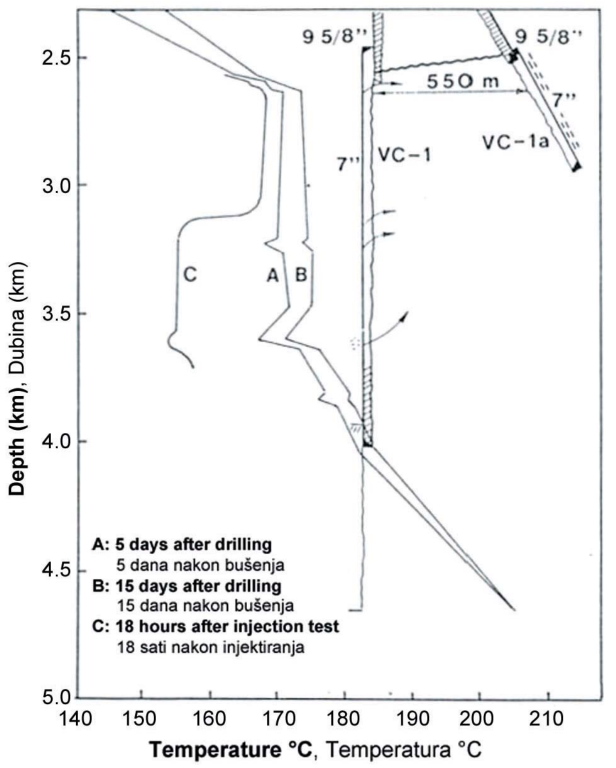

Fig. 1. Temperature measurements in the VC-1 well
Sl. 1. Mjerenja temperature u bušotini VC-1

ered. However, a very interesting geothermal potential was discovered in fractured Triassic dolomites.

In order to verify that potential for the purpose of future exploitation, the author proposed to drill a geothermal well.

The proposal was based on the following facts:

- the highest geothermal gradient in the Pannonian basin was registered (above 0.062 6 °C/m) with almost even temperature across the whole thickness of the Triassic carbonate complex, which is evidence of intense convection through the entire fracture network;
- intense convection takes place only in thick reservoirs of high vertical permeability;
- high permeability was confirmed by temperature measurements, which indicated super permeable zones, with losses of 13 614 m^3 of drilling mud, and 24 621 m^3 of technical water;
- favourable location of the most permeable zones in the deeper part. In addition to gravity effect, it will prevent fast breakthroughs of re-injected water into the production well, which will penetrate only the top part of the reservoir.

The INA-Naftaplin Management accepted the proposal, partly due to the fact that drilling rig could not be engaged in a new location (crisis of exploration programs).

However, unfavourable surprise was encountered during designing of new well trajectory. The presented geological structure of the geothermal reservoir had a very unfavourable shape: tectonic uplift, small surface areas and high throws of normal faults surrounding it. In order to avoid the well bore bypassing the Triassic reservoir deposits, a very limited deviation angle of a new VC-1a well was selected. At the top of the geothermal reservoir, horizontal distance between the bores of two wells is approx. 560 m. Horizontal distance from the bottom of the VC-1a well to the vertical bore of the VC-1 well is 701 m. For such highly permeable deposits, even in the case of oil reservoir waterflooding, the distances are too small.

Still, the VC-1a well achieved very good results. It confirmed the expectations about high productivity and, even more importantly, indicated that the geothermal reservoir volume was considerably larger than it appeared at the time when the well was located. Namely, it crossed a reverse fault which increases reservoir depth and does not represent a barrier. It was confirmed that reverse fault zones are the most permeable parts of the reservoir. In VC-1a it was confirmed by temperature peak at the depth of 2 550 m (vert.) during production test. The VC-1a well penetrated the Triassic carbonate complex in the inclined 2 569 - 2 956 m interval or at vertical depth of 2 462 - 2 787 m. The zone was protected by slotted liner of 177.8 mm diameter.

