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THERMAL WATERS AND THE EFFECT OF THEIR USE ON THE ENVIRONMENT

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Geothermal industrial activity disturbs in one way or another the ecological balance in nature. In the USSR, estimation of detrimental environmental effects with rapidly developing world economy is now considered not only in theoretical terms, but also as a complex and urgent problem, which has not been studied enough by scientists. Not very long ago this problem troubled only a small group of technologists. Recently, however, economists have become more experienced in this problem, who rely very heavily upon the results processed by computers. Industry and agriculture are vital for human well-being within a desirable environmental setting and extraction of thermal waters can be of much use within the USSR in reaching such objectives. Against this background we should consider the undesirable effects of the thermoenergetic and chemical use of thermal waters on nature.

What damage does the environment suffer from withdrawing considerable thermal groundwaters to the surface? The answers to this question are as follows:

1) chemical incompatibility between thermal waters and surface species;

2) gas contamination of the atmosphere by noncondensable gas components;

3) thermal pollution;

4) disturbance of water balance on the surface by extra inundation of poorly drained parts of the landscape; and

5) alteration of the landscape and involuntary occupation of land at the expense of drilling, pipeline construction, and plant operation.

Before considering this problem in detail, we shall briefly describe thermal waters as a physical and chemical component of the lithosphere.

Natural water, according to Academician V. I. Vernadsky, is a peculiar mineral with a complex chemical structure. Pure water designated by the symbol H_2O is actually a compound of hydrogen and oxygen atoms in a polymer structure, where water molecules are united into three-dimensional chains. Such ordered structure of the water determines many of its parameters which differ from the properties of other liquids. Among other things, it has a universal ability to solve solid and gas compounds.

All waters contain different salts and gases in solution. The smallest salt content is observed in atmospheric precipitation and in waters of thawing glaciers and snows. Total mineralization (salt content) of such waters usually does not exceed 0.1 g/liter. Groundwaters, associated with salt-bearing sea and continental basins are mineralized most considerably. Their total salt-content can be as large as 500-600 g/l.

The salt concentration of a water determines its properties, both physical and chemical. Increased salinity increases the boiling point of a solution and decreases its freezing point. Saline waters dissolve gases less intensely, but their aggressiveness towards the rocks and minerals is considerably increased, compared to pure water. High chloride brines can dissolve many compounds which are practically insoluble in chemically pure water. For example, the solubility of galenite in distilled water is 0.000001 g/l, while chloride brines with mineralization of 300 g/l can dissolve about 0.9 g/l; i.e., the solubility increases approximately by one million fold. This increased solubility with salinity is especially troublesome for nonorganic lead compounds which generally are toxic.

Thermal waters, as other groundwaters, can be subdivided into three main chemical types determined by the anion composition of their components (4):

1) bicarbonate with predominance of dissolved salts of carbonic acid ($NaHCO_3$, $Ca/HCO_{3/2}$, $Mg/HCO_{2/2}$);

2) sulphate - with predominance of sulphate salts (Na_2SO_4, $CaSO_4$, K_2SO_4);

3) chloride ($NaCl$, KCl, $CaCl_2$, $MgCl_2$).
The variety of subtypes is determined by the ratio between cations and alkaline and alkaline-earth metals, and by noncondensable

gas concentration, (e.g., O_2, N_2, H_2S, CH_4, CO_2) which frequently can be related to the chemical environment in the thermal water.

This report examines a few of the many types and quantities of salt and gas components in hydrothermal waters. In successive order, we shall consider the chemical composition of hydrothermal fluids (from fresh water to brines).

Fresh waters are characterized by bulk salt content that does not exceed 1 g/l; mineralized brackish waters in which the salt content varies between 1 and 10 g/l, and saline waters in which the salt content varies between 10 and 35 g/l. Waters with mineralization exceeding 35g/l (the saturation concentration of NaCl), the waters are called saturated brines.

Commercial reserves of fresh thermal waters are not abundant, since in most geological situations, they react with the formation rock and extract various elements. Nevertheless, a few hydrothermal fluids with mineralization below 1 g/l have been found. The small mineralization results from the fact that they circulate in well eluted terrigenous or fractured magmatic rocks. Such formations do not contain easily dissolved minerals. Exceptions are volcanic glass, some types of micas and potash feldspar, which are poorly soluble but still capable of mineralizing water. The results are nitric alkaline fluids with mineralization between 0.5 and 1.0 g/l. Their anion complex contains chloride, bicarbonate and fluoride-ions and cation complex - Na- and K-ions. Such waters also contain undissociated compounds, such as saturation groundwater concentration of silicic acid and boric acid.

