# DEVELOPMENT OF A THREE-DIMENSIONAL NUMERICAL MODEL AND EVALUATION OF THE GENERATING CAPACITY OF THE DACHNY GEOTHERMAL RESERVOIR, MUTNOVSKY HYDROTHERMAL SYSTEM, KAMCHATKA, RUSSIA

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ABSTRACT

The spatial distribution of pre-exploitation conditions (i.e., temperature and pressure distribution, liquid and vapor saturations, circulation characteristics of high-temperature fluids) in the Dachny site of the Mutnovsky hydrothermal system, obtained by Kiryukhin et al.(1991) using a 3-D mapping method, are revised on the basis of natural-state simulations performed using the computer code TOUGH2 (Pruess, 1987, 1991). A 3-D model of the natural-state conditions at the Dachny site was developed. The fine-tuning of the model was achieved by comparing computed results to the observations made in geothermal wells flow-tested during 1983-88. Also studied was the behavior of the field in response to different exploitation scenarios assuming production from existing and additional wells needed to supply sufficient steam to a proposed 80 MWe power plant.

Key words: simulation, two-phase flow, double porosity, Russia, field case.

## INTRODUCTION

The Mutnovsky geothermal field is located 75 km south of the city of Petropavlovsk-Kamchatsky, close to the northern foothills of Mutnovsky volcano (Fig. 1), at an elevation of 800 to 900 meters above sea level (masl). The results of geothermal and geochemical investigations of the Mutnovsky geothermal field were presented by Vakin et al. (1986). More recently, a 3-D mapping of lithologic units, temperature and pressure fields and a natural-state (pre-exploitation) model of fluid flows within the Dachny site were completed (Kiryukhin et al., 1991; Kiryukhin, 1993).

It was felt that results of these studies should be checked against those of a distributed-parameter numerical model. In addition, even though by 1990 sufficient steam reserves to generate 78 MWe had been demonstrated (Perveev, S.L., personal communication, 1990), it is important to compute numerically the estimated long-term generating capacity of the field. For these purposes the computer code TOUGH2 (Pruess, 1991), with the addition of subroutines to simulate two-phase well discharge (Kiryukhin and Sugrobov, 1987; Aunzo et al., 1991), were used.

## DESCRIPTION OF INPUT DATA TO MODEL THE DACHNY RESERVOIR

The underlying model to compute the natural state of the Dachny site was based on results of the three-dimensional (3-D) mapping of the lithology, temperature and pressure fields, chemistry and tracer test data, as well as on simple lumped-parameter analysis of flow test information (Kiryukhin, 1993). The updated model (Perveev, S.L., personal communications, August 1990, September 1993), shown schematically in Fig. 2, corresponds to a parallelepiped with prescribed internal temperature, pressure and petrophysical distributions, and inflows and outflows along its boundaries (Kiryukhin et al., 1991; Kiryukhin, 1993). The dimensions of the model correspond to the known volume of the Dachny hydrothermal reservoir and includes all of its main features.

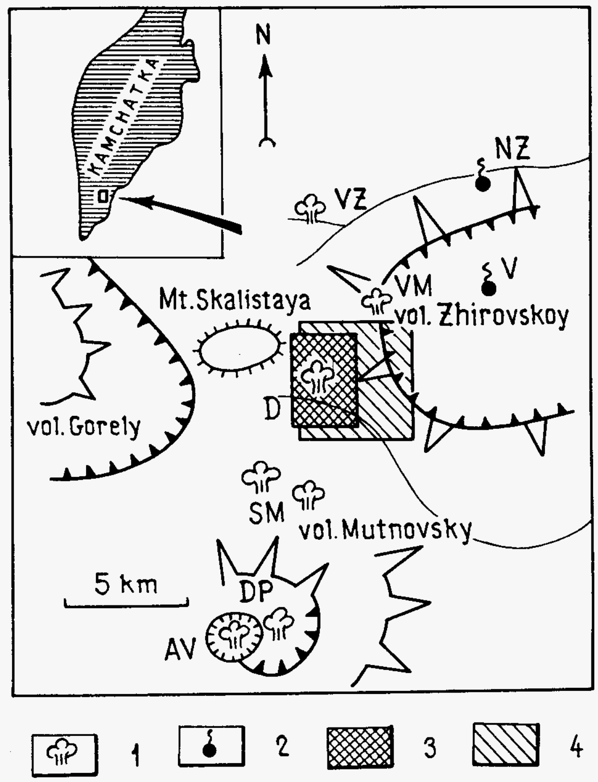



Fig. 1. Location of the Dachny site, Mutnovsky hydrothermal system.
1: steam discharge areas: AV - Activnaya voronka; DP - Donnoe pole; SM - Severo-Mutnovsky (two sites); D - Dachny; VM -Verkhne-Mutnovsky; VZ - Verkhne-Zhirovsky
2: Hot water discharge areas: V - Voinovksy; NZ - Nizhne-Zhirovsky.
3: Area studies by Kiryukhin (1993)
4: Present study area.

### Computational Grid

A regular 3-D Cartesian grid was used to model heat and mass transfer within the system (Fig. 3). The grid consists of five layers, each layer having one hundred 1.25 x E+8 m3 cubic elements. The center of the top-layer elements is at 750 masl. The name of the elements (AIJ K) indicates the layer number (I = 1, ... ,5), the number in the y direction (J= 1, ... ,9,A), and the number in the x direction (K = 1, ... ,10).

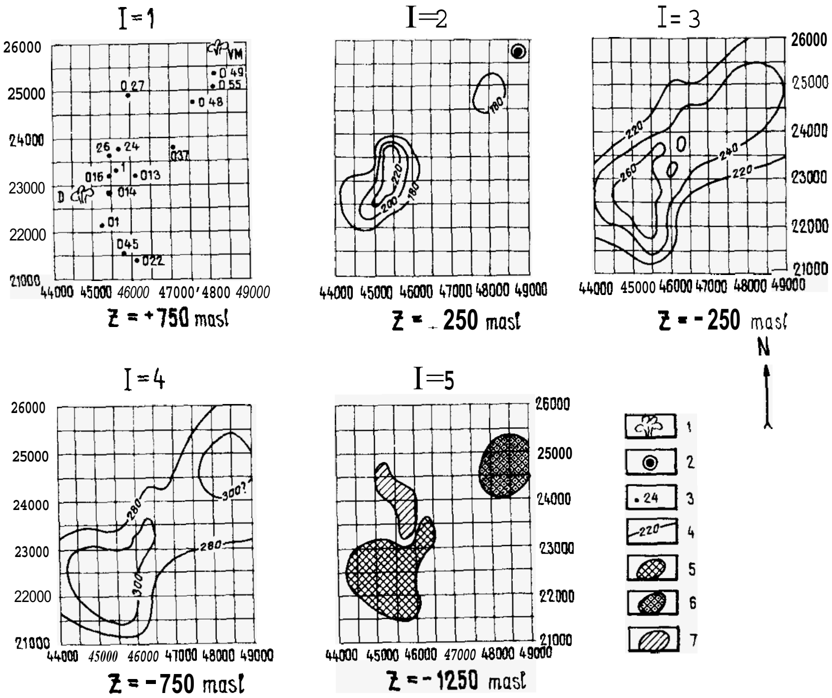



Fig. 2. January 1990 temperature distribution, recharge/discharge areas in the Dachny and Verkhne-Mutnovsky geothermal reservoirs of the Mutnovsky hydrothermal system. Dimensions in meters.
1: steam discharge areas; D:Dachny; VM:Verkhne-Mutnovsky
2:hot water discharge element ,reflecting Nizhne-Zhirovsky and Voinovsky outside the area shown in the figure)
3: geothermal wells to be used for fluid production; well 027 will be an injector
4:isotherms (oC)
5-6: areas at the bottom of the reservoir with ascending high-temperature fluid flows( 5: Main and NEI upflows, 6: NEII upflow)
7:areas at the bottom of the reservoir with descending fluid flows.

