MODELING AND FORECAST OF THE EXPLOITATION THE PAUZHETSKY GEOTHERMAL FIELD, KAMCHATKA, RUSSIA

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ABSTRACT

3D numerical model generated based on conceptual hydrogeological model of the Pauzhetsky geothermal field. Numerical model cover 4 * 5 km2 and include three layers: (1) base layer with feeding channels; (2) hydrothermal reservoir; (3) upper layer with discharge and recharge\infiltration windows. TOUGH2\iTOUGH2 based numerical model of the Pauzhetsky geothermal field calibrated on natural state and 1960-2006 exploitation data. Five principal unknown model parameters such as hydrothermal reservoir fracture permeability and fracture porosity, initial natural upflow rate, base layer porosity, permeabilities of infiltration windows were estimated. Heat and mass balances derived from the model explain the sources of exploitation reserves. Numerical model used for the next 25 year forecast of the enthalpy of production wells and reservoir pressure in 95% confidence interval at constant extraction rate. Modeling forecast for the next 25 year at specified WHP of nine existing production wells and four additional make-up wells confirm possibility of sustainable average steam production at level 28.9 кг/с, that is sufficient to maintain 6.8 MWe of Pauzhetsky Power Plant.

INTRODUCTION

3D numerical model generated based on conceptual hydrogeological model of the Pauzhetsky geothermal field (Kirykhin et al, 2006a, 2006b). Numerical model cover 4 * 5 km2 and include three layers: (1) basement with feeding channels; (2) hydrothermal reservoir with an average thickness 500 m, fracture spacing 105 m and fracture/matrix ratio 0.3/0.7; (3) upper caprock with discharge and recharge\infiltration windows (Fig.1).

Numerical model setup (grid generation, boundary conditions, zonation and rock properties, double-porosity conversions) was discussed in papers (Kirykhin et al, 2006a, 2006b). The following parameterization (e.g. key parameters to be estimated in the model) of Pauzhetsky geothermal field used (Fig.1):

(1) Hydrothermal reservoir (mid-layer) fracture permeability $\mathbf{k_r}$, m^2
(2) Mass flow rates at the bottom of the base layer $\mathbf{Q_b}$, kg/s
(3) Hydrothermal reservoir (mid-layer) compressibility $\mathbf{C_r}$, Pa^{-1}
(4) Hydrothermal reservoir (mid-layer) fracture porosity $\boldsymbol{\phi_f}$
(5) Base layer compressibility $\mathbf{C_b}$, Pa^{-1}
(6) Base layer porosity $\boldsymbol{\phi_b}$
(7) Base layer vertical permeability $\mathbf{k_b}$, m^2
(8) Upper layer North site “Hydraulic window” permeability $\mathbf{k_N}$, m^2
(9) Upper layer East site “Hydraulic window” permeability $\mathbf{k_E}$, m^2
(10) Upper layer West site “Hydraulic window” permeability $\mathbf{k_W}$, m^2

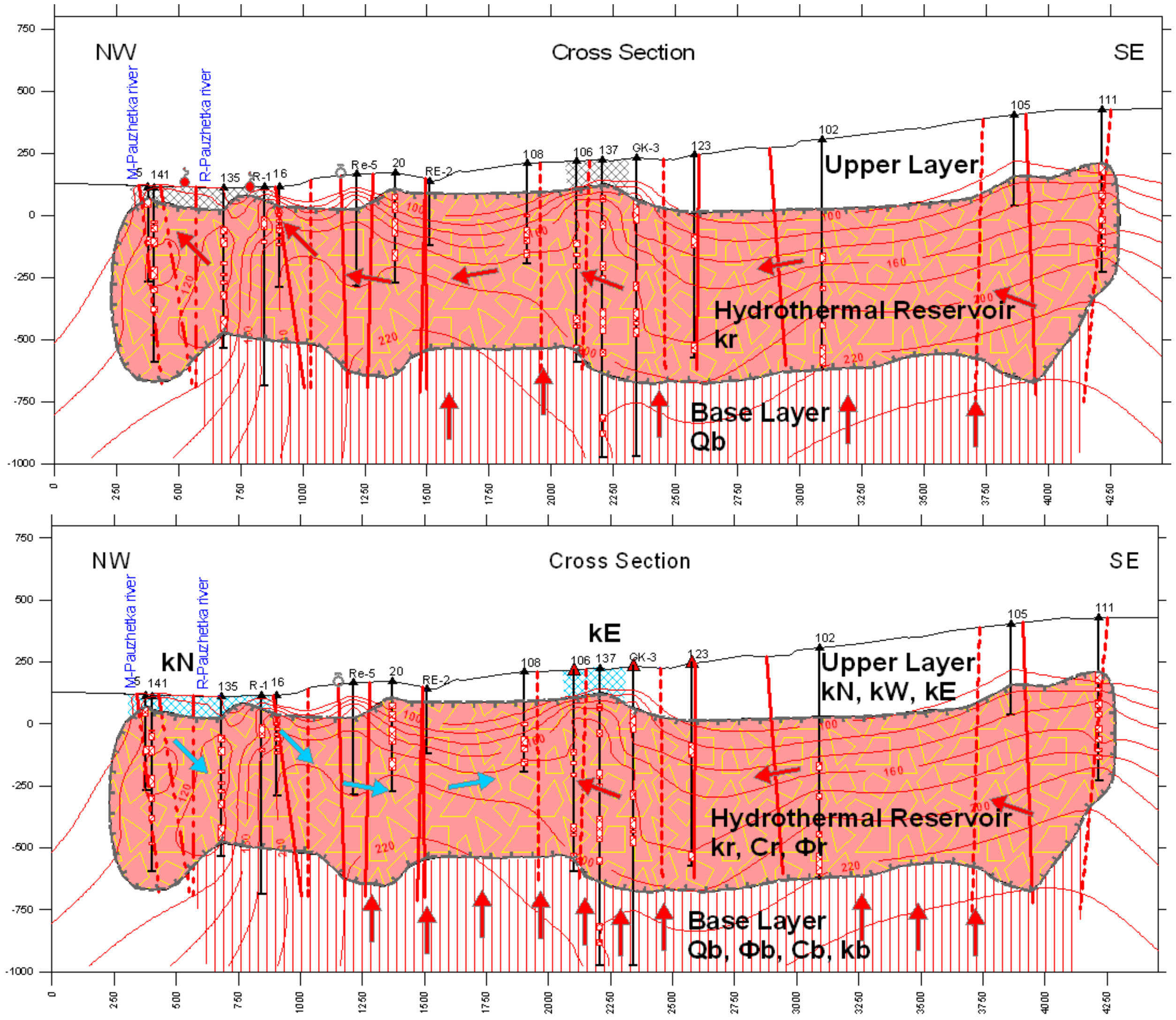

Fig.1 Conceptual hydrogeological model of the Pauzhetsky geothermal field and parameterization of corresponding numerical model: natural state (above) and exploitation (below).

INPUT DATA FOR MODEL CALIBRATION

Calibration data for the natural state inverse modeling (iTOUGH2) include 68 points (2 natural discharge rates Q, 14 reservoir pressures P at -250 m.a.s.l., 52 reservoir vertically averaged temperatures T). The different quality of the calibration points was expressed by specifying appropriate standard deviations ($\sigma T=1\text{-}3^{o}C$, $\sigma P=0.1\text{-}0.5$ bars, $\sigma Q=15\text{-}50\%$).

Calibration data for the 1960-2006 exploitation inverse modeling (iTOUGH2) include 58 datasets: enthalpies h of the exploitation wells (10 data sets), pressures P in monitoring wells (22 data sets), and temperatures T in monitoring wells (26 data sets), for a total of 13757 calibration records. The different quality of the calibration points was expressed by specifying appropriate standard deviations ($\sigma T=5^{o}C$, $\sigma P=0.3$ bars, $\sigma h=20$ kJ/kg).

Exploitation was assigned in the model by specifying monthly averaged production and reinjection rates (January 1960 – December 2006) (Fig. 2, 3).

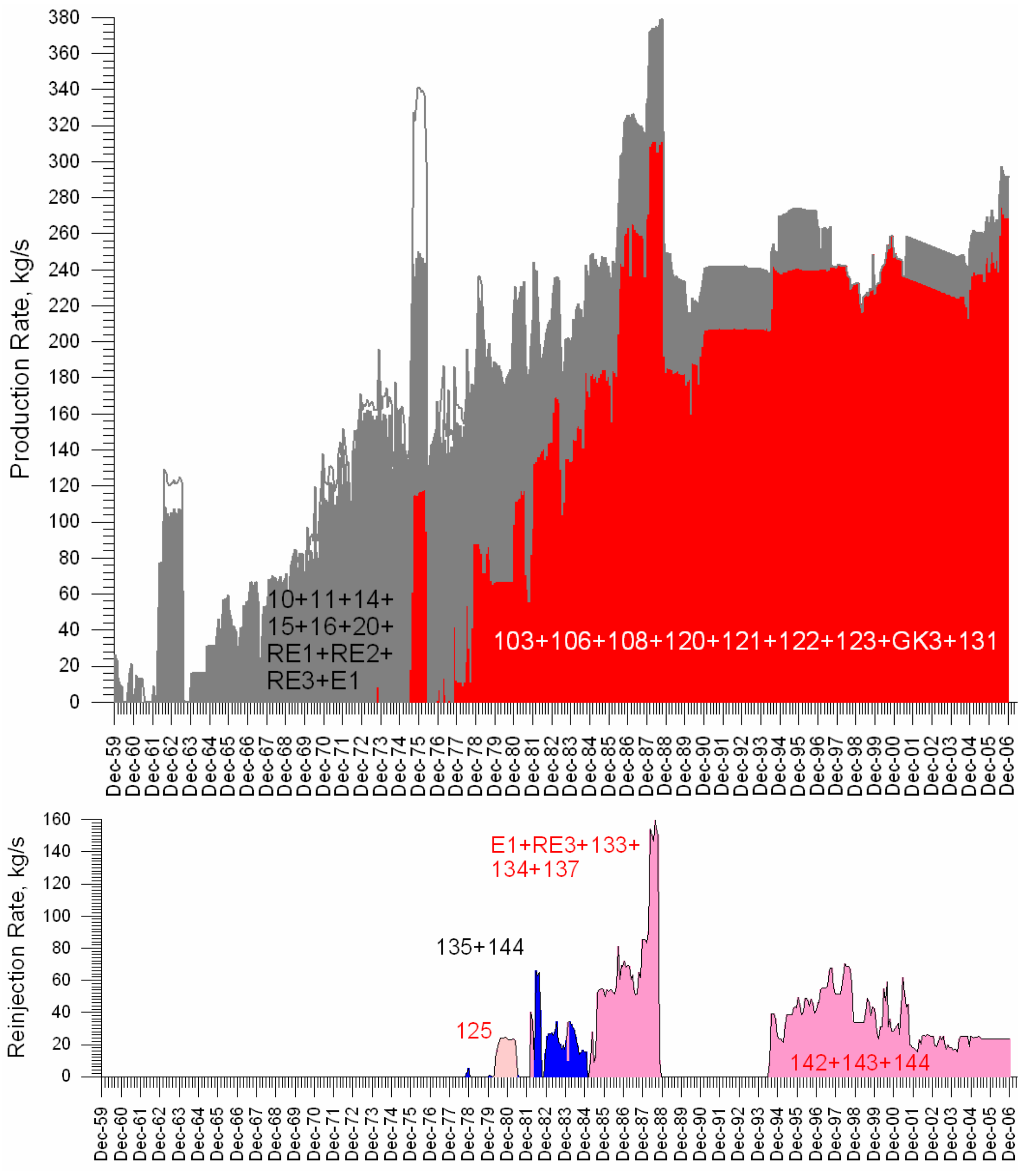

Fig. 2 Extraction (above) and reinjection (below) rates during exploitation period 1960-2006 year. Old North Site production wells – grey, cold water reinjection – blue, 100-120^{o}C reinjection –pink color.

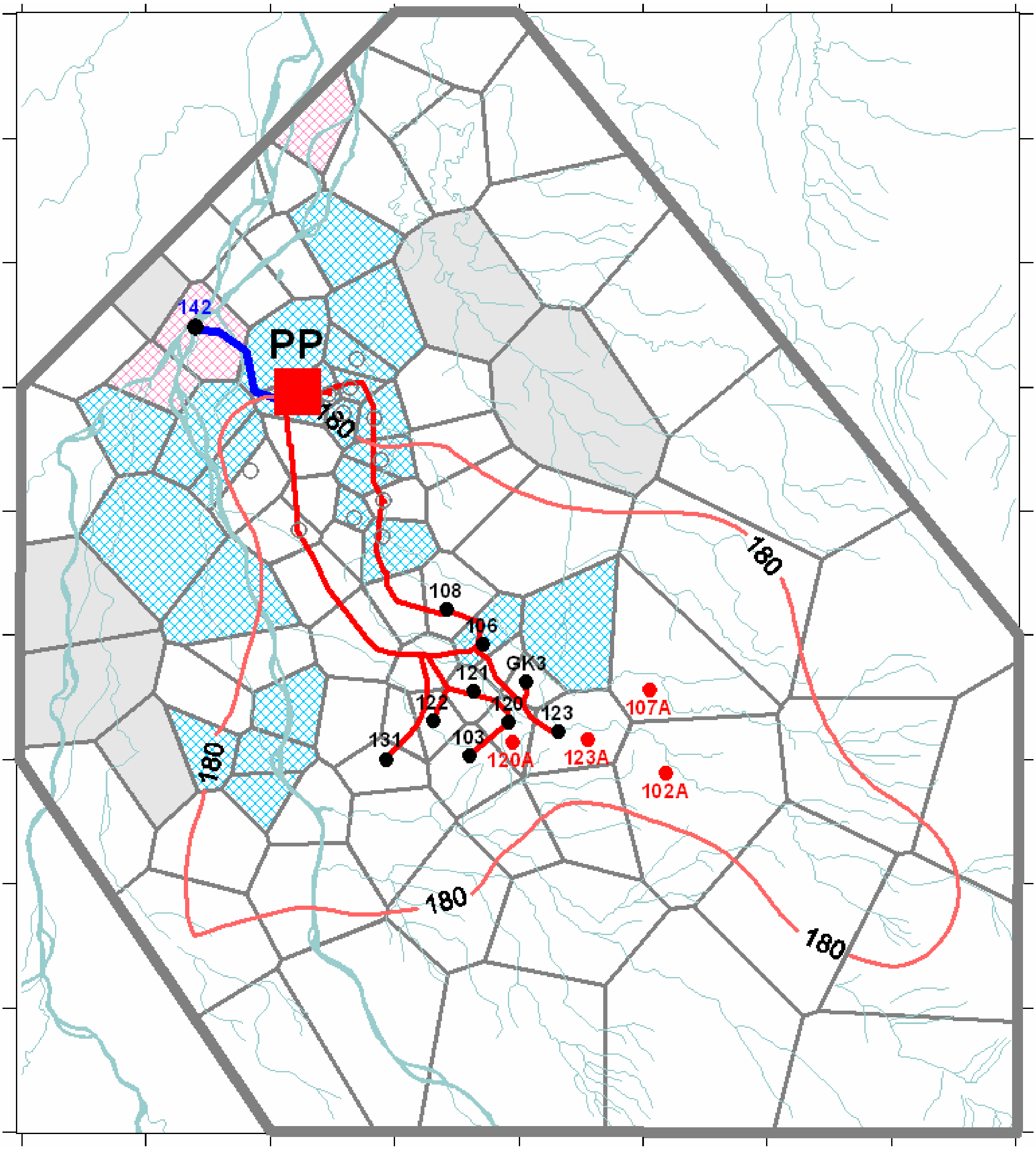

Fig. 3 Schematic map of the Pauzhetsky geothermal field. Thick line – boundaries of hydrothermal reservoir, confirmed by modeling; polygons - numerical model elements; grey region – relatively low permeability domains; isoline – 180°C temperature contour, upflow zone (natural state model); crossed areas – recharge\discharge windows; black filled circles – existing production wells, red filled circles – suggested positions of additional production wells, open circles – old abandoned production wells; red thick lines – steam pipelines, blue thick line – reinjection pipeline. Scale bar - 0.5 km.

PAUZHETSKY MODEL CALIBRATION RESULTS

Inverse iTOUGH2 modeling revealed that principal heat and mass transfer processes of Pauzhetsky geothermal field controlled by: (1) Active volume of hydrothermal reservoir, defined by hydrothermal reservoir fracture porosity ϕ_f and compressibility C_f, which are responsible for effective heat and mass capacity of the hydrothermal reservoir, (2) Upflow from base layer, defined by initial natural upflow Q_b and additional upflow from base layer caused by pressure drop during exploitation and defined by group of four parameters (hydrothermal reservoir (mid-layer) fracture permeability k_r, base layer porosity ϕ_b , base layer compressibility C_b, base layer vertical permeability k_b), (3) Inflows of cold meteoric waters from above, defined by permeabilities of infiltration windows in upper layer: k_N (North Site), k_W (West Site), k_E (East Site) and k_r fracture permeability of hydrothermal reservoir itself.

In particularly, natural state inverse modeling indicated that it is very unlikely that an open lateral boundary exists. Therefore, the lateral boundaries were closed, and the following estimates were obtained (run #NS7-4k6): permeabilities of 83 mD and total upflow rate of 46.5 kg/s (with enthalpy 950-1050 kJ/kg) (Table 1). Residual analysis shows the following standard deviations: temperature - 7.5°C, pressure - 0.5 bars, the discharge rate was matched to 6% of the observed value. The relatively large pressure deviations are considered acceptable because of the poor quality of the pressure data.

Exploitation inverse modeling (runs #EX-7Y8, #EX-7YC) used the natural state temperature and pressure distribution (run #NS7-4k6) as initial conditions. The corresponding parameters estimations are listed in Table 2. Residual analysis (run #EX-7Y8) shows the following standard deviations: temperature – 12°C, pressure - 0.4 bars, enthalpy – 36 kJ/kg. Nevertheless, iTOUGH2 modeling show some of estimated parameters show strong correlation that mean impossibility of reliable estimation of all parameters in one time (run #EX-7Y8). Due to this, reservoir and base layer compressibilities were assigned as $2\ 10^{-6}$ Pa^{-1}, and base layer permeability assigned as 5 mD (run #EX-7YC), having in the mind strong (-1) negative correlation of those parameters with porosities.

Integrated natural state + exploitation inverse modeling (run ##NSEX-6B, Table 1) used to verify model parameters estimations obtained above. Residual analysis (run #NSEX-6B) shows the following standard deviations: temperature - 16°C, pressures - 0.41 bars, enthalpy – 38.8 kJ/kg.

Heat and mass balances derived from the model explain the sources of exploitation reserves. According to modeling scenario run ##EX-7YC by 2005 year mass balance include upflow from base layer (40.6%), meteoric origin inflow through infiltration windows (30%), storage of hydrothermal reservoir (21.1%) and reinjection (8.3%). Heat balance includes convective heat upflow from base layer (50.7%), heat capacity of hydrothermal reservoir (43.4%), reinjection (5.1%), and conductive heat from base layer (0.8%). Chemical balances (chloride) confirm estimations above.

Table 1. Parameters estimations and their uncertainties. Natural state inverse modeling (run #NS7-4K6) and integrated natural state + exploitation inverse modeling (run #NSEX-6B).