The gas composition of nitric alkaline fluids is represented mainly by nitrogen of atmospheric origin and small quantities of carbon dioxide and methane. The absence of oxygen is explained by active reduction processes, usual for the considerable depths where oxygen is absorbed.

Another example of fresh thermal waters is volcanic hydrothermal fluids of near-surface origin. A magmatic body solidifying at considerable depth creates around itself a wide zone of groundwater boiling. The steam initially generated in this zone moves upward along faults and near the surface, where its temperature drops to 100-200°C. At this point, the steam may be condensed and transformed into liquid water. Frequently the steam-bearing fissures heat the formation rock to such a temperature that the initial steam either does not condense at all, or condenses during a cold season. Such steam jets and steam-gas fumaroles are abundant on Kamchatka and the Kuril Islands. In mountains with glaciers and snowbanks condensation of the initial steam is inevitable. In this case, the thaw waters with temperature from 0 to +4°C are saturated with minerals from all near-surface rocks. Secondary heating of glacial waters by hot steam jets can occur with formation of hydrothermal water with the smallest salt concentrations (0.1-0.2 g/l).

Such condensed hydrothermal fluids can have higher mineralization - 1.0-5.0 g/l, as the initial steam can contain aggressive gases, such as carbon dioxide, hydrogen sulphide and sulphur dioxide. The dissolution of these gases in water and interaction between the solution and rocks can increase mineralization and alter the chemical composition of hydrothermal water.

Condensed carbon dioxide bearing steam jets usually form chloride bicarbonate-sodium hydrothermal fluids with the following composition:

$$M_{0.-5.0} \frac{Cl^- \; HCO_3}{Na^+} \qquad (8)$$

Sulphur and hydrogen sulphide fumaroles form sulpho-sodium waters with a small amount of chloride and bicarbonate.

$$\text{Composition: } M_{0.1-5.0} \frac{SO_4^{2-}(Cl^-, HCO_3^-)}{Na^+}$$

While the anion composition of condensed hydrothermal fluid is determined by presence of one or another gas in the initial steam, their cation composition varies in sodium, potassium and calcium content, depending on the type of enclosing rocks.

Brackish and saline hydrothermal waters. Waters of this class are possibly the most abundant. The chemical type of brackish and saline hydrothermal water are very diversified with large ranges of chemical composition.

Thermal waters with mineralization up to 35 g/l are formed both on the platforms and in tectonically active zones with a higher hydrothermal gradient. The enclosing rocks for such fluids are represented, as a rule, by sandy-clayey deposits, and fissured, carbonate and sulphate rocks without spatial contacts with salt-bearing deposits.

This class includes the overwhelming majority of mineral waters: carbonate, sulphuretted, methane-nitric. These fluids are widespread in the young mountain folded regions, in submontane and intermontane troughs, and marginal parts of the platforms.

Thermal brines. Thermal brines are formed during long-term surface evaporation of saline waters. The 10-20 fold decrease in volume by evaporation creates a solution precipitating sodium and potassium chlorides, thus forming commercial deposits of rock salts, which sooner or later become involved in active sphere of hydrothermal waters. The latter results in formation of thermal brines by leaching.

Thermal brines belong to a class of chloride waters, where chloride is the predominant anion. Numerous studies showed that the chemical composition of thermal brines is determined by the type of their formation (5). In case of concentration of marine waters, the composition of evaporates gradually changes along the following scheme:

$$M_{35-100}\,\frac{Cl^{-}SO_4^{2-}}{Na^{+}Mg^{2+}} \longrightarrow M_{100-150}\,\frac{Cl^{-}}{Na^{+}} \longrightarrow$$

$$\longrightarrow M_{150-300}\,\frac{Cl^{-}}{Na^{+}Ca^{2+}\ (K^{+})} \longrightarrow$$

$$M_{>300}\,\frac{Cl^{-}}{Ca^{2+}\ Mg^{2+}(K+)}$$

On the other hand, if the brines are formed by leaching of rock salts, their chemical composition appears to be more stable. As the rock salts consist mainly of NaCl with small amounts of KCl, the leaching brines correspondingly acquire the following composition:

$$M_{250-300}\,\frac{Cl^{-}}{Na^{+}}\ ;\ M_{250-300}\,\frac{Cl^{-}}{Na^{+}\ K^{+}}$$

Thermal brines are found in many regions of the USSR and the volume of these waters is very considerable. Among these are several oil- and gas-bearing provinces rich in thermal brines, such as the Fore-Carpathians, Fore-Caucasus and Fore-Urals, the Apsheron peninsula, West and East Turkmenistan, and West Siberia.

Why are thermal waters valuable? It is clear that 30% solutions of NaