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Using the Paratunsky Geothermal Field to Provide Heating for Kamchatka

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Abstract—The Paratunsky geothermal field has been in operation since 1964, mostly in a self-flowing mode, with a discharge rate of approximately 250 kg/s of thermal water at temperatures of 70–90°C (47 MW, with the waste water having a temperature of 35°C). The water drawn from the field is used for local heating, spa heating, and for greeneries in the villages of Paratunsky and Termal'nyi (3000 residents). The potential market of thermal energy in Kamchatka includes Petropavlovsk-Kamchatskii (180000 residents), Elizovo (39000), and Vilyuchinsk (22000). The heat consumption in the centralized heating systems for Petropavlovsk-Kamchatskii is 1623000 GCal per annum (216 MW). A thermohydrodynamic model developed previously is used to show that the Paratunsky geothermal reservoir can be operated in a sustainable mode using submersible pumps at an extraction rate of as much as 1375 kg/s, causing a moderate decrease in pressure (by no more than 8 bars) and temperature (by no more than 4°C) in the reservoir. Additional geothermal sources of heat energy may include the Verkhne-Paratunsky and Mutnovsky geothermal fields.

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1. INTRODUCTION

The Paratunsky geothermal field has been in production since 1964. A total of 321 million tons of thermal water at temperatures of 70–100°C have been extracted. The water is currently used for district heating, spa heating, and greeneries in the villages of Paratunsky and Termal'nyi. The productive volcanogenic reservoir of the block-fissure type has an approximate volume of 40 km^3, the measured temperatures reach 107°C, and the thermal waters have a Cl–Na, Cl–SO_4–Na composition with the gas phase being dominated by N_2 (96–98%). We examined the thermohydrogeochemical history of production using 3D thermohydrodynamic simulation (TOUGH2-EOS1 + tracer, a polygonal grid, 9727 grid elements, and 8 layers). The model was calibrated based on the initial temperature distribution and the pressure variation in the reservoir during the 1964–2014 operation. This inversion simulation revealed high values of filtration and capacity properties of the productive reservoir (permeability up to 1.4 D and compressibility up to 4×10^{-8} Pa^{-1} with a thickness of up to 1200 m) and determined the total natural inflow of deep-seated heat carrier (190 kg/s). We found the boundary condition for the areal discharge of thermal water and for the inflow of chloride ground water across the eastern boundary of the geothermal reservoir. Sixteen main plane-oriented productive zones have been identified within the geothermal reservoir. The forecasting simulation for the variation in pressure and temperature in the productive reservoir of the Paratunsky geothermal field for the time until 2040 assuming a total extractable load of 256 kg/s (mostly in a freely flowing mode) showed a moderate decrease in the reservoir pressure (by at most 0.7 bars) with an insignificant decrease in the temperature (Kiryukhin et al., 2017a, 2017b), which indicates that the extraction of the heat carrier can be increased.

The potential market of thermal energy in Kamchatka includes Petropavlovsk-Kamchatskii (180000 residents), Elizovo (39000), and Vilyuchinsk (22000) (Fig. 1), with the total heat consumption in the centralized heating systems of Petropavlovsk-Kamchatskii being 1623000 GCal per annum (216 MW) (see Appendix to the Order of Petropavlovsk-Kamchatskii Administration no. 132 as of February 5, 2016). At present the thermal energy production uses hydrocarbon fuel.

The search for solutions to the problem of heating for Kamchatka using geothermal sources started in 1994 when the Icelandic *Virkir Orkint* company prepared a project of heat supply to the Petropavlovsk-Kamchatskii agglomeration using the heat energy stored in the heat carrier separate (160°C) that is being extracted at the Mutnovsky geothermal field. The main parameters of the project were as follows: (1) the thermal energy stored in the separate is transformed at