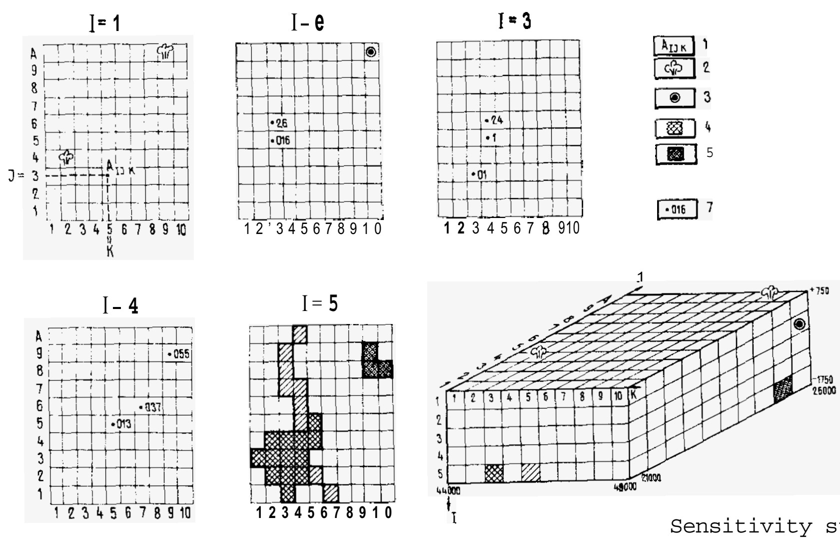



Fig. 3. Best Model. Geometry of the 3-D computational mesh, showing the different layers of the model.
1: element identification
2:inactive elements (steam discharge, 2-phase conditions)
3:inactive elements (water discharge)
4: sources (Main and NE I upflows) with an enthalpy of 1390 kJ/kg
5: sources (NE upflow II) with an enthalpy of 1270 kJ/kg
6:sinks (Condensate downflow)
7:key elements used for model calibration (see text).

MODELING THE NATURAL (STEADY) STATE OF THE DACHNY RESERVOIR

Key Elements For Model Calibration

The thermodynamic conditions of some elements in the mesh were selected as key points to calibrate the model (see Table 1). Most of these key elements are associated with areas where flow tests were performed and where pressure-temperature log data are available.

Table 1.Key Elements For Model Calibration

| Element | Well | T Na-K ( C) | Temperature ( C) | Phase Satur. or Pressure |
|---|---|---|---|---|
| A25 3 | 016 | - | 228 | 2-Phase |
| A26 3 | 26 | - | 236 | 2-Phase |
| A33 3 | 01 | 298-310 | 275 | 2-Phase |
| A35 4 | 1 | 275-285 | 276 | 2-Phase |
| A36 4 | 24 | 276 | 265 | 6.2 MPa |
| A45 5 | 013 | 301-306 | 305 | 10.0 MPa |
| A46 7 | 037 | 282-298 | 284 | 9.8 MPa |
| A49 9 | 055 | 284 | | |

Sensitivity studies

A number of sensitivity studies were performed on the parameters that have large control on the distribution of pressure, temperature, saturation and flow in the reservoir, as well as permeability. These were done by completing a number of steady-state computer runs that allowed to estimate the effect of these parameters on the fluid flow regime in the reservoir (and are not discussed here).

Best Model of the natural state of Dachny reservoir.

Based on calibration and sensitivity studies a model that best reproduces the natural state conditions was selected. Some characteristics of this "Best Model" are shown in Figs. 3 to 6.

Table 2 shows the heat and mass recharges into the reservor and discharges from it corresponding to the Best Model. The total thermal recharge is equal to the total discharge 74.9 MWt , the mass balance is very good too (i.e., the total recharge is equal to the discharge 54.1 kg/s).

Fig. 4. Best Model. Computed natural state of the Dachny and Verkhne-Mutnovsky reservoir. Distribution of steady-state temperatures in Layers 1-5.
1: temperature ( C)
2: steam discharge inactive elements
3: hot water discharge inactive elements.

