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MODELING OF THE FAULT TYPE GEOTHERMAL RESERVOIR (DACHNY SITE, MUTNOVSKY GEOTHERMAL FIELD)

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ABSTRACT

Fault-type geothermal fields are common in recent volcanism areas. The recent model of the Dachny site, Mutnovsky geothermal field (Kamchatka, Russia) represented a single fault production zone with the heat exchange to ambient rocks expressed in terms of “confining beds TOUGH2 option” (Kiryukhin, Stanford Workshop 2004) was improved by add of the 5-layer external grid connected to the production zone. Model calibration against 2002-2004 exploitation data and modeling of the possible future scenarios to maintain sustainability of the 50 MWe PP (Dachny) discussed.

INTRODUCTION

The history of numerical models applications to Mutnovsky geothermal field started from large-scale 3D rectangular models (Kiryukhin, 1992, 1996) which were designed to understand heat and mass transfer processes in geothermal reservoir as a whole, and to forecast possible exploitation scenarios. This model (1996) consist of 500 elements 500 x 500 x 500 m^3 each with total volume of 5 x 5 x 2.5 km^3 used to forecast 20 year period of exploitation based on existing wells and it shown 44 MWe as a minimum yield of the field. Later this model was used by WestJec (Japan) company to do feasibility study of the Mutnovsky PP (1997).

Since the fault geometry of specific production zones distribution reveals (Kiryukhin et al, 1998), and central part of the Dachny Site proved to be a single-fault type geothermal field (the Main Production Zone in Dachny site strikes north-north-east and dip east-east-south at the angle 60^o), next development of numerical modeling applications to this field was targeted to description of specific geometry of the Main Production Zone (Kiryukhin et al, 2003, 2004, 2005).

Reservoir modeling also used as an instrument for optimal design of the exploitation load of the Dachny Site in Mutnovsky geothermal field, where SC “Geotherm” having put 50 MWe PP into operation in October 2002.

MODEL SETUP

Grid generation

Geothermal reservoir is represented as association of the Main Production Zone (MPZ) reservoir and Host Rocks (HR) reservoir (Fig.1). Both reservoirs grids coincide with the Basic Grid (grid related to existing wells) in horizontal projection (Fig.2).

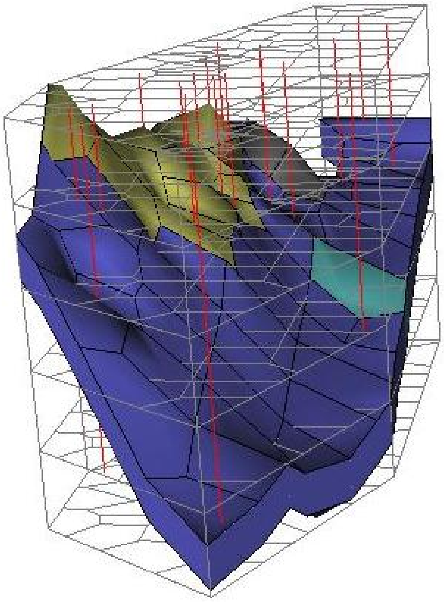

Figure. 1.Geometry of the 3-D numerical model of the Main Production Zone of the Dachny Site Mutnovsky geothermal field.

Basic Grid created on AMESH preprocessor (1999), which generated TOUGH2 mesh file in terms of horizontal connections parameters d1, d2, AREA.