Numerous tests were performed immediately after completion of drilling, i.e. during February and March 1991:

- interference test, during which VC-1a was used as an active well and VC-1 as an observation well; very fast hydraulic connection between the wells and limited extent of the reservoir was established;
- deliverability tests for well VC-1a; optimal deliverability could not be achieved due to technical reasons; maximal (short-term) inflow was 4 770 m^3/d, at wellhead pressure of 35 bar, and temperature of 152 °C;
- static temperature of 175 °C (even higher in later measurements) was estimated by extrapolation of measured unsteady values of temperature on a semi-log (Horner type) plot;
- temperature measurements to establish injectivity and productivity zones;
- injectivity and productivity tests; injectivity and productivity values are very high (depressions and repressions are barely noticeable);
- quantities of gases dissolved in water were established (27 m^3/m^3, CO_2 with traces of CH_4 and H_2S) as well as minerals (26 644 mg/l);
- scale deposition tendency was tested and it was established that scale deposition was intense at pressures below 20 bar, and that use of inhibitors is necessary at pressures of 20-28 bar;
- corrosive properties of geothermal fluid were tested;
- radioactivity of geothermal fluid was tested and found not to be a hazard for the environment.

During the Liberation War the wells were plugged by cement bridges. Several scientific and expert papers were prepared at that time, which analysed the impact of individual reservoir and well parameters on possible exploitation of the reservoir. Simplified hydraulic models of the reservoir were used due to the fact that geological and geophysical reinterpretation was not completed at that time. In one of the most valuable works from that period[1], the undergraduate student Z. Buza, under the guidance of Prof. M. Zelić, prepared a computer programme of flow through the VC-1a production well. The result was that VC-1a well would be able to produce 10^4 m^3/d of water with temperature of 172 °C at wellhead pressure of 26 bar.

The methodology for calculation of reservoir temperature changes was also reviewed.[2] Until then analytical solution was used for calculations in Croatia and only fixed injection-drainage surface area in a homogeneous environment was taken into consideration. This is the surface covered by injected fluid at the time of its first breakthrough into production well. It is well known in petroleum reservoir engineering that such surface increases in further displacement. It contributes to more realistic (slower) decrease of oil cut in calculated production. In geothermal reservoirs it also contributes to a more realistic (slower) calculated temperature drop at the exit from the reservoir. In geothermal literature the question of injection-drainage area increase (in a case of homogeneous reservoir) is known as Gringarten-Sauty method.[6] To tell the truth, it has to be pointed out that this method was originally created in petroleum reservoir engineering practice.[7] Calculations using the Gringarten-Sauty method were done (for a hypothetical reservoir) in an excellent diploma thesis.[5] Unfortunately, there are no indications that it has been used ever again in Croatia. Everything was solved on the basis of fixed drainage surfaces.

In 1994 the Management of INA-Naftaplin accepted the proposal for preparation of a Pre-Feasibility Report (based on our data and suggestions) on profitability of co-generation of heat and electricity on the Croatian fields of Lunjkovec-Kutnjak and Velika Ciglena by the Icelandic company Virkir-Orkint. For that purpose the Exploration Department of INA-Naftaplin (Mr. S. Kolbah) prepared a structural and tectonic solution of Velika Ciglena, which was the basis for a flow model under the name Z-model. The report[11] was submitted in May 1995. Before we proceed to review the Z-model, let us say in brief that the report[11] showed very good economic results under the following assumptions:

- that discharge of CO_2 into the atmosphere will be permanently pemitted (only water is reinjected), and that the Z-model is truly realistic.

Neither was easy to prove. The Velika Ciglena idea was postponed for better times. However, new tests, practically of the same extent as in 1991, were made in 1996. The novelty was that it contemplated thermosyphone technique for reinjection of water and CO_2 mixture (without pumps and compressors). Such technique has been in use for the geothermal system of the Mladost sports park in Zagreb since 1993.[7] Programming of thermosyphone parameters in that case was relatively easy, since it involved a single-phase fluid. In the case of Velika Ciglena (two-phase fluid), programming was considerably more complex, but was successfully resolved.[10] Unfortunately, this useful idea has never been applied for the Velika Ciglena.

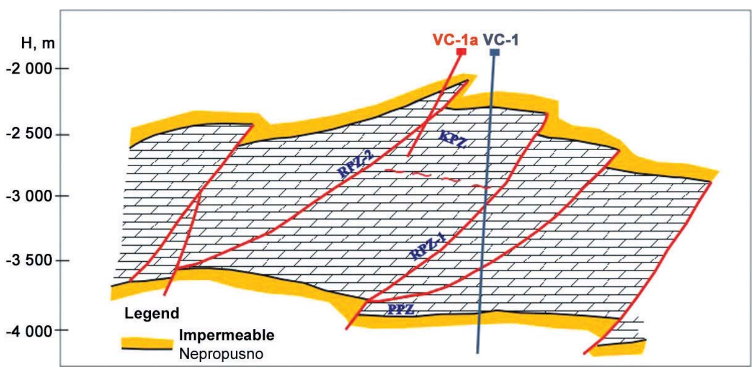

Fig. 3. Longitudinal cross-section across the VC-1 and VC-1a wells
Sl. 3. Uzdužni profil preko bušotina VC-1 i VC-1a

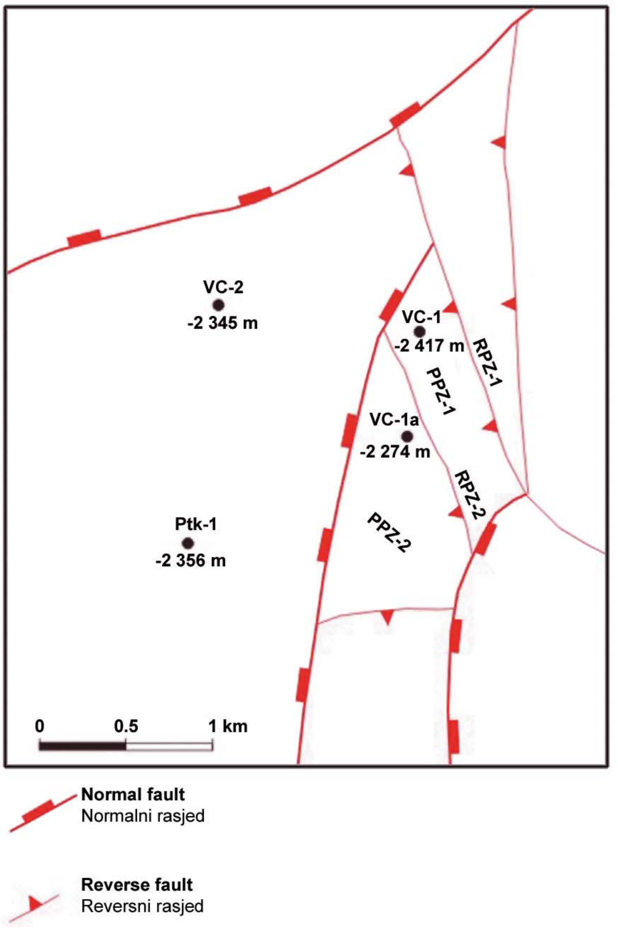

Fig. 2. Tectonic map of the Velika Ciglena geothermal reservoir
Sl. 2. Tektonska karta geotermijskog ležišta Velika Ciglena

2. Development of ideas about the Z-model

The latest structural and tectonic solution of the Velika Ciglena geothermal reservoir[4] is shown schematically on the map (Fig. 2), and on the longitudinal cross-section (Fig. 3). The first version was made as the basis for the Virkir-Orkint study in 1994. A very similar disposition of faults was shown at that time, the only differences being distances between them. The later solution was affected by additional seismic measurements and the results of drilling of two (dry) exploratory oil wells (VC-2, Ptk-1). Those two wells penetrated only a small part of the geothermal reservoir thickness. Indirectly, it is evident from the high temperature and drilling fluid circulation losses that a geothermal reservoir of good flow properties was penetrated. Description of geological setting[4] stresses that normal faults are probably barriers. Because of that, the new wells are probably not hydraulically connected with wells VC-1 and VC-1a. Such conclusion can also be made on the basis of the above mentioned interference test.

The interference test was performed in February 1991, between the VC-1 well as an observation well and the VC-1a well as an active one. During testing the observation gauge was far above the reservoir at a depth of 1 800 m (5 905 ft), due to temperature constraints. It unfavourably affected reliability of results obtained by test analysis. A repeated test in 1996 gave almost identical results to those obtained in 1991.

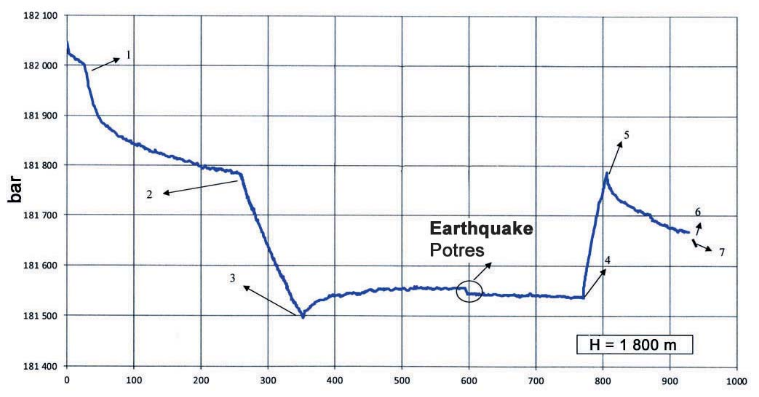

Fig. 4. Pressure changes at the depth of 1 800 m in the VC-1 well during interference test

Sl. 4. Promjene tlaka na dubini 1 800 m u bušotini VC-1 tijekom testa interferencije

Fig. 4 shows pressure changes in the observation well, and Table 1 the sequence of activities during the 1991 test.

The test was performed under serious technical restrictions. Unfavourable gauge position has already been mentioned. The biggest problem is the small mud pit volume used for discharge of produced geothermal water. Due to that, inflow was limited to 1 220 m^3/d, which is far below the well potential.

At the end of inflow, the parameters were as follows:

- water inflow 1 220 m^3/d (7 673 bbl/d)
- wellhead temperature 147 °C (296,6 °F),
- wellhead pressure 26 bar (377 psi).

Pressure response in observation well was very quick, maybe only 1 second. It could indicate the presence of a super-permeable fractured zone intersected by both well bores, which could cause a fast injected water breakthrough. Such danger is considerably alleviated by the above mentioned gravity effect, which will be used in injection strategy. Naturally, the effect will grow more favourable with injected water temperature decrease. Besides, there are no indications of such danger in the description of geological setting.[4] A sudden pressure drop occurred during measurement of pressure build-ups (both wells closed) due to the earthquake registered by the Seismological Institute. The epicentre was under the Bilogora Mountain (distance 15 km). After that the pressure continued to build-up, seemingly at a slower rate. Unfortunately, deeper analyses related to the earthquake were not made, but porosity volume seems to have increased.

The type of reservoir rock porosity can be assumed from pressure change analyses. As known, the fracture system is characterized by two parameters: interporosity flow coefficient (λ) and storativity ratio (ω). In this case the values of these parameters are exceptionally low (λ=0.008; ω=1.94 E+8), which means that the ratio of

Table 1. The sequence of activities in the interference test

Points	Activity	Remark
1 - 2	Both wells were closed after a short production and injection test	The observation well pressure continues to drop slowly (before stabilization)
2 - 3	Pressure drop period 92.9 hours; VC-1a was producing at the rate of 50 m^3/h	At the end of the period: at the wellhead of VC-1a; p=26 bar; T=147 °C
3 - 4	VC-1a was closed; pressure build-up period; an earthquake was recorded	An earthquake (about 3-4 on the Richter scale), epicentre under the Bilogora mountain, distance 15 km;
E to 4	Pressure build-up period continues	Pressure build-up slower than expected
4 to 5	Injection into VC-1a	Rate 120 m^3/h, wellhead p=0
5 to 6	Both wells closed	Pressure drop registered
7	VC-1a opened for production test	Production rate 240 m^3/h