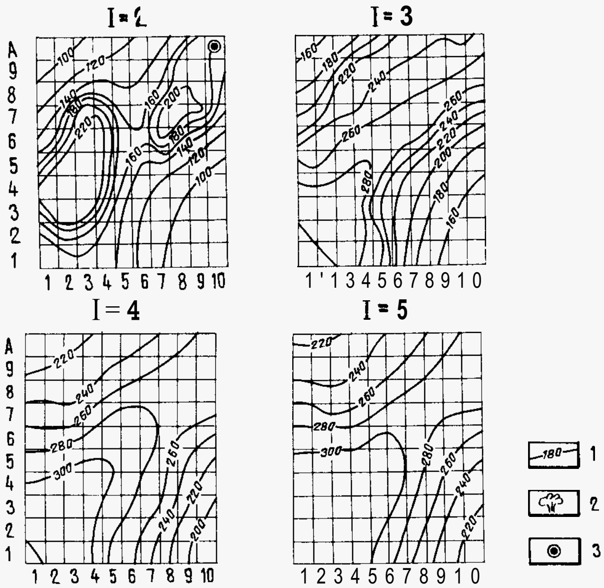



Fig. 5. Best Model. Computed natural state of the Dachny and Verkhne-Mutnovsky reservoirs. Distribution of steady-spate saturations in Layers 2-3.

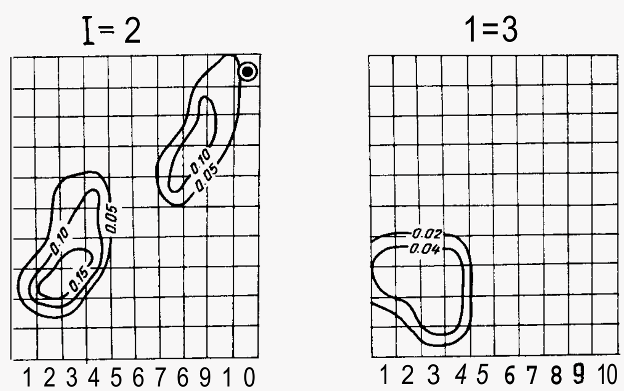
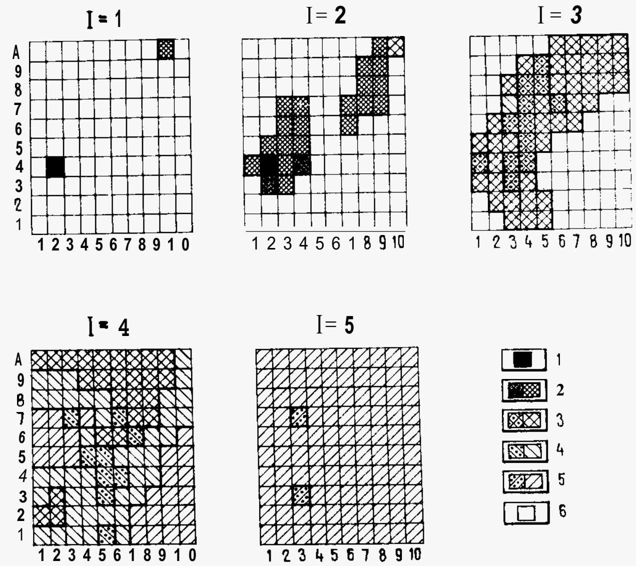



TABLE 2. Best Model. Heat and mass recharges and discharges.

| | | |
|---|---|---|
| RECHARGE | | |
| Convective | | |
| Main+ NE I Upflows 39 kg/s of 1390 kJ/kg fluids: | | 54.2 MWt |
| NE II Upflow 15 kg/s of 1270 kJ/kg fluids: | | 19.1 MWt |
| Downflow from the 1-st Layer 0.1 kg/s of 63 kJ/kg (15 C) fluid | | 0.01 MWt |
| Conductive | | |
| Total (distributed over the entire system): | | 1.6 MWt |
| | 54.1 kg/s | 74.9 MWt |
| DISCHARGES | | |
| Condensate downflow (Qd) | 16 kg/s: | 18.4 MWt |
| Steam discharges | | |
| Dachny site | 0.9 kg/s: | 2.7 MWt |
| Verkhne-Mutnovsky site | 0.04kg/s: | 0.3 MWt |
| Liquid discharge into inactive element 2A10 | 37.2 kg/s: | 40.7 MWt |
| Conductive losses from Layer 1: | | 12.8 MWt |
| | 54.1 kg/s | 74.9 MWt |

Fig. 6. Best Model. Distribution of basic petrophysical-permeability domains. Domains representing highly fractured (more than 4 high permeability zones per 1 km of drilling) regions within Domains 2-5 are shown by the stippled areas.