Estimated parameter	#NS7-4K6	#NS7-4K6 95% confidence	#NSEX-6B	#NSEX-6B 95% confidence
k_r ,m^2	**83**	**76-93**	89.9	87.7-92.2
Q_b, kg/s	**46.5**	**41.6-51.4**	40.3	40-40.6
ϕ_f			0.098	0.096-0.100

Table 2. Parameters estimations and their uncertainties. Exploitation inverse modeling (runs #EX-7Y8, #EX-7YC).

Estimated parameter	#EX-7Y8	#EX-7Y8 95% confidence	#EX-7YC	#EX-7YC 95% confidence
C_r, Pa^{-1}	4.6 10^{-6}	3.8 10^{-6} -5.5 10^{-6}		
ϕ_f	0.079	0.071- 0.085	**0.094**	**0.090-0.098**
C_b, Pa^{-1}	4.0 10^{-7}	-		
ϕ_b	0.1	-	**0.045**	**0.037-0.053**
k_b,m^2	6	2-20		
k_N,m^2	95	89-102	**145**	**129-162**
k_E,m^2	9	8-10	**11**	**10-12**
k_W,m^2	281	234-338	**490**	**371-645**

FORECAST OF EXPLOITATION 2007-2032 AT CONSTANT RATES LOAD

Numerical model of the Pauzhetsky geothermal field calibrated on 1960-2006 exploitation data (model parameters set correspond to #NS7-4K6, #EX-7YC) allow to forecast enthalpy of production wells and reservoir pressure at specified exploitation load. In this forecast current exploitation rates used (Table 3) for the next 25 years prediction until year 2032. Error propagation analysis based on FOSM (First-Order-Second-Moment) intrinsic iTOUGH2 procedure applied to guaranty 95% confidence forecast interval. In this case errors correspond to uncertainty of estimated parameters (Tables 1 and 2). Fig.4 shows enthalpy prediction for production well 106 into the range of 691.5 – 712.1 kJ/kg in 95% confidence interval by year 2032. Prediction of reservoir pressure in well 124 (central part of the field) shows pressure decline into the range of 30.3 -31.3 bars in 95% confidence interval by year 2032 (Fig. 5). Its worth to note, that model prediction uncertainty is less than input data uncertainty.

Table 3. Characteristics of Pauzhetsky exploitation and reinjection wells by November 2006.

Well #	Rate, kg/s	Enthalpy kJ/kg	Separation Pressure, bars	WHP, bars	Steam rate, kg/s	PI, 10^{-12}m^3
Production wells						
103	23.9	830.5	3.24	5.98	2.9	8.00
106	32	722.4	2.35	3.14	2.9	0.20
108	24.6	730.3	2.35	**2.75**	2.3	3.02
120	18.8	786.5	3.24	4.61	1.9	1.48
121	21.2	819.6	3.24	3.43	2.4	1.475
122	43.8	814.5	3.14	4.61	5.0	43.00
123	46.8	769.3	3.24	3.83	4.3	18.50
GK3	29.2	824.6	2.45	2.55	3.9	11.00
131	34.6	808.7	2.55	5.49	4.3	4.20
Reinjection well						
142	18.0	535.0				