Table 2. Reservoir and fluid properties for interference test analysis

Property	Symbol	Value	Unit
Initial reservoir pressure at 3 130 m (reservoir centre of gravity)	p_i	301.8	bar
Initial reservoir temperature at 3 130 m (centre of gravity)	T_i	175.8	°C
Gas dissolved in water, at p_i, T_i	R_{sw}	27	m^3/ m^3
Water mineralization		26 600	mg/l
Volume factor of water, at p_i, T_i	B_{wL}	1.0909	
Water compressibility, at p_i, T_i	c_v	1.354 E-4	bar^{-1}
Reservoir rock compressibility, at p_i, T_i	c_f	5.7 E-5	bar^{-1}
Total reservoir compressibility, at p_i, T_i	c_t	1.924 E-4	bar^{-1}
Porosity, at p_i, T_i	φ	0.16	
Water viscosity, at p_i, T_i	μ_w	0.18	mPa·s

Table 3. Reservoir water volume according to material balance equation

Quantity of water produced during the test	V_{wp}	4 722	m^3
Reservoir pressure drop (181.783 bar at 181,557 bar)	Δp_r	0.226	bar
Total reservoir compressibility	c_t	1.93 E-4	bar^{-1}
Formation water volume factor	B_w	1.090 9	
Formation water volume (related to wells)	V_{rw}	118.477 500	10^6 m^3

matrix in the flow is negligible. Therefore, flow takes place only in fractures.

The volume of formation water, which reacted to pressure changes during the interference test, was estimated on the basis of the following equation (material balance):

$$V_{vr} = \frac{V_{vp} \cdot B_w}{\Delta p_r \cdot c_t}$$

The required data and calculation results are shown in Table 3.

This result has to be compared with the results of volumetric calculation.[4] The reservoir is formed by the following hydraulically connected permeable zones.

- base rock permeable zone (PPZ) with reservoir volume of 60 × 10^6 m^3, and the volume of reservoir fluid of 7 × 10^6 m^3;
- faulted permeable zone-1 (RPZ-1) with reservoir volume of 7 × 10^6 m^3, and the volume of reservoir fluid of 2 × 10^6 m^3;
- top rock permeable zone, block 1 (KPZ-1) with reservoir volume of 210 × 10^6 m^3, and the volume of reservoir fluid of 34 × 10^6 m^3; according to well logging results, effective thickness of the zone is 174 m, at the depth of 2 585 to 2 940 m;
- top rock permeable zone, block 2 (KPZ-2) with reservoir volume of 84 × 10^6 m^3, and the volume of reservoir fluid of 14 × 10^6 m^3;
- faulted permeable zone -2 (RPZ-2) with reservoir volume of 37 × 10^6 m^3, and the volume of reservoir fluid of 4 × 10^6 m^3;

In total in all the zones reservoir volume is 398 × 10^6 m^3, and the volume of reservoir fluid is 61 × 10^6 m^3. In the volumetric method the volume of block 2 was probably underestimated. It means that during possible exploitation it would be possible (justifiable) to drill a new well bore with higher inclination from the bore of VC-1a (into block 2) with the purpose to extend the life of constant outlet temperature.

If there were a hydrodynamic connection with the block where VC-2 and Ptk-1 wells were drilled, the interference test would have indicated a considerably larger volume. Consequently, only the volume that communicates with the tested wells should be treated as a reservoir in a sense of exploitation.