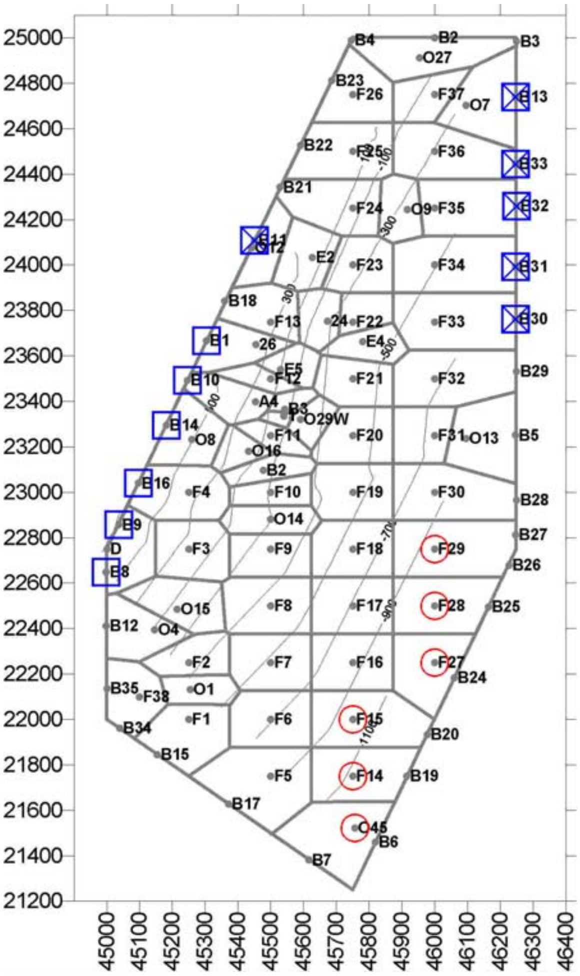

Figure. 2. Basic Grid of the reservoir. Counters elevations (m.a.s.l.) correspond to the top of the Main Production Zone. Open circles - sources assigned in the model, squares – inactive boundary elements valid for natural state stage (steam discharge), crossed squares- inactive boundary elements valid for natural state and exploitation (liquid discharge).

Main Production Zone subdivided on two reservoirs: A-reservoir and B-reservoir. A-reservoir corresponds to the Main Production Zone itself with averaged vertical thickness 240 m (actual thickness 120 m), each element of which is located at the specified elevation corresponding to the roof of the Main Production Zone (Figs.1 and 2). B-reservoir correspond to diorite intrusion contact permeability zones, adjacent to Main production zone. Additional correction procedure was applied to mesh file to specify vertical component of grid connection, including more accurate BETAX presentation (format F20.14 instead of F10.4) to avoid "parasitic circulation" in the model (according to K. Pruess, pers. com., 1998) (Fig.3).

Host Rocks (HR) grid generated as a 5-layer system (at elevations +750, +250, -250, -750, -1250 m), each element of which connected to the Main Production Zone (MPZ) element, if such MPZ element center occur inside of HR element volume.

Basic Grid include 24 existing wells, 39 additional interior elements (F-elements and D-element) and 12 boundary (inactive) elements (B-elements). Total number of the elements of the model is 378 (Fig.1).

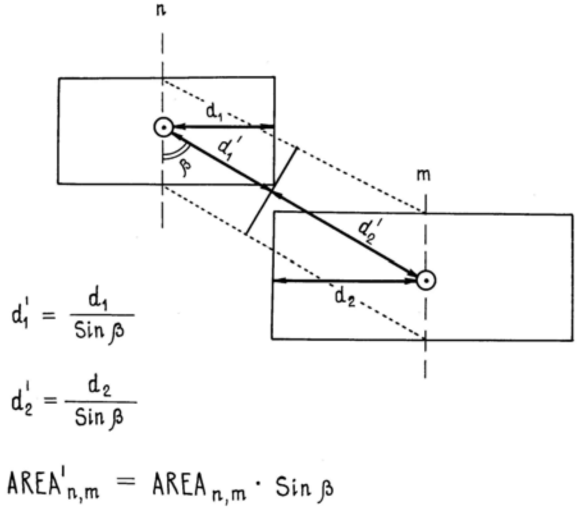

Figure. 3. Mesh parameters (d1, d2, AREA) corrections applied to A-MESH output.

Sinks/Sources, Permeability Distribution and Boundary Conditions

Figs. 2 and 4 demonstrates grid and permeability distributions assigned to the Main Production Zone reservoir of the model. «Sources» in the model are O45, F27, F28, F14, F15, F29 (9 kg/s, 1390 kJ/kg), permeability and rock properties assign based on the previous natural state modeling results (1996-2005).

Boundary conditions assign in B-elements (Fig.2). Liquid discharge elements assigned as P=const and T=const and are valid anytime in the model. These elements simulate liquid discharge from hydrothermal system to Verkhne-Zhirovsky natural discharge area and into ambient aquifers. Steam discharge elements assigned as P=const and S=const, and valid only for natural state modeling. Those elements correspond to unsaturated zone (Dachny steam discharge area), so they switch to "no flow" conditions after exploitation started. Host Rocks reservoir assigned with permeability 10^{-16} m^2.