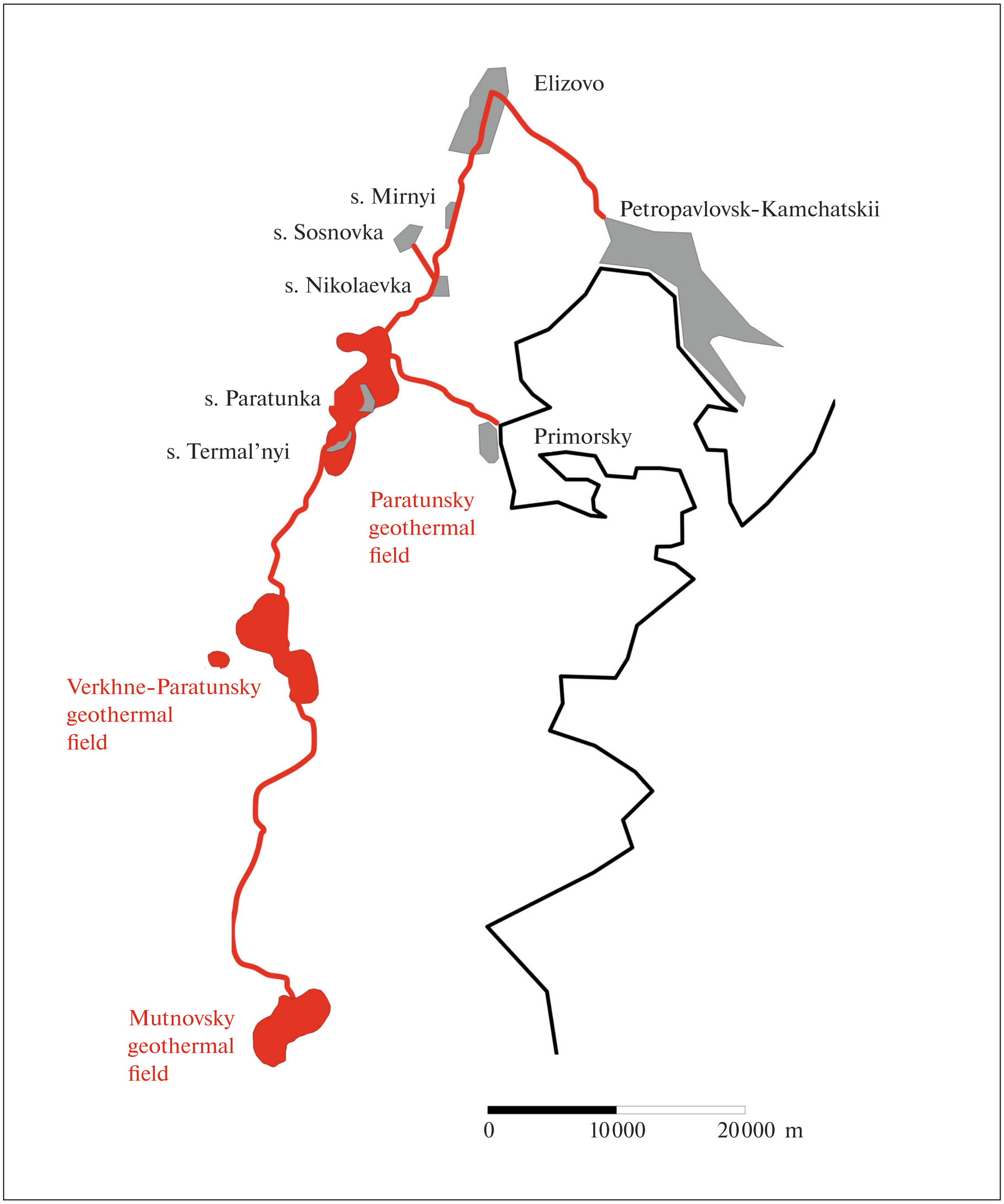

Fig. 1. The main users of thermal energy in Kamchatka, potential sources of geothermal heat supply, and possible routes of pipelines for the heat carrier.

the geothermal power plant into the thermal energy of fresh water (666 kg/s, 150°C); (2) the hot water is pumped via a main pipe from the Mutnovsky geothermal field to Elizovo, Petropavlovsk-Kamchatskii, and Vilyuchinsk, as well as being distributed over the adjacent villages; (3) the thermal power is estimated as 360 MW, with the total annual economized hydrocarbon fuel being estimated as 263000 tons; (4) the investments required to implement the project were estimated to be 157 million 1994 US dollars, or 420 million 2018 US dollars, with the annual inflation rate being 4%.

There is another option for the heating of Petropavlovsk-Kamchatskii (Fedotov et al., 2007). These authors proposed a hypothetical magma chamber beneath Avachinsky Volcano as the source of geothermal energy; it was inferred to be an ellipsoid with the top at sea level and the horizontal and vertical semiaxes 4.5 km and 3 km long at the 700°C isotherm, respectively. It was shown that a block of hot rocks with a volume on the order of 50 km^3 when used for 100 years can supply approximately 250 MW of electrical energy. However, this hypothesis of a productive geothermal reservoir beneath Avachinsky Volcano and the characteristics of that reservoir have yet to be corroborated by exploration drilling.

Therefore, the present study considers the potential for increased heating energy to provide for remote Kamchatka consumers based on the well-known Paratunsky geothermal field, which has been in operation for many years. The production in the freely flowing mode has evidently reached the maximum possible level. We consequently consider how the extraction of thermal water can be increased at the Paratunsky geothermal field using submersible pumps. Our analysis relies on the thermohydrodynamic model mentioned above that has been refined by more accurately describing the inflow from the overlying cold ground water (which is of exceptional importance for sustainable exploitation of the geothermal field). The estimates derived by thermohydrodynamic simulation are accompanied by analyses of economic viability.

2. EXPERIENCE GAINED DURING THE OPERATION OF LOW TEMPERATURE GEOTHERMAL FIELDS USING SUBMERSIBLE PUMPS

Low temperature geothermal fields, which are defined as having reservoir temperatures below 150°C at a depth of 1 km (Rybach, 1981; Axelsson and Gunnlaugsson, 2000; Johannesson et al., 2016), have demonstrated the potential of multiyear (for some decades) operation in Iceland, Hungary, China, Turkey, France, Germany, Russia, and other countries. This production history aided our understanding how such fields are formed, including the conditions of water and heat recharge under natural conditions and during extraction, and toward estimating reservoir characteristics and the degree of renewable potential of the reserves. As an example in Iceland it was shown that the capital (Reykjavik) and nearby population centers (160000 inhabitants) can be heated at a rate of thermal energy consumption 11 PJ/yr (Axelsson and Gunnlaugsson, 2000) using three low temperature geothermal reservoirs (Reykir, Ellidaar, and Laugarness). We note that by 2016 the Reykjavik heating system had added 450 MW of thermal energy supplied by a combined heat and power plant that draws on two high temperature geothermal fields, the *Nesjavelir* and *Hellysheidi* fields (Johannesson et al., 2016).

This study is concerned with the Paratunsky low temperature geothermal fields, Kamchatka, which are adjacent to active volcanic areas and are composed of volcanogenic rocks, like the Icelandic fields referred to above. The current conceptual model of low temperature geothermal systems assumes deep-seated circulation of meteoric waters with water recharge due to higher areas, involving heating in deep-seated systems of fissures and dikes, and discharge by ascending flows and hot springs in relief lows and in valleys (Bodvarsson, 1983). The dominant meteoric origin of the Icelandic low temperature geothermal systems has been proven by studies of isotopic compositions of the water (Arnason, 1976). A careful analysis of the long-term operation of the nine Icelandic low temperature geothermal fields where submersible pumps are used for extraction (Axelsson et al., 2010) showed that in spite of the analogous mechanisms that are responsible for their formation several types of reservoir can be identified.