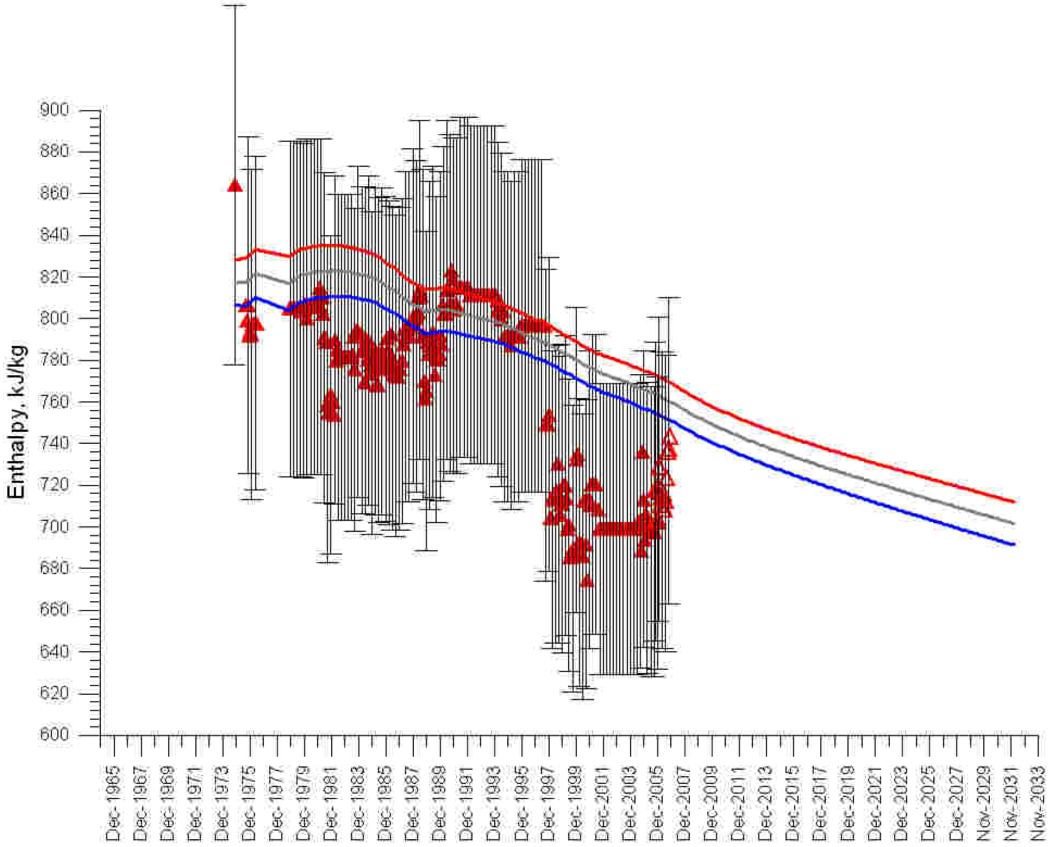

Fig. 4 FOSM error propagation analysis of the Pauzhetsky model applied to well #106 enthalpy forecast for 1960-2032 year. Lines – 95% confidence interval for the model. Triangles – observation data. Bars – 95% confidence interval for observations (standard deviation of observations assumed as σ=20 kJ/kg).

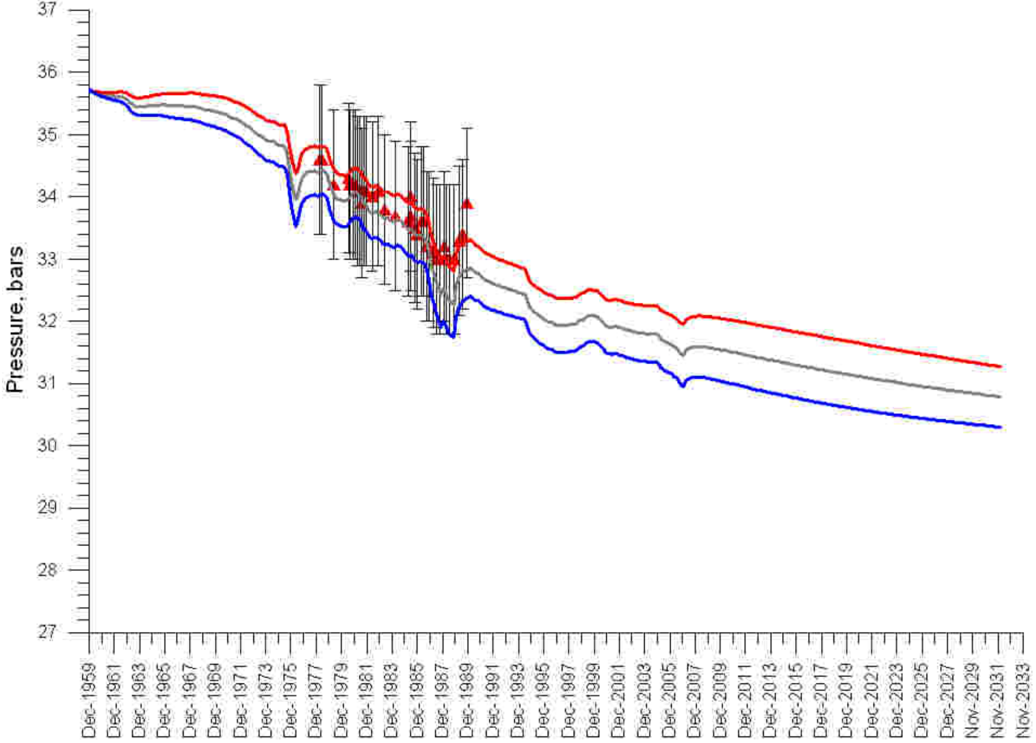

Figure. 5. FOSM error propagation analysis of the Pauzhetsky model applied to well #124 pressure forecast for 1960-2032 year. Lines – 95% confidence interval for the model. Triangles – observation data. Bars – 95% confidence interval for observations (standard deviation of pressure measurements assumed as σ=0.3 bars).

MODELING FORECAST 2007-2032 (CONSTANT WELLHEAD PRESSURES)

Exploitation of the Pauzhetsky geothermal field production wells conducted at constant wellhead pressures. Hence coupled TOUGH2 wellbore-reservoir option used for modeling 2007-2032 exploitation forecast scenario. Exploitation wells 103, 106, 108, 120, 121, 122, 123, GK3 and 131 were assigned in the model with wellhead pressures (WHP) according to Table 3. Bottom hole pressures tables calculated for each well based on HOLA wellbore simulator, accordingly to wells specific design. Exploitation wells production indexes PI were estimated directly in the model based on the current rates of production wells (Table 3).