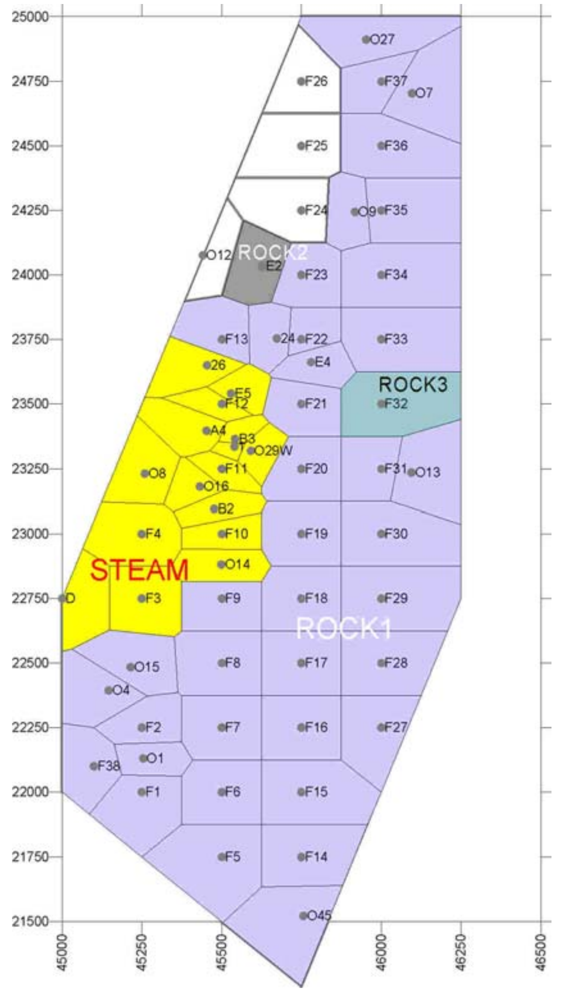

Figure. 4. Permeability distribution in the A-reservoir (Main Production Zone): STEAM, ROCK1, ROCK2 and ROCK3 domains with 100 mD, 100 mD, 1 mD and 0.01 mD, correspondingly.

Modeling of the well-reservoir interaction

The TOUGH2V2.0-based coupled wellbore flow option used (K.Pruess, 1999). For this purpose the total production indexes were split:

$$PI = (k_{rs}\rho_s/\mu_s + k_{rw}\rho_w/\mu_w)\,PI_0$$

,where $k_{r\beta}$ relative phase permeability, μ_β viscosity Pa*s, ρ_β density, kg/m^3, PI_0 productivity indexes (m^3) (liquid (β=w) or steam (β=s)). Productivity indexes PI_0 of five production wells were estimated according to wells rates (Q) at corresponding wellhead pressure (WHP) (referenced to initial exploitation data), flowing enthalpies h, reservoir P_r and bottomhole P_b pressures, and relative permeabilities (k_{rs}, k_{rw}) derived from the natural state model and wellbore calculations (P_b) (Table 1). Grant type relative permeabilities used. Productivity indexes of the additional wells (F-wells, Table 2) (suggested to be drilled in the south-east portion of the Main Production Zone to maintain sustainability of steam production for Power Plant) assigned as 7.50 10^{-12} m^3 (average of wells 4E, O29W, 5E).

Bottom hole pressure P_b(WHP, Q, h, d) is calculated in the form of electronic tables based on HOLA code. Its worth to note, that liquid dominated reservoir wells sensitive to enthalpy variations: enthalpy decline below 1100 kJ/kg may turns off production wells, in contrary, enthalpy increase may cause quenching of wells in case of extensive boiling in reservoir. Steam wells production is less sensitive to reservoir enthalpy variations.

Table 1. Input data for exploitation wells (O16, 26, E4, O29W, E5 and F-wells) production indexes estimations.

Well	Q kg/s	WHP bar	h kJ/kg	P_b Bar	P_r Bar	PI kg/s bar	k_{rs}	k_{rw}	PI_0 m^3
O16	17	7.5	2400	13.9	21.6	2.2	0.9640	0.0360	2.52 10^{-11}
26	18	7.5	2800	13.7	25.5	1.5	0.9999	0.0001	1.97 10^{-11}
4E	26.7	9	1338	24.9	58.2	0.8	0.3077	0.6923	1.37 10^{-12}
029W	72.5	9	1216	50.4	58.4	9.1	0.0330	0.9670	1.20 10^{-11}
5E	39	7	1072	27	33.5	6.0	0.1296	0.8704	9.22 10^{-12}
F-wells									7.50 10^{-12}

Table 2. Assumed F-wells drilling parameters.