1. High production reservoirs (65–877 kg/s, up to 80 kg/s/bar); due to permeability and boundary conditions, these reach quasi-equilibrium at a constant rate of water withdrawal and in the absence of reinjection (Reykir, Reykjahlid, Laugarnes (150 kg/s, the water level drop by 140 m), Ellidaar, and Ashildarholtvatn).

2. Less productive reservoirs (15–38 kg/s, 0.7 kg/s/bar) that do not reach equilibrium; some possess favorable boundary conditions (Skatudalur, Hamar), while others need recharge in the form of a 15–25% reinjection (Laugaland) in order to stabilize the pressure reduction; in some cases a magnitude 6.6 earthquake can enhance productivity (Gata).

3. Highly productive reservoirs under the inflow of cold ground water (Thorleifskot).

The relative amount of thermal water extraction is estimated as 25–80% of the total pore space volume (Laugarnes, Hamar), which can account for the absence of noticeable chemical and temperature-induced changes in most of the systems mentioned above.

In recent years considerable amounts of information have been acquired concerning the engineering geothermal systems (EGS) of the Upper Rhein Graben (Sauerlach, Insheim, Beinheim, Brühl, Soultz, Bruchsal, and Landau) where low temperature geothermal reservoirs were identified in granite and in zones of contact with adjacent metamorphic units (Schill and Genter, 2003; Genter et al., 2016). In that case the natural fissure systems are stimulated and then operated using LSP submersible borehole pumps installed at depths reaching ~370 m to extract heat from a closed circulation system consisting of double wells. The productivity of the "one-fissure" reservoirs in the Rhein Graben is comparable to those of the Icelandic reservoirs: Insheim (85 kg/s at 160°C, borehole doublets at a distance of 1 km), Beinheim (70 kg/s at 140°C), Brühl (70 kg/s), Bruchsal (30 kg/ at 126°C), Landau (50–70 kg/s at 160°C), Rittershoffen (70 kg/s at 160°C), and Soultz (32 kg/s at 155°C). Heat extraction from igneous rocks is also of interest in con-

Table 1. The filtration, capacity, and thermophysical properties, as determined for the 4HM-GROWA model of the Paratunsky geothermal field

Reservoir parameters		Model domains								
		top layer			middle layer				bottom layer	
		CAPRK	CAPR2	GROWA	RESER	RESPR	BUFER	BUFE2	BASEF	BASE
Porosity	θ	0.1			0.1	0.1	0.1		0.1	0.1
Lateral permeability, mD	k	3.1	0.01	1000	0.1	1410	10	10	741	1
Vertical permeability, mD	k	3.1	0.01	1000	0.1	167	167	167	167	1
Thermal conductivity, W/m °C	λ	1.0	1.0	1.0	1.4	1.4	1.4	1.4	2.0	2.0
Specific heat, J/kg °C	c	1000			1000	1000	1000		1000	1000
Compressibility, Pa^{-1}	c	10^{-8}			10^{-8}	4.1×10^{-8}	4.1×10^{-8}		10^{-8}	10^{-8}

nection with the operation of the Paratunsky reservoirs, where diorite bodies have been reached in two locations.

These examples of Iceland and of the Rhein Graben are helpful in that they serve as analogues of the Paratunsky low temperature geothermal systems and suggest feasible ways for enhancing the potential of the Paratunsky reservoirs to be operated using submersible pumps and reinjection.

3. A DESCRIPTION OF THE 4HM-GROWA THERMOHYDRODYNAMIC MODEL

One critical issue that arises for the transition from the self flowing-mode operation of the Paratunsky geothermal field to extraction using submersible pumps, which leads to a drop of thermal water level to 100–150 m below the ground surface, consists in being able to predict the inflow of ground water from the 40–180-m top layer (alluvial deposits consisting of sand, gravel, and pebble) to the productive geothermal reservoir through the intervening aquifuge 10–150 m thick, which is composed of hydrothermally altered rocks (Lower Quaternary aleurolite with fine-grained sandstone interbeds).

Accordingly, we modified the thermohydrodynamic model as described by Kiryukhin et al. (2017a, 2017b) by making a finer numerical vertical grid to represent the top layer in the model, while retaining the horizontal polygonal division into grid elements (the total number of model elements in a layer is 1223). As a result, the total number of active elements was increased to reach 11488. Below, we provide a layer-by-layer description of the 4HM-GROWA model referred to above (from top to bottom) with accompanying brief characterization of their filtration and capacity properties, boundary conditions, the distribution of mass sources and sinks, and the locations of producing wells.

3.1. The top layer of the model

The top layer includes a ground water horizon underlain by a "relative" aquifuge. The top layer has a total thickness of 180 m and is divided into four horizontal sublayers 45 m thick each, with the lower three sublayers being active; these are shown in Fig. 2a with their centers at absolute depths of $Z = -47.5$, $Z = -92.5$, and $Z = -137.5$ m.

The permeable ground water horizon (the GROWA domain) was defined to be in the $Z = -47.5$ m abs. sublayer; its contour can be seen in Fig. 2a.

A fixed condition was specified for the GROWA ground water horizon (temperature 7.3°C and pressure 10 bars).

The dividing aquifuge (the CAPRK domain) was specified in the model to reside beneath the ground water horizon (the GROWA domain) in the $Z = -92.5$, $Z = -137.5$ m abs. sublayers. The low-permeability CAPR2 domain was specified for the $Z = -137.5$ m abs. sublayer along the periphery of the dividing aquifuge (at a fixed condition of 10.0°C temperature and 19 bars pressure) (see Fig. 2a, Table 1).