1: Domain 6 (90 mD); 2: Domain 2 (2.9 mD); 3: Domain 3 (4.5 mD); 4: Domain 4 (3.2 mD); 5: Domain 5 (0.3 mD); 6: Domain 1 (0.001 mD).




A comparison between the observed and computed spatial distributions of temperatures in Layers 2-4 of the model (Figs. 2 and 4) show that the temperatures in Layers 2 and 3 are somewhat high in the central part of the thermal anomalies (by about 5-10oC in Layer 2, and 15-20oC in Layer 3). However the match is considered reasonable because of the significant cooling that occurred during drilling; most production zones were found at these depths, and most wells showed significant drilling mud losses. On the other hand, Layer 4 does not show the 1.2 km-diameter, 300oC anomaly "observed" in the NE part of the system. But note that this anomaly seems to have been extrapolated from data from temperature logs obtained in shallow wells, and was not confirmed by the Na-K geothermometer data.

The computed steam saturations in the Best Model are shown in Fig. 5. Steam saturation in Layer 2 is up to 0.15; in Layer 3 up to 0.04. Only liquid is found in Layers 4 and 5.

The best model permeability distributions are shown in Fig.6. Only Grant relative permeability were used in the model and low permeabilities (Domain 1) were assigned to most elements in Layer 2 (with the exception of the elements assosiated with steam zones) and to the NW and SE regions of Layer 3 (see Fig.6) outside of the reservoir boundaries.

## MODELING EXPLOITATION OF THE DACHNY SITE

### Modeling geothermal wells (sinks)

The usual method of simulating a geothermal well as a sink (or source) with constant rate or constant bottom-hole pressure is not appropriate for studying the Dachny site, because the rate equation is nonlinear:

$$Q = PI*[Pr - Pb(WHP,Q,h,d)] \qquad (1a)$$

$$PI = PI0*(Rs*ROs/MUs + Rw*ROw/MUw) \qquad (1b)$$

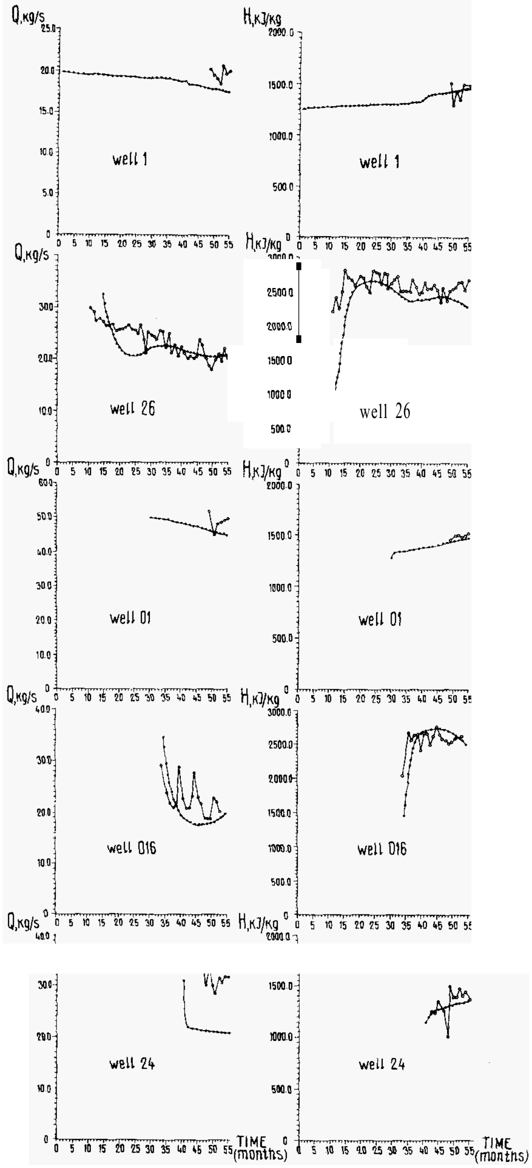



Fig. 7. Match of 1983-88 flow test data for various wells. Q: flow rate (kg/s); H: enthalpy (kJ/kg); TIME: time (months)
empty cirles - observed
solid circles - calculated.