F-wells	Depth, m	Horizontal deviation, m	Angle of vertical deviation
O13-F30	1792	254	8.2
O10-F16	1901	795	24.7
O10-F17	1755	709	23.8
O13-F18	1588	596	22.1
O13-F19	1414	418	17.2
O13-F20	1277	345	15.7
O10-F29	1963	461	13.6

NATURAL STATE MODELING

Natural state modeling was run with the same boundary and sink/sources conditions as mentioned in the paper (Kiryukhin, 2005). In particularly, total upflow rate assign in the model is 54 kg/s, mass rates and enthalpies specified as 9 kg/s and 1390 кJ/кg (water 307°C) in each "source" element (Fig.2). Permeability distributions in the Main Production Zone A-reservoir domains STEAM, ROCK1, ROCK2 and ROCK3 assign as 100 mD, 100 mD, 1 mD and 0.01 mD correspondingly, in B-reservoir ROCK1 domain - 100 mD (Fig. 4). Host Rocks reservoir estimated permeability 10^{-16} m^2. It was found no satisfactory match in key calibration elements (modeling pressures lowering), if Host Rock permeability increases above 10^{-16} m^2 (that mean permeable production volume of the central part of the Dachny Site is basically limited to the Main Production Zone space).

MODELING OF THE EXPLOITATION (MAIN PRODUCTION ZONE OF THE DACHNY SITE)

Data for Model Calibration

Exploitation model calibration is based mainly on the data received from initial production tests of wells 016, 26, 029W, 4E and 5E (used for PI estimations, Table 1), operating wellhead pressure of the exploitation wells (Fig.5) and data of the total steam and total separate production from Mutnovsky PP separator (wells 016, 26, 029W, 4E, 5E, A2, O37 and 24) (Fig.6). There is no reliable data for individual exploitation wells production history. Pressure monitoring in well O12 (0.75 bar drop per year) rather characterized Host Rocks reservoir conditions, than production zone.

While production took place, individual wells wellhead pressures (Fig.5) and PP separator pressures (Fig. 6) gradually decline. From 5.4 bars to 5.0 bars (ati)) at PP separator during 1.5-year exploitation period) (Fig.6).

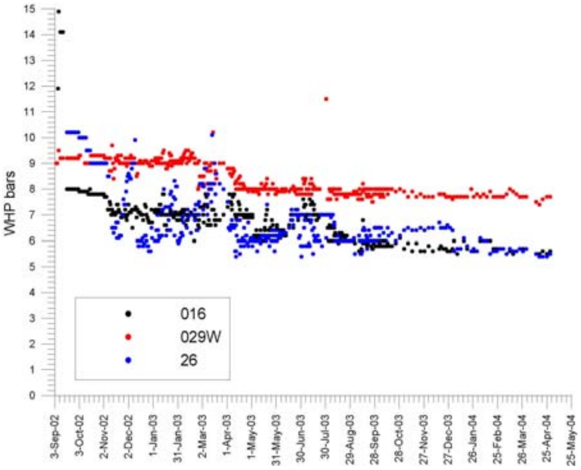

Figure. 5. Well Head Pressure (WHP, bars (ati)) variations) in exploitation wells of the Dachny site Mutnovsky geothermal field (SC "Geotherm", 2004).

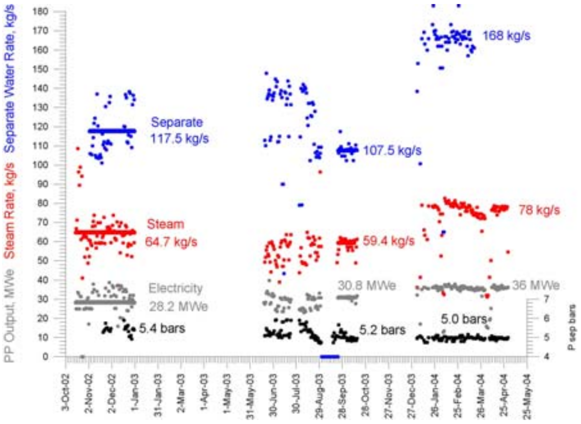

Figure. 6. Mutnovsky PP electricity output, total steam and separate water production, and separator pressure (bars, ati) (SC "Geotherm", 2004).