3.2. The middle layer of the model

The middle layer includes a productive reservoir and low-permeability host rocks in the depth range between –1360 and –160 m abs. The layer is subdivided vertically into six sublayers 200 m thick each with their centers at absolute depths of –260, –460, –660, –860, –1060, and –1260 m. The middle layer is subdivided horizontally into the RESPR domain with productive reservoirs and a temperature above 60° C (corresponding to the Sredny, Nizhne-Paratunsky, Severnyi, and Mikizhinsky areas, respectively) and the host-rock RESER domain with lower permeability and a temperature below 60°C, the buffer BUFER zone with higher permeability near the open eastern

(a)

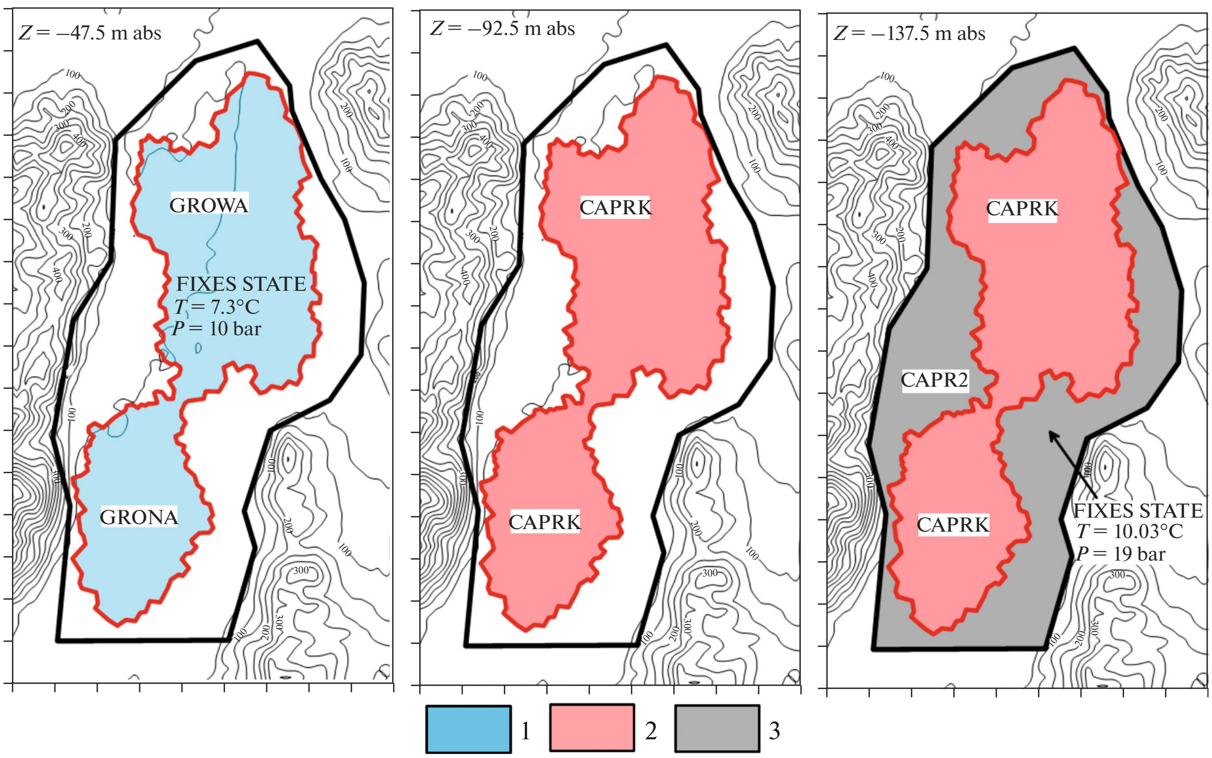

Fig. 2. The geometry and zoning of the 4HM-GROWA thermohydrodynamic model for the Paratunsky geothermal field. (a) stratification and zoning of top layer (the sublayers are at –47.5, –92.5, and –137.5 m abs., each 45 m thick) in the 4HM-GROWA thermohydrodynamic model for the Paratunsky geothermal field: (1) GROWA domain: ground water horizon, (2) CAPRK domain: a dividing aquifuge, (3) CAPR2 domain: low permeability domain. Explanations are in the main text and in Table 1; (b) zoning of the middle layer (the sublayers are at –260, –460, –660, –860, –1060, and –1260 m abs., each 200 m thick) in the 4HM-GROWA thermohydrodynamic model for the Paratunsky geothermal field: (1) RESPR domains that represent the productive reservoir of high permeability, (2) BUFER domain that represents a buffer zone of higher permeability near the open eastern boundary, (3) RESER domain representing host rocks of lower permeability, (4) envisaged producing wells with submersible pumps (see Section 4), (5) inflow of chloride water into the productive reservoir during extraction, (6) boundaries of the model (*a* impermeable, *b* open), (7) projections of zones where the inflow of deeper heat carrier occurs, see Fig. 2c (BASEF domain). Explanations are in the main text and in Table 1; (c) zoning of the bottom layer ($Z = -2180$ m abs.) in the 4HM-GROWA thermohydrodynamic model for the Paratunsky geothermal field: (1) BASEF domain was found to have high permeability and inflow of deeper heat carrier (discharge (kg/s) and enthalpy (kJ/kg) are indicated by numerals); the domain represents the following areas: Sredny (SR), Nizhne-Paratunsky (NP), Severnyi (N), and Mikizhinsky (M), (2) BASE domain represents the low permeability host rocks. Explanations are in the main text and in Table 1.

boundary, and the eastern boundary itself specified in the model as the BUFE2 boundary domain with a fixed condition (see Fig. 2b, Table 1).

3.3. The bottom layer of the model

The bottom level in the model includes the basement of the Paratunsky geothermal field as determined in the depth range between –1360 and –3000 m (the elements are centered at an absolute height of –2180 m). In this layer we specified a BASEF domain with a high permeability and inflows of deep-seated heat carrier relevant to the Sredny, Nizhne-Paratunsky, Severnyi, and Mikizhinsky areas, and a BASE domain (low-permeability host rocks) (see Fig. 2c, Table 1). All elements of the bottom layer are assigned a conductive heat flux of 60 mW/m^2.