Model parameters set correspond to #NS7-4K6, #EX-7YC. Four additional make-up wells were assigned in the model to maintain sustainable production 120A (turn on in 2008 year), 123A (2012 year), 107A (2016 year), 102A (2025 year). Location of additional make-up wells shown in Fig.3, wells designed as a typical Pauzhetsky exploitation wells (250 m\219 mm, then 190 mm), WHP assumed as 4 bars and separation pressure as 2.84 bars. PI indexes of additional wells estimated based on assumption of initial 30 kg/s production rates. It was also found necessity of switch WHP at well 131 to 3.0 bars (2020 year) and in well 122 to 3.5 bars (2028 year) to maintain sustainable production of those wells.

Figs. 6 and 7 shows modeling forecast for total flowrate and steam rate at separation pressures of wells 103, 106, 108, 120, 121, 122, 123, 131, GK3, 120A, 123A, 107A, 102A for time period of exploitation 2007-2032 year. Total flowrate of production wells will maintain in the range 257.1 – 324.4 kg/s (287.4 kg/s in average), total steam production at separation pressure will maintain in the range 25.7 - 32.2 kg/s (28.9 kg/s in average).

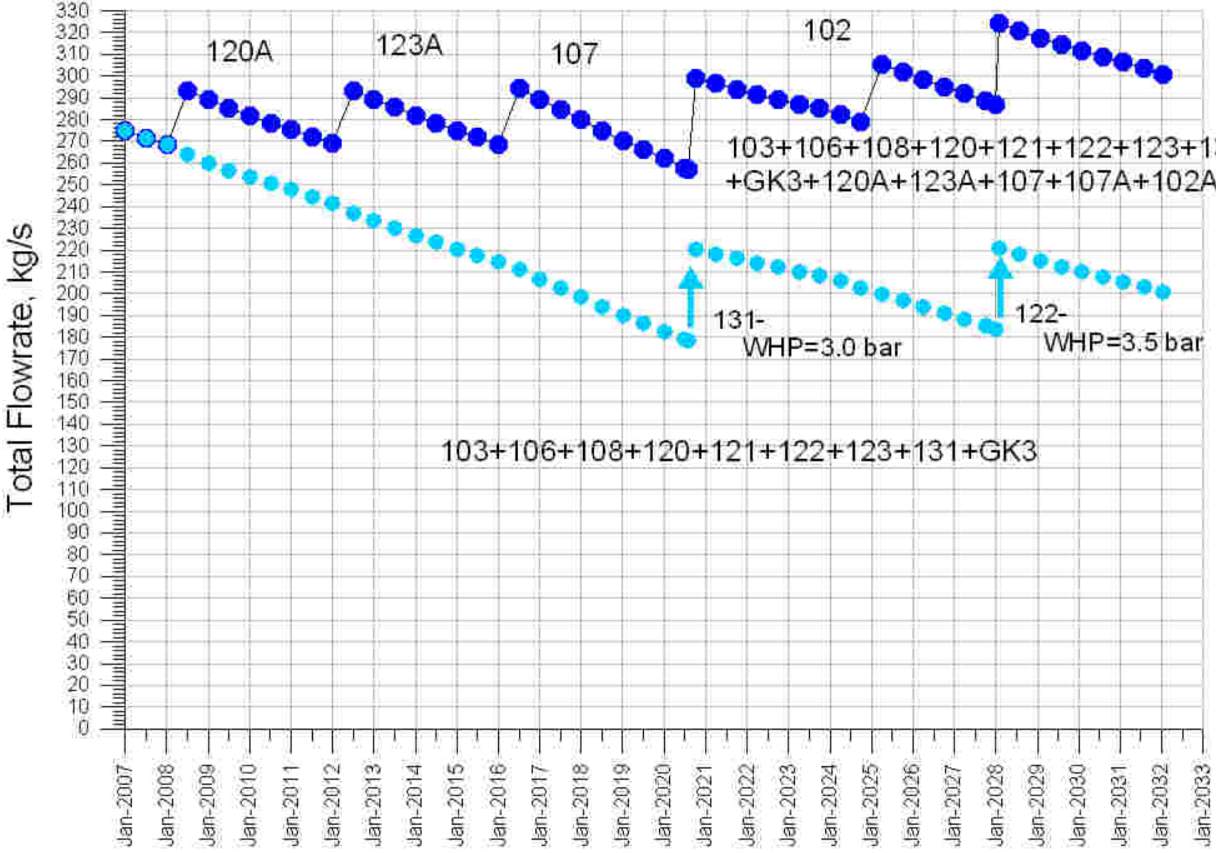

Fig.6 Modeling forecast for total flowrate of wells 103, 106, 108, 120, 121, 122, 123, 131, GK3, 120A, 123A, 107A, 102A for time period of exploitation 2007-2032 year.