Total steam production varies from 64.9 kg/s (2002) to 59.4 kg/s (2003) and to 78 kg/s (2004), the total separate production varies from 117.5 kg/s (2002) to 107.5 kg/s (2003) and to 168 kg/s (2004). Wells A2, 24 (Dachny) and O37 (Verkhne-Mutnovsky) contribution (steam – 3.5 kg/s (2003), 18.3 kg/s (2004), separate - 15 kg/s (2003), 77.7 kg/s (2004)). Hence, the total production of wells (wells 016, 26, 029W, 4E and 5E) estimated as 64.9 kg/s (2002), 55.9 kg/s (2003), and 59.7 kg/s (2004) (steam at PP separator at 5.0 – 5.4 bars (ati)), and 117.5 kg/s (2002), 104.0 kg/s (2003) and 90.3 kg/s (2004) (separate at PP).

Exploitation Model Calibration

Compressibility coefficient assign 5.0 10^{-7} Pa^{-1} in the Main Production Zone reservoir and 2.0 10^{-8} Pa^{-1} in the Host Rock reservoir. Well 027 (North Reinjection Site) assign as reinjection with 150 kg/s rate and enthalpy of 700 kJ/kg. The switch to "no flow" boundary conditions during exploitation implemented in B1, B10, B14, B16, B9, B8 boundary elements of the model. Production wells specified at wellhead pressure conditions corresponding to the PI_0 data from Table 1. Two-phase wells were switched off, if mass flowrate dropped less than 5 kg/s, steam wells were switched off, if mass flowrate dropped below 2 kg/s.

Model calibration targeted to match total steam (referenced to 5.2 separation pressure) and total separate production data against modeling (wells 016, 26, 029W, 4E and 5E) data. Actual production data estimated as 64.9 kg/s (2002), 55.9 kg/s (2003), and 59.7 kg/s (2004) (steam at PP separator at 5.0 – 5.4 bars (ati)), and 117.5 kg/s (2002), 104.0 kg/s (2003) and 90.3 kg/s (2004) (separate at PP).

Initial model scenario #1 show good steam production match (56.0 kg/s vs 59.7 kg/s), and not satisfactory separate production match by the end of 1.5-year exploitation period (Fig. 7). Separate production decline more rapidly (30 kg/s), compare to actual data with additional wells correction (90.3 kg/s) (Fig.7).

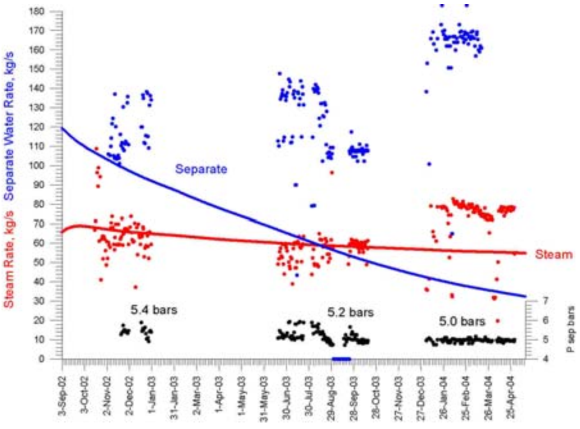

Figure. 7. Model match (Initial scenario #1): modeling steam and separate production from wells 016, 26, E4, 029W, E5 (referenced to 5.2 separation pressure, ati) against total PP production during exploitation of the Dachny site. Dots – PP exploitation data (Fig.6), solid line – modeling results.

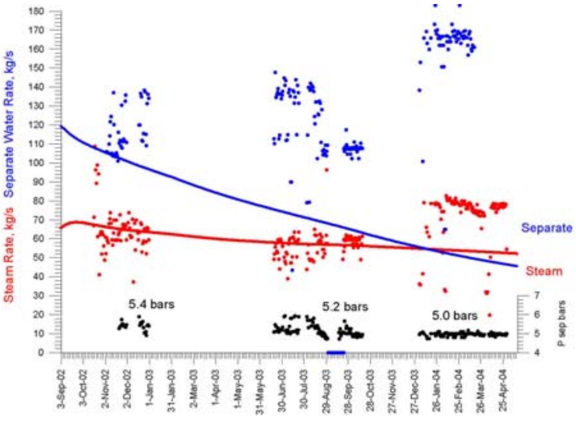

Figure. 8. Model match (scenario #2): modeling steam and separate production from wells 016, 26, E4, 029W, E5 (referenced to 5.2 separation pressure, ati) against total PP production during exploitation of the Dachny site. Dots – PP exploitation data (Fig.6), solid line – modeling results.