3.4. Simulated determination of predictive producing wells

We simulated the pumping operation of the Paratunsky geothermal field using submersible pumps during 25 years by specifying 11 additional producing wells with a given discharge (see Fig. 2b), with all of the existing producing wells being switched off. The producing depth ranges of the additional wells were specified to be between –1160 and –960 m abs. The simulation involved three options for the operation of the geothermal field with different discharges of the producing wells: 75 kg/s, 100 kg/s, and 125 kg/s each

(b)

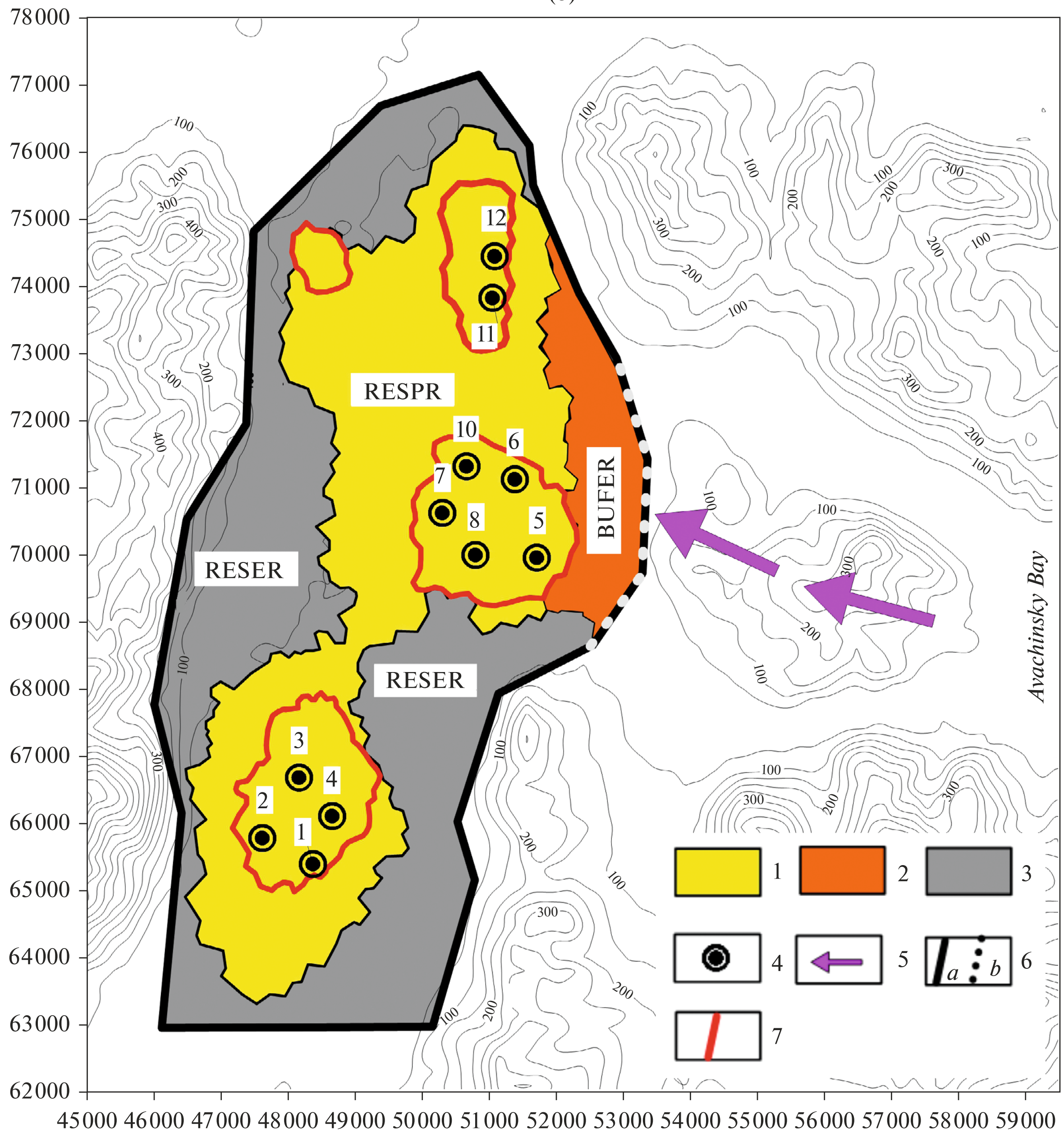

Fig. 2. (Contd.)

(the respective total discharges were 825 kg/s, 1100 kg/s, and 1375 kg/s).

4. PREDICTING THE THERMOHYDRODYNAMIC MODE OF OPERATION FOR THE PARATUNKA GEOTHERMAL FIELD USING PRODUCING WELLS EQUIPPED WITH SUBMERSIBLE PUMPS

Simulation of operation using submersible pumps was carried out for a period of 25 years. The results showed varying pressure and temperature at observing wells 9, GK8, 52, GK12, 66, and 39. Wells 9, GK8, 52, and GK12 in the Sredny area showed moderate rates of decreasing pressure and temperature, and so are shown in a single figure (Fig. 3, well 9). Well 39 characterizes the rates of decreasing pressure and temperature for the Sredny area (see Fig. 3b) while well 66 does this for the Nizhny and Severnyi areas (see Fig. 3c).

From these results it follows that a 25-year pump operation at a maximum total discharge rate of 1375 kg/s would reduce the reservoir pressure by no more than 7–8 bars and the temperature by no more than 4°C.