TABLE 3. Results of calibration of the individual wells (PI - Production Index, kg/s/MPa, RFS - Rectangular Fracture Spacing, m ; MP - Matrix Permeability, millidarcies; FP - Fracture Permeability, millidarcies; FMR - Fracture/Matrix Ratio).

| Well | Element | PI | RFS | MP | FP | FMR |
|---|---|---|---|---|---|---|
| 1 | A35 4 | 100 | 200 | 0.0001 | 0.6 | 0.3E-3 |
| 26 | A26 3 | 400 | 60 | 0.0004 | 9.0 | 0.1E-1 |
| 01 | A33 3 | 100 | 200 | 0.0001 | 1.5 | 0.2E-3 |
| 016 | A25 3 | 400 | 25 | 0.0002 | 6.0 | 0.1E-1 |
| 24 | A36 4 | 100 | 200 | 0.0001 | 0.45 | 0.3E-2 |

where Q is well mass rate, PI the total productivity index, PI0 the productivity index, Rs and Rw the relative permeabilities, ROs and ROw the densities, MUs and MUw the viscosities of steam (s) and water (w), respectively, Pr the reservoir pressure, Pb the bottom-hole pressure, WHP the wellhead pressure, h the flowing enthalpy, and d a function of well design/diameter.

To solve Eq. (1) for each of the producing wells in the model a modified version of DEBIT (Kiryukhin and Sugrobov, 1987) was used. This subroutine which was added to the code TOUGH2 (Pruess, 1991), computes at each time step a new value of $Q$ for each element, containing a well. PI0 (productivity index), Pr (reservoir pressure in the grid block containing a well), Pb, WHP, h, and d were considered as an input data. The bottom-hole pressures (Pb) are obtained using tables of bottom-hole pressures generated by HOLA ( Aunzo et al. (1991)).

FINE TUNING OF THE EXPLOITATION MODEL BASED ON MATCHING FLOW TEST DATA

Flow-tests were conducted during 1983-88 in wells 016, 26, 01, 014, 1, 24 and 013. Unfortunately only in the late 1987 three of the wells (1, 01, 24 ) were equipped with James tanks for accurate measurement of discharge and enthalpy. Therefore, one can only match well characteristics for the last period of observations. Wells 016 and 26 produce only steam so that the use of small calorimeters is appropriate to assess the enthalpy of their discharge.

In the model, when wells come on line, their discharge is obtained by either using subroutine DEBIT with bottom-hole pressures generated by HOLA (i.e., wells 01, 1, 24, 016, 26), or assuming a constant value in wells where discharge rates and enthalpies were not measured (i.e., well 013, 35 kg/s; well 014, 8 kg/s).

Preliminary modeling studies of the Dachny reservoir (Kiryukhin, 1991) showed that a double-porosity model is needed to simulate reservoir behavior; a single-porosity aproach gives unreasonably low enthalpy values for the above mentioned wells. Hence GMINC approach (Pruess, 1983) was used to develop the mesh for the double-porosity model. Only two shells were used in elements that included production wells. The double-porosity approach was not implement in the other elements of the mesh to reduce computational time.

A number of computer runs were made to calibrate the exploitation model (Fig. 7). On the basis of the calibration results, appropriate changes in the permeability of five elements A25 3, A26 3, A33 3, A35 4, A36 4 in the basic model were made ( Table 3).

MODELING OF DIFFERENT EXPLOITATION SCENARIOS

Modeling the behavior of wells 26, 016, 1, 01, 24 with production from additional wells (Table 4) during a 20-year exploitation period were very useful in predicting the possible response of the reservoir during the operation of the proposed 80 MWe (or even 160-200 MWe) development. These 80 MWe are scheduled to be installed in a stepwise fashion, using four 20 MWe modules between by 1996-98 (Perveev and Zorin, 1992). The study was performed based on the improved natural-state model of the system (described above). The production rates for the individual wells in Table 4 correspond to the planned 80 MWe development for the Mutnovsky geothermal field.