The main issue of reservoir development is as reliable prediction of the injected (cooled) fluid path. With that in mind, construction of a logical hydro-geological model was attempted. It was based on the previously mentioned temperature measurements, interference test, petrophysical analyses and structural and tectonic solution. We have to bear in mind that during the injectivity test in 1991, the liner was perforated at interval 3 585 - 3 596 m, i.e. opposite of the base rock permeable zone (PPZ). Most of the injected fluid entered the PPZ, but behind the liner it rose even as far as RPZ-1. It is important that it did not flow behind the liner into the KPZ intervals. Danger of injected fluid breakthrough behind the liner into the top of KPZ-1, i.e. into the first total losses zone, was investigated in 1996. During preparations for isolation of a part of annulus behind the liner, perforations were made in the 2 680 - 2 686 m and 2 780 - 2 786 m intervals. Fortunately, isolation works were not realized, because they would have brought more damage than benefits. Injectivity test was repeated several months after the perforating and it again showed that injected fluid again entered only the PPZ and RPZ-1 zones. Still, new perforations could be useful. They will redirect a part of the injected fluid downward flow through the annulus (behind the liner), thus slowing the pressure drop due to friction. The reason why injected fluid did not enter the KPZ zone primarily lies in the difference of densities between the injected and reservoir fluids (gravity effect). Even during eventual exploitation, the difference in densities will be considerable. Density of fluid in the reservoir is 934 kg/ m^3, and density of injected fluid on the opposite side of the reservoir is about 1 000 kg/m^3 (water and dissolved CO_2, at 80 °C). Due to that, repression will increase from the top towards deeper intervals, with simultaneous increase of injectivity.

Expected path of the injected fluid would be as follows:

- across PPZ downwards to the connection with RPZ-1, and along it upwards to KPZ-1; it will continue across KPZ-1 as a 1 350 m wide front to the reverse fault RPZ-2. The flow continues upwards across that fault zone to the VC-1a well bore, entering parts of block 2, i.e. KPZ-2. As already stressed, gravity effect will smooth the injected fluid front. Fluid path from the injection to the production well resembles letter "z". The hydraulic model is therefore shaped like letter Z (Fig. 5).

This model is the basis for calculation of production life at constant temperature.

Let it be mentioned that the flow surface widths (in Z-model) are smaller than on the structural map. In that way the areal sweep efficiency coefficient was indirectly introduced. Z-model volume calculation is shown in Table 4.

The total volume value in this table is practically the same as in official documentation about geothermal wa-

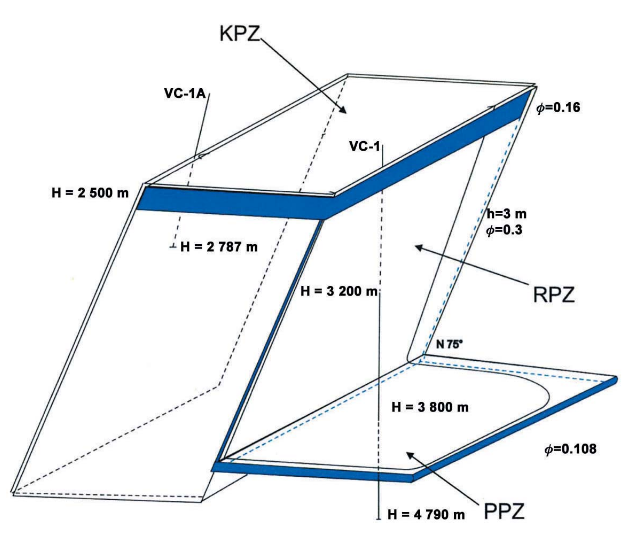

Fig. 5. Z-model of flow in the Velika Ciglena geothermal reservoir
Sl. 5. Z-model protjecanja u geotermijskom ležištu Velika Ciglena

ter reserves.[4] Certain parameters were somewhat corrected. For example, on Z-model presentation in official the document, width of the front for PPZ and RPZ is the same as in the initial solution (2 350 m) from 1994. Here it is harmonized with the official structural and tectonic solution (Fig. 2.).

3. Discussion about Z-model reliability

Total volume of water that can be produced at approximately constant temperature at the outlet depends on reservoir volume size and the ratio between specific heat capacity of the reservoir and specific heat capacity of formation water.

It is calculated using the expression:

$$W_{pct} = \frac{W_{LP}\left(c_\rho\right)_L}{\left(c_\rho\right)_{wL}}$$

where:

W_{LP}	reservoir volume, m³,
$(c_\rho)_L$	volume specific heat capacity of the reservoir, J/m³
$(c_\rho)_w$	volume specific heat capacity of reservoir fluid, J/m³

In the concrete case[4], the following is obtained:

$$W_{pct} = \frac{94\,332\,600 \cdot 2.677\ \mathrm{E}+6}{3.975\ 6\ \mathrm{E}+6}$$

$$W_{pct} = 63\ 497\ 201\ \mathrm{m}^3$$

For expected daily production of 7 200 m³/d (170 °C, 28 bar), annual water production will be[4]:

$$\Delta W_p = 7\ 200 \cdot 365 = 2\ 628\ 000\ \mathrm{m}^3$$

Time of constant temperature at the outlet is:

$$\tau_{ct} = \frac{W_{pct}}{\Delta W_p} = \frac{63\,497\,201}{2\,628\,000} = 24.2\ \text{years}$$

If we look at table 4, we shall see that the volume of KPZ-1 has the strongest impact on production time at constant temperature. It was assumed that the fluid flows through a 61 m thick zone, and total effective thickness of that zone is 174 m. Accordingly, only one third of the thickness was taken as active. It is not excessive.

It is hard to find arguments which would testify that the flow does not follow the Z-model. However, without test production and tracer testing it is impossible to prove the path (reservoir volume) through which the injected fluid flows.

The initiators of geothermal energy utilization in Croatia implied the necessity of test production and testing in the course of its duration. At the same time they stressed their ultimate goals. For example, generation of electricity at Velika Ciglena can without any doubt reach 4.7 - 5 $\mathrm{MW_e}$ (at design inflow of 7 200 m³/d and temperature of 170 °C). However, it is uncertain when and how the production will decline.

From the viewpoint of test production, unfavourable fact is that distance to the city of Bjelovar, i.e. to large consumers of heat energy, is considerable. Nobody will invest in consumers of heat energy only for the purpose of test production. On the other hand, test production must be cheap. A precondition is the use of thermosiphon. In order to make the thermosiphon functional[10], we must utilize the significant difference in temperature, at the flow rate of up to approx. 5 000 m³/d. In the case of Velika Ciglena, the only consumers of heat energy during test production could be greenhouses. But, greenhouses were not attractive to potential investors.

4. Conclusion

The geothermal potential at Velika Ciglena has been on hold for 20 years, waiting for investment decision about

Table 4. Reservoir volume and reservoir fluid volume in the Z-model

	Width, km	Length, km	Area, km²	Effective thickness, m	Reservoir volume, 10⁶ m³	Porosity, fraction	Fluid volume, 10⁶ m³ (res. cond.)
KPZ-1	1.350	0.820	1.107	61	67.527	0.16	10.804
KPZ-2	1.350	0.050	0.067 5	47	3.175	0.16	0.510
RPZ-1	1.350	1.900	2.565	3	7.695	0.300	2.310
RPZ-2	1.350	0.600	0.81	30	2.430	0.106	0.729
PPZ	1.350	0.800	1.35	10	13.500	0.164	1.431
Total					94.332		15.740

its activation. In the last 13 years numerous scientific projects about Velika Ciglena have been prepared.[4] All possible parameters were analysed and only the Z-model remained untouchable. Nobody tried to investigate whether different flow paths were possible. Can it not be presumed from latest seismic measurements that there are other faults in the Triassic dolomite complex?

In most cases, when making investment decisions banks (in the world) rely on the size of 50% probability reserves. It can be expected that in the case of Velika Ciglena probability approach would indicate a production life (i.e. recoverable energy) with at least 50% probability and with regard to designed power - probability would be close to 90%.

Finally, let us remind that probability with regard to size of reserves in fracture type reservoirs is considerably lower than in those with inter-granular porosity. But, fractured systems usually yield higher flow rates, i.e. energy in unit of time. The same applies to geothermal reservoirs.

Maybe the problem lies in the fact that investors have a different approach to risk than active geologists and reservoir engineers. The question was a topic also discussed in earlier periods.[9]

A totally new approach to characterization of reservoirs and risks might be the answer.[8]

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