(c)

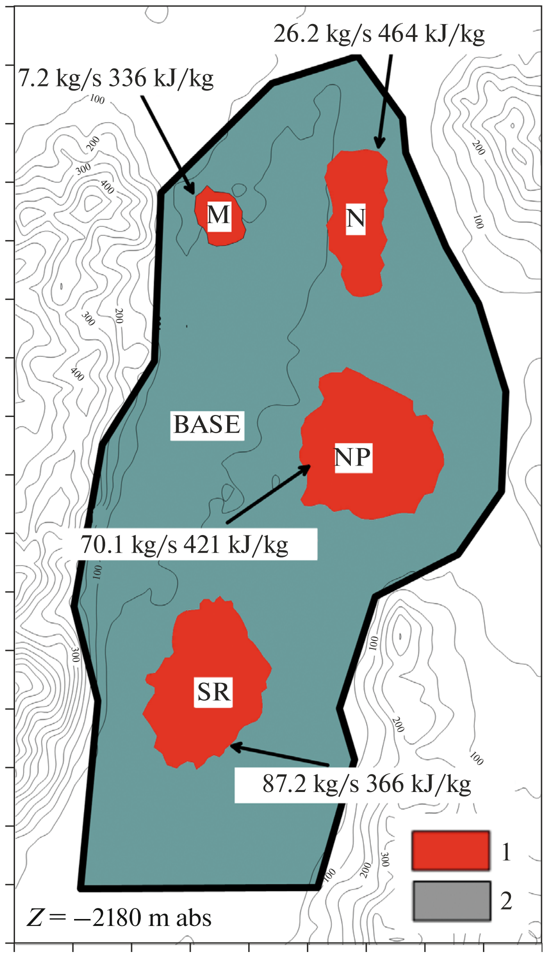

Fig. 2. (Contd.)

The mean productivity index for the producing wells at the Paratunsky geothermal field is 6 kg/s/bar (0.6 L/s/m) with well diameters of 112–145 mm (catalog of the wells). Assuming the mean productivity index for future producing wells to be 10 kg/s/bar (by expanding the diameter to reach 245 mm and the well depth to reach 900 m), we obtain the result that the reduction in bottom-hole pressure due to the operation of a single well at a discharge of 75 kg/s would amount to 7.5 bars, with the respective values being 10.0 bars for 100 kg/s and 12.5 bars for 125 kg/s.

The total reduction in bottom-hole pressure and temperature in the producing wells with due account of their interaction for a 25-year operation is shown in Table 2.

5. ASSESSING THE ECONOMIC EFFICIENCY FOR THE OPERATION OF THE PARATUNKA GEOTHERMAL FIELD USING SUBMERSIBLE PUMPS

5.1. The Data Set for Assessment of Economic Efficiency

The operation procedure. The requirement is to extract 1035 kg/s of heat carrier at an initial temperature of 80°C and an end temperature of 30°C, after use (subsequently, the exhaust thermal water can be dumped into the existing purifying facilities at the village of Paratunsky, which can receive 3000 m^3/hr, and/or be reinjected). The extraction of heat from thermal water is envisaged to be carried out using heat exchangers and heating fresh water in a closed contour with subsequent supply to remote consumers of thermal energy. The heat carrier can be transported via 820 × 9 tubes, which would be made of electrically welded steel and with preliminary isolation of polyurethane foam 122.5 mm thick (GOST_30732_2006). The heat loss due to this process can be estimated as 132 W/m using the steady-state conductivity assumption with 90°C for the heat carrier temperature and 0°C for ambient temperature. Accordingly, the transport of 1000 kg/s water over a distance of 50 km will involve a heat loss of 6.6 kJ/kg, or less than 1.6°C in the temperature. The pressure loss with the heat carrier parameters as indicated above can be estimated as 7.3 bars using the Darcy–Weisbach equation. That is to say, the temperature and head losses that the transport of heat carrier in a thermally insulated pipe incurs are acceptably low for implementation of the technical operation project. There are several Russian manufacturers of thermally insulated pipes, these include, teploenergoplast.ru, zti_ppu.ru, and other manufacturers.

Summing up, the annual production of thermal energy would amount to 1630000 GCal.

Table 2. The maximum predicted decrease in pressure and temperature in the reservoir and of bottom-hole pressure in producing wells in relation to the water extraction rate during 25 years of operation

Total extraction rate, kg/s	Decrease in reservoir pressure, bars	Decrease in reservoir temperature, °C	Decrease in bottom-hole pressure in producing well, bars
825	3.8	2.0	11.3
1100	5.7	2.9	15.7
1375	7.7	3.8	20.3