Scenario #2 assume possibility of the lateral cold water recharge to the Main Production Zone reservoir from Host Rock reservoir by assuming elimination production zone boundaries under exploitation conditions (Host Rock permeability assign 2 10^{-15} m^2). The explanation of the physical meaning of such boundary conditions switch under exploitation conditions explained in Geothermics Vol.25 #1 p.85 (Kiryukhin, 1996), when possibilities of different exploitation scenarios of the Mutnovsky field were discussed.

In case of such "lateral cold water recharge" (scenario #2) good steam production match (54.0 kg/s vs 59.7 kg/s), and more satisfactory separate production match (52 kg/s vs 90.3 kg/s) by the end of 1.5-year exploitation period obtained (Fig. 8).

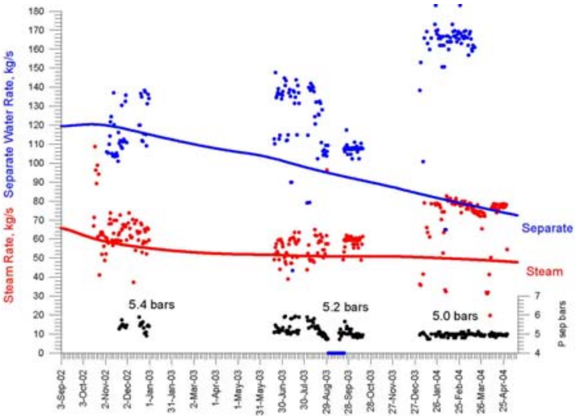

Figure. 9. Model matches (scenario #3): modeling steam and separate production from wells 016, 26, E4, 029W, E5 (referenced to 5.2 separation pressure, ati) against total PP production during exploitation of the Dachny site. Dots – PP exploitation data (Fig.6), solid line – modeling results.

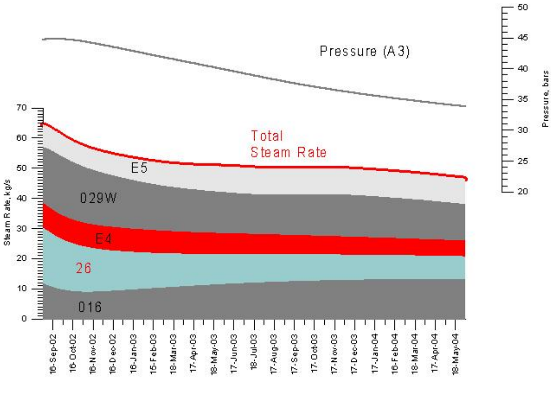

Figure. 10. Scenario #3: modeling of the steam production at 7 bars (wells 016, 26, E4, 029W, E5) and reservoir pressure (A3 model element) response in the Dachny site.

Scenario #3 assume possibility of vertical downflow of the cold water recharge to the Main Production Zone reservoir directly from abandoned wells of the Dachny Site Mutnovsky geothermal field. Those wells are basically characterized by poor casing cementing. Downflows from local cold groundwater aquifers with water levels near surface into geothermal reservoir with levels –600 m through abandoned wells casings is possible and really observed in some wells (O11, O42, etc). High possibility of such scenario un-directly confirmed by high fractions of meteoric gases observed in production wells during exploitation (Kiryukhin et al, 2005). To model such possibility additional cold water sources were assigned in the elements E4, E5, O29, O16, B2, where abandoned wells and significant pressure drop co-exist. Sources parameters assign: rates 12.0 kg/s (total downflow rate 60 kg/s), enthalpies 420 kJ/kg.

In case of "abandoned wells recharge" scenario #3 relatively good steam production match (50.0 kg/s vs 59.7 kg/s), and relatively satisfactory separate production match (82 kg/s vs 90.3 kg/s) by the end of 1.5-year exploitation period obtained (Figs. 9 and 10). Note some increase of actual production rates by 2004 may caused by wellhead pressures decline of production wells (Fig.5), which not accounted in the model.

F-wells Exploitation Scenarios

Mutnovsky 50 MWe PP needs 95 kg/s of 7 bars steam in stable terms during exploitation period. Previously obtained modeling results show existing wells (016, 26, 029W, E4 и E5) are not able to maintain steam supply for PP needs. So, additional production wells needed to maintain sustainable PP operations.

Study of the possibility of sustainable steam production (from model elements F16, F17, F18, F19, F20, F29 and F30) was performed. Corresponding F-wells locations and constructions are shown in Fig.11 and Table 2. F-wells targeted to the high temperature upflow zone in the south-eastern part of the Main Production Zone. All F-wells suggested deviated wells, drilled from positions of existing wells O13 and O10 correspondingly (Fig. 11). Wellbore diameter assumed to be 0.246 m until depth 900 m, and then 0.168 m. Time-schedule of the F-wells putting into operation is the following: F20 (immediately), F19 (1 year), F18 (2 years), F30 (3 years), F29 (4 years), F17 (6 years), F16 (8 years).

Modeling of the steam production from additional F-wells confirm possibility of the 97.8 kg/s steam production in average terms during 10-year exploitation period, which is sufficient for 50 MWe Power Plant production (Fig. 12) for scenario #1. In case of cold water recharge inflows scenarios #2 and #3 – 96.3 kg/s and 86.7 kg/s steam production available in average terms during 10-year exploitation period.

Although scenario #3 ("abandoned wells recharge") seems as the most probable of discussed above, there is possibility to switch to scenario #1, in case of isolation of the Main Production Zone reservoir from the leakage above by proper cementing of all abandoned wells.

Modeling of various reinjection regimes (based on scenario #1) show there is no important where reinjection took place (North or South Reinjection Sites) and whether reinject or not to reinject during first 10-years exploitation period (Fig.13). The situation is changes significantly by 10-year of exploitation. At this time reservoir boiling may induce significant pressure drop, with magnitude depending of reinjection regime. The optimal strategy was found in the model is - to reinject no less then 75 kg/s in the South Reinjection Site which maintain sustainable conditions for 50 MWe PP during 20-year exploitation period (Fig. 13).

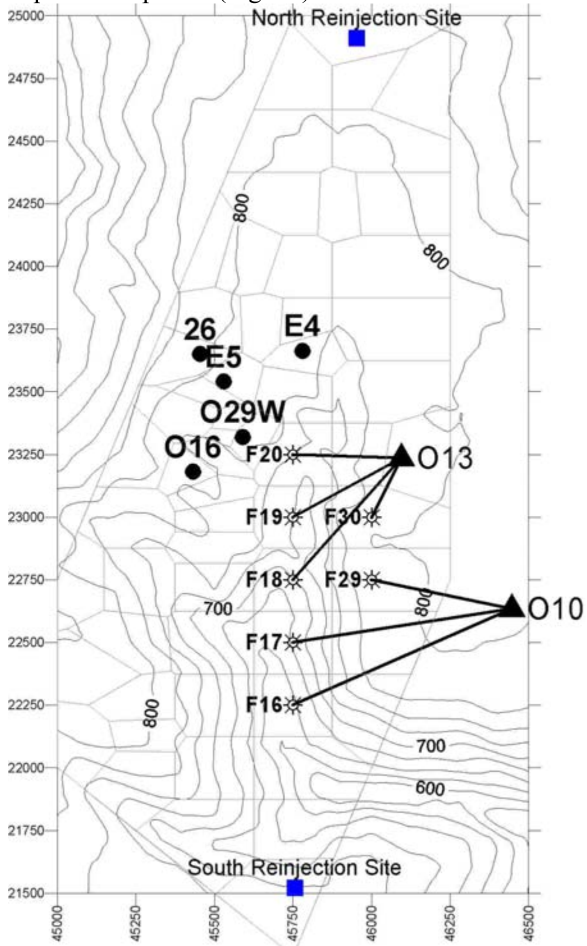

Figure. 11. Existing operating wells: solid circles. Additional F-wells: drilling targets (stars) and drilling rig positions (triangles). Reinjection Sites – squares.

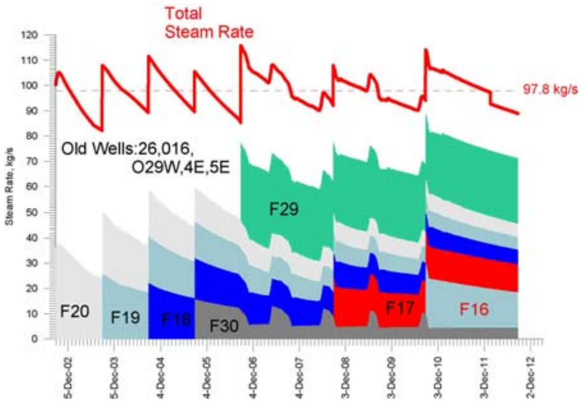

Figure. 12. Scenario #1. Modeling of the steam production (old wells: 016, 26, E4, 029W, E5 and additional F-wells) in the Main production fault zone Dachny Site. Reinjection 150 kg/s (South poligon) assign.

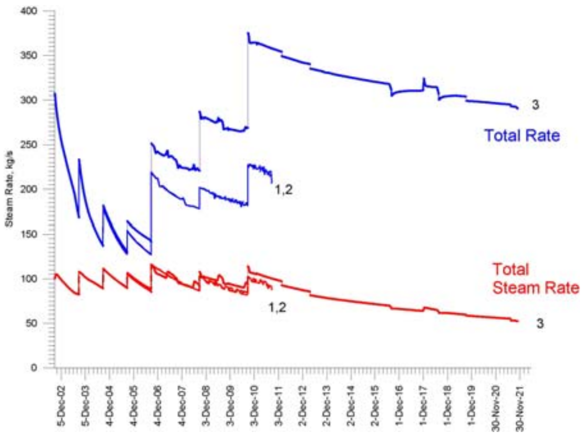

Figure. 13. Influence of reinjection on steam production sustainability of the Main Production Zone of the Dachny Site (based on model scenario #1): 1 - no reinjection, 2 - reinjection 150 kg/s in well O27 (North Reinjection Site), 3- reinjection 150 kg/s (South Reinjection Site). Upper graphs - total production rates, lower graphs - steam production at 7 bars.

CONCLUSIONS

1. The previous model of the fault type Main Production Zone of the Dachny Site Mutnovsky geothermal field (Kiryukhin, 2004) was up-dated based on TOUGH2V2.0 coupled wellbore flow option; and by introducing the Host Rocks as a 5-layers array, with the elements directly connected to corresponding elements of the Main Production Zone (which occurs along 60^o dip fault zone).

2. Model calibration based on 1.5-year exploitation data reveals the most probable conditions during exploitation is downflow recharge (60 kg/s, 420 kJ/kg) into the Main Production Zone reservoir. This scenario explained change of the total steam and separate production from group of the wells (016, 26, E4, 029W, E5).

3. Modeling of the additional F-wells (wells to drill in the south-east portion of the MPZ) exploitation scenario confirmed possibility of the 97.8 kg/s steam production in average terms during 10-year exploitation period (which is sufficient for 50 MWe Power Plant production), if cold water inflows to production zone will be neutralized.

4. In terms of long-term exploitation (more than 10 years) the importance of reinjection strategy increase. Modeling shows that North Site reinjection has no effect on production characteristics of the field, and by 10-year of exploitation reservoir boiling may induce significant pressure drop, which quenches some of production wells. In opposite to this, reinjection into the South Site of the field (at least 75 kg/s, 700 kJ/kg) show positive influence on the total steam productivity, which may extend sustainable production for at least 20-year exploitation period.

5. In terms of stable conditions of steam supply to 50 MWe Mutnovsky Power Plant and future extension of PP's capacity - the possibility of use Verkhne-Mutnovsky site located 1.5-2.5 km north-east from Dachny site should be analyzed (Fig.13). This study is on-going.

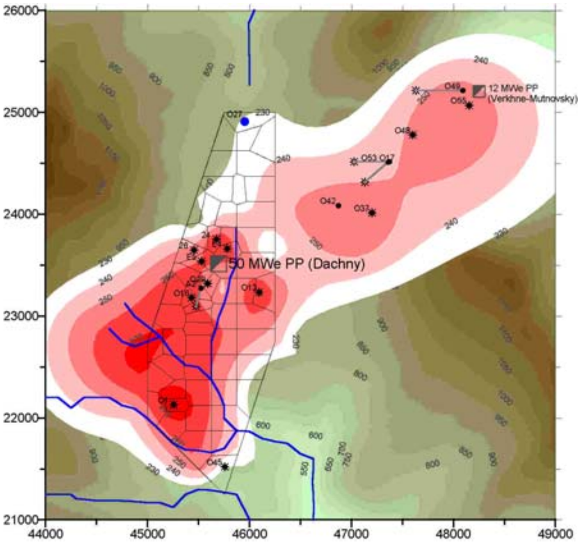

Figure. 14. Mutnovsky geothermal field in the limits of the model-1996, grid corresponding to Main Production Zone reservoir, topo counters, temperature distributions at –250 m.a.s.l., and Power Plants positions are shown too. Production wells – filled circles, feed zones projections – stars.

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