Table 4. Constant-production wells added in the modelling of the 20-year explotation

| Well | Production Rates (kg/s) | Well | Production Rates (kg/s) |
|---|---|---|---|
| 013 | 35 | 055 | 30 |
| 014 | 8 | 049 | 30 |
| 037 | 30 | 045 | 30 |
| 048 | 65 | 022 | 25 |
| Total | 258 | | |

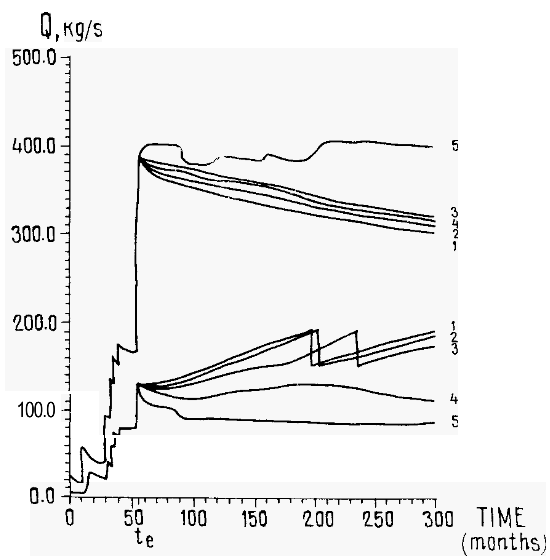
The total rate of the "constant-rate" wells (including wells 014 and 013) was specified as 258 kg/s. The temperature, pressure, and saturation data measured at the end of the 1983-88 after the 55 month flow test were assumed to be the initial conditions for the exploitation modeling study. All "constant-rate" elements were assigned the average double-porosity parameters : matrix permeability 0.0001 mD, fracture spacing 200 m and fracture/matrix ratio .2E-03.

It is not clearly known how the boundary conditions that were proven to be appropriate for the natural state model will change in response to exploitation. Also presently unknown is the injection program that will be implement in the field. This is because of the possibility that the effluents might be used for the district heating systems of the cities of Petropavlovsk-Kamchatsky and Elisovo, a project presently in the planning stage. Therefore the following scenarios of possible changes in boundary conditions and injection rates were analyzed:

1. No changes in boundary conditions. No injection.
2. The steam discharge areas (Dachny and Verkhne-Mutnovsky) will change into water recharge areas. No injection.
3. Same as 2, but with 100 kg/s of 420 kJ/kg fluid injected into well 027.

4&5. Same as 2, but cold water inflow from surrounding rocks (Domain 1, Fig.6) with permeability of 2 mD (4) and 10 mD (5) into the reservoir occurs.

Fig. 8. Wells 1, 01, 24, 26, 016, 013, 014, 037, 048, 055, 049, 055 and 022. Computed total production for the 1983-88 flow tests and the 20-year exploitation period under scenarios 1 to 5. Upper graphs: Total steam-water discharge; Lower graphs: Total steam discharge. te - 55 months well test period.




The computed total flow and steam discharge for ail wells, including the "constant rate" wells, is shown in Fig. 8.

DISCUSSION OF POSSIBLE EXPLOITATION REGIMES

The shape of the curves shown in Fig. 8 is important for stable production of electricity on power plant or hot water for the district heating systems of the cities of Petropavlovsk-Kamchatsky and Elisovo , so we have to explain what are the reasons of these possible breaks and changes in slope in production rates, especially for scenarios 1,2,3,5 to avoid these unstability during future exploitation.

Breaks in total production of steam for the 20-year exploitation period under scenarios 1 ,2 ,3 reflects turn off "constant-rate" well 048 , which is not able to produce steam for power plant when the reservoir pressure drop to zero. Note, that "constant-rate" wells 013 and 045 are on the way to break too , because by the end of 20-year exploitation period these wells transfer to steam-dominated wells with enthalpies about *2800* kJ/kg , that is a sign of near pressure depletion. That is why, load of 65 kg/s , 35 kg/s and 35 kg/s in the elements of the model, corresponding to wells 048, 013 and 045 seems to be excessive for the project of exploitation under scenarios 1 ,2 ,3.