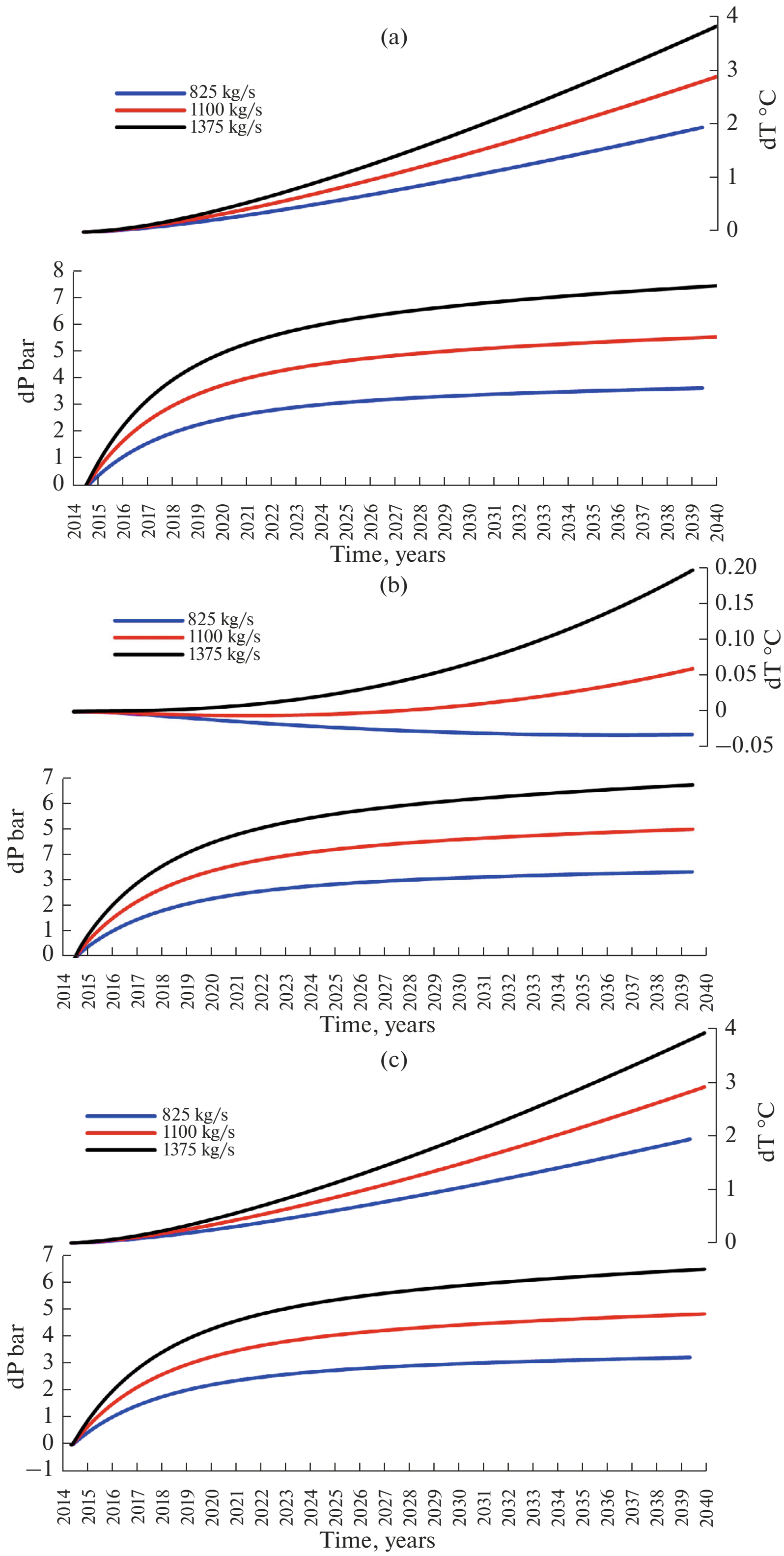

Fig. 3. Predicted decreases of pressure and temperature for different water extraction rates during the 25-year operation of the Paratunsky geothermal field. (a) predicted decrease in temperature and pressure in the Sredny area at well 9 ($Z = -260$ m abs.) for total water extraction rates of 825 kg/s, 1100 kg/s, and 1375 kg/s; (b) predicted decrease in temperature and pressure in the Nizhne-Paratunsky area at 39 ($Z = -460$ m abs.) for total water extraction rates of 825 kg/s, 1100 kg/s, and 1375 kg/s; (c) predicted decrease in temperature and pressure in the Severnyi area at well 66 ($Z = -260$ m abs.) for total water extraction rates of 825 kg/s, 1100 kg/s, and 1375 kg/s.

Table 3. Well design

Drilling		Casing		Cemented range, m	Goal of descent of the casing
drilling bit diameter, mm	drilling range, m	casing diameter, mm	casing range, m		
Pit		530	0–2	0–2	Prevention of water affecting the well head
494	2–50	426	0–50	0–50	Overlaying of unstable Quaternary rocks
394	50–300	324	0–300	0–300	
295	300–1500	245	270–1500	No cementing	Installing a filtering column

The cost of one GCal is 2700 rubles for the existing conditions of thermal energy transport, which does not exceed the cost of thermal energy at collectors of the source of thermal energy as supplied by the PAO Kamchatskenergo company to consumers in the Petropavlovsk-Kamchatskii City District during 2016–2018 (the decision of the Regional Service for Prices in Kamchatka Krai no. 176 as of June 30, 2017).

Capital expenditures: (1) the construction of fifteen producing wells 1500 m deep (the coefficient of successful drilling is taken to be 0.75 for the Paratunsky reservoir) (the envisaged well design is given in Table 3); (2) submersible pumps (15 items); (3) thermally insulated pipeline 50 km long; (4) above-ground thermal pumping station for pumping heat to the end user (50 km); (5) heat pumps (in case the electrical energy supplied by the Mutnovsky geoelectric plant for extra heating is used); and (6) the construction of fifteen reinjection wells 1500 m deep (the coefficient of successful drilling is taken to be 0.75 for the Paratunsky reservoir). Table 4 gives a rough estimate of the capital expenditure for the implementation of the project. The final cost will be more accurately determined during work and design.

Table 4. A rough estimate of capital expenditures for implementation of the project (as given by the *AO Teplo Zemli* company)

#	Type of expenditure	Cost, million rubles
1	Producing wells 1500 m deep: 15 items	2250
2	Submersible pumps: 15 items	45
3	Well binding: 12 km 300 mm	1000
4	Thermally insulated pipeline 50 km*	4500
5	Thermal pumping station for transport to users (50 km)*	2000
6	Thermal pumps (in case the electrical energy from Mutnovsky power plants is used for extra heating)	
7	Reinjection wells (in case the operation includes reinjection) 1500 m deep: 15 items	2250
	Total:	12045

* Prices are indicated by analogy with the data of the *Virkir Orkint* project with due account of inflation.

The operation expenditure is 350 million rubles per year.

The design term of operation for this calculation of economic efficiency is 10 years.