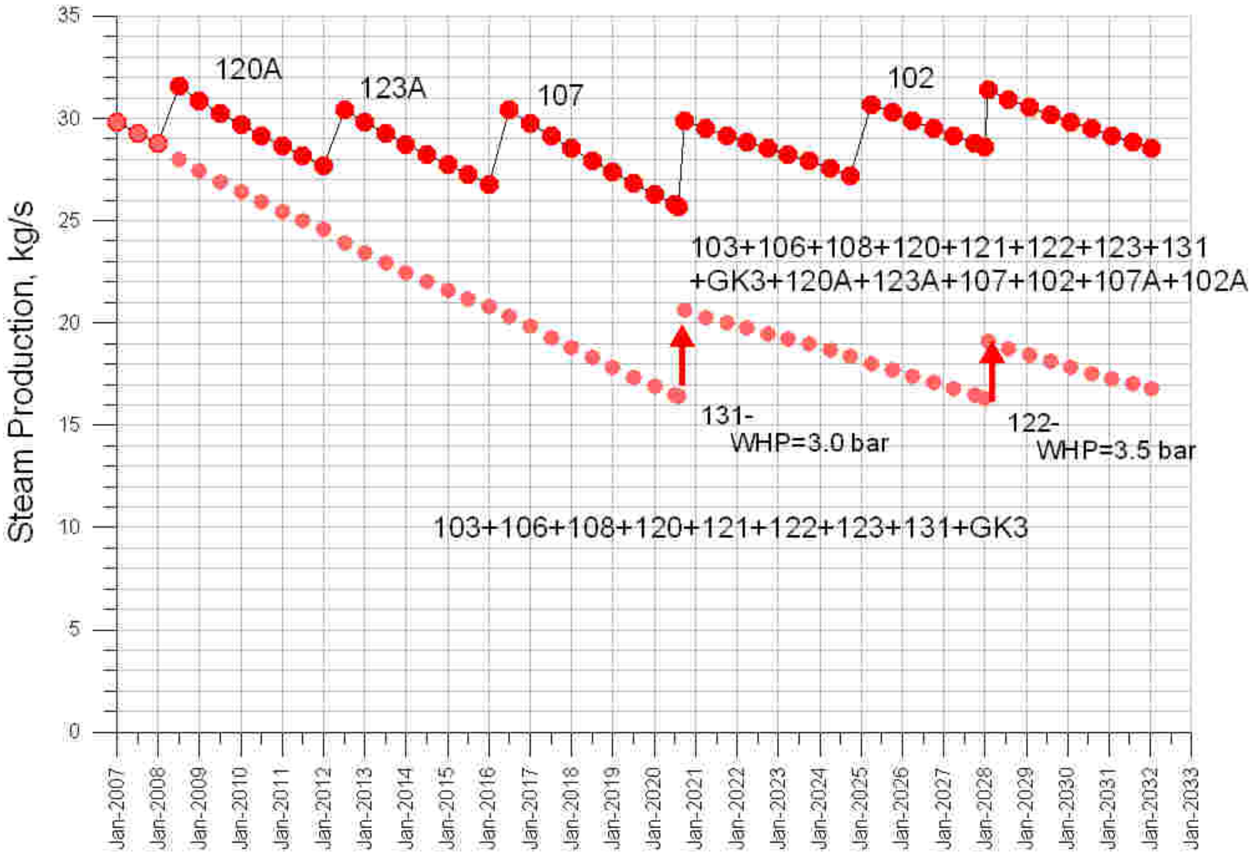

Fig.7 Modeling forecast for steam rate at separation pressures of wells 103, 106, 108, 120, 121, 122, 123, 131, GK3, 120A, 123A, 107A, 102A for time period of exploitation 2007-2032 year.

CONCLUSIONS

1. TOUGH2\iTOUGH2 based numerical model of the Pauzhetsky geothermal field calibrated on natural state and 1960-2006 exploitation data. Principal unknown model parameters were estimated: hydrothermal reservoir fracture permeability k_r and fracture porosity ϕ_f, initial natural upflow rate Q_b, , base layer porosity ϕ_b, permeabilities of infiltration windows in upper layer: k_N, k_W, k_E. Heat and mass balances derived from the model explain the sources of exploitation reserves: upflow from base layer (40.6%), meteoric origin inflow through infiltration windows (30%), storage of hydrothermal reservoir (21.1%) and reinjection (8.3%). Numerical model used to forecast enthalpy of production wells and reservoir pressure. If current exploitation rates used for the next 25 years, then 95% confidence interval forecast shows the rate of enthalpy decline 63 kJ/kg and pressure decline 0.7 bars in the most affected parts of the production zone.

2. Modeling forecast at specified WHP of nine existing production wells and four additional make-up wells of the Pauzhetsky geothermal field for the next 25 years shows the total flowrate maintain in the range 257.1 – 324.4 kg/s (287.4 kg/s in average), total steam production at separation pressure maintain in the range 25.7 - 32.2 kg/s (28.9 кг/с in average). This steam production is sufficient to support 6.8 MWe of Pauzhetsky Power Plant output in average terms (minimum 6.1 MWe). Average steam production rate 28.9 kg/s correspond to explotation reserves "A+B" category according to Russia Federal State Commission on thermal waters reserves estimations requirements.

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