Rapid decrease in total steam production and break in total production of steam and water for interval 95 - 210 months of the 20-year exploitation (Fig.8 graph 5) period under scenario 5 reflects possible cold water inflows in the geothermal reservoir, especially through the Dachny steam discharge area in the interval 140 -200 months of the 20-year exploitation period due to change in boundary conditions . In this case steam dominated wells 016 and 26 should transfer to water dominated wells with the enthalpies 850 - 900 kJ/kg,two-phase wells also decrease there enthalpies to 1100-1350 kJ/kg.By 210 month of exploitation system will reach equilibrium in mass rates , unless steam production will not recover.In this case,load of the field in the vicinity of cold water inflow regions (shallow wells 016 and 26 ) shold be minimized.

CONCLUSIONS

1. Based on simulation studies carried out using the computer code TOUGH2, the 3-D natural-state qualitative circulation characteristics of the high-temperature fluids obtained earlier (Kiryukhin et al., 1991 Fig.56 ; Kiryukhin, 1993 Fig.8) have been generally confirmed for the Dachny system.

2. Some unrealistic behavior observed during the simulation (i.e. liquid discharge in the "steam discharge" areas ,when too large values of upflow rates were assigned ) allowed to improve the natural-state model of the Dachny system, i.e.: (a) The upflow rate appears to be about 54 kg/s and downflow rate about 16 kg/s (that is significantly smaller than estimations previously made (Kiryukhin et al., 1991; Kiryukhin, 1993), (b) The steam output in the discharge areas seems not to exceed a few kg/s.

3. Subroutine DEBIT was incorporated into TOUGH2 to model production wells operated at constant wellhead pressure (the usual method of simulation production wells operation considered two options : constant rate and or constant bottomhole pressure). Constant wellhead pressure could be better approximation in situations showing significant changes in the enthalpy of the produced fluids and non-linear well/reservoir interaction.

4. Fine-tuning of the permeability distribution in the model, including the implementation of a double-porosity model with the help of the computer code GMINC (Pruess, 1983), was based on matching the enthalpy-discharge characteristics of wells 016, 26, 01, 1 and 24 measured during the 1983-88 flow tests.

5. Five scenarios of 20 years of exploitation of the Dachny site were studied. Production from wells 26, 016, 1, 01, and 24 (with option for "well/reservoir" interaction) and from wells 014, 013, 037, 048, 049, 055, 045, and 022 ("constant rates wells" with a total discharge of 258 kg/s) was assumed.

The total computed steam production from all wells varies from 87.9 to 169.7 kg/s (equivalent to 44.0-84.9 MWe), depending of what boundary conditions and exploitation regime will actually be implemented during the 20 year-exploitation period.

6. It is important to continue the modeling studies and flow tests in the Mutnovsky geothermal field before starting large-scale exploitation. One should concentrate these efforts on following studies:

(a) Long-term multi-well flow tests in wells 048, 049, 055, 013, 037, 022 and 045 (wells sheduled for exploitation) with appropriate equipment (James tanks and reservoir pressure measurements) to establish the local permeability and fracture porosity characteristics around these wells, and to determine if any meteoric water recharges the reservoir. At this respect, the collection of tritium and other geochemistry data is important. No additional drilling will be need in this part of the field at this time.
(b) Tracer tests between injection and production wells to determine the characteristics of the field in regions where injected water might penetrate the main reservoir.
(c) Additional reservoir simulation studies using updated model parameters , more realistic treatment of all production wells behavior could be also considered, avoiding the use of "constant rate" production wells, and implementing a smaller grids in the elements containing production wells for short-time matches, if necessary . More realistic treatment of the lateral liquid discharge from Mutnovsky hydrothermal system (element A2A10) is needed too, probably. Unless these studies are performed, it will be very difficult to predict the response of the Dachny system to the planned 80 MWe power plant development.

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