5.2. The Economic Efficiency of Operation for the Paratunsky Geothermal Field using Submersible Pumps

The economic efficiency of this project is based on the data presented in 5.1 using the *Investment Analysis 2.9* program (http://www.finanalis.ru/programs/340/2247.html).

The project requires a starting credit of 9.8 billion rubles (without reinjection, see Table 4), the interest on credit is taken to be 18%, the loan repayment would begin from the third year of operation, the discount rate for attracted credit resources is 18%, and the inflation rate is specified as 8.4%.

Table 5 and Fig. 4 show design figures for the economic efficiency of the project. The payback period incorporating the discount will be 4.8 years, the internal rate of return is 29.3%, and the discounted net income is 6.95 billion rubles.

6. CONCLUSIONS

A refined version of the existing numerical thermohydrodynamic model for the Paratunsky geothermal field has been developed (Kiryukhin et al., 2017a, 2017b), featuring the top layer as a ground water horizon plus a dividing relative aquifuge. The goal of this refinement was to derive a more accurate estimate for the inflow of cold ground water into the productive geothermal reservoir, when the operation would be based on the use of submersible pumps leading to a decrease in the thermal water table below the ground surface.

The model as modified in the manner indicated above was used for predicting three scenarios in the operation of the field with the total extraction rate from eleven producing wells equal to 825, 1100, and 1375 kg/s, respectively, for a term of 25 years. The

Table 5. Indices of economic efficiency of the project

Simple payback period, years	3.5
Discounted payback period. years	4.8
Internal rate of return, %	29.3%
Net cash flow, in 1000 rubles	25933941.3
Net discounted income, in 1000 rubles	6953666.1

results of this prediction simulation show that the maximum decrease in the pressure in the reservoir would not exceed 8 bars and the maximum decrease in the temperature would remain below 4°C. Calculations of bottom-hole pressure in the producing wells show that the wells can be operated at the specified discharges, when submersible pumps with appropriate capacities are installed at depths of 120, 160, and 210 m, respectively.

An analysis of the economic efficiency for the project of operation in the Paratunsky geothermal field using submersible pumps that provide the extraction of 1150 kg/s of heat carrier at an initial temperature of 80°C and a terminal temperature of 30°C after use shows that the payback period of the project for the existing prices of thermal energy with due account for discounting and inflation would be 4.8 years, the discounted net income would be 6.95 billion rubles during 10 years of operation. When the credit has been paid back, the price of thermal energy can be reduced to reach the level of the operation cost. The production of thermal energy for remote users (Petropavlovsk-Kamchatskii, Elizovo, and Vilyuchinsk) would be 1630000 GCal per year (216 MW of heat), which is sufficient to supply heating to the Petropavlovsk-Kamchatskii centralized heating systems.

The addition of the Verkhne-Paratunsky field to the operation, which is an analogue of the Paratunsky field and has comparable reserves of geothermal energy, or the use of heat pumps powered by the electrical energy of the Mutnovsky geothermal power plants that is not required during the night (50 MW of electrical energy), would fully resolve the problem of heating for the main users in Kamchatka by geothermal sources of energy. In compliance with the requirements of the Federal Law as of July 27, 2010 no. 190-FZ On Heat Supply requiring priority to be given to a combined production of electrical and thermal energy, the issue of synchronization between the production of thermal energy (the Paratunsky geothermal fields) and of electrical energy (the geothermal fields of the Mutnovsky geothermal area) is an urgent one. The assessment of the potential for increased production of electrical energy at the Mutnovsky geothermal field to raise it to 105 MW of electrical energy is, in particular, provided in (Kiryukhin et al., 2018), while further work will have to focus on additional possibilities for increasing the production of the Mutnovsky geothermal power plants by drilling adjacent areas and depths down to 3 km.

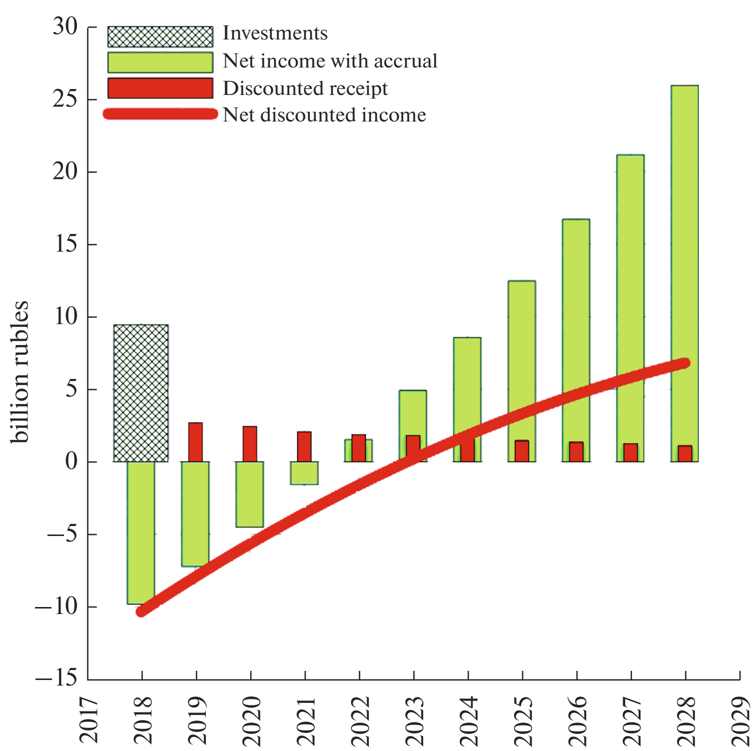

Fig. 4. The discounted net income from the operation of the Paratunsky geothermal field using submersible pumps.

We also wish to note that the centralized heating of Petropavlovsk-Kamchatskii by the Paratunsky geothermal field is equivalent to an economy of hydrocarbon fuel for Russia to an amount of approximately 219 700 tons of equivalent fuel per year (or $104.7 million per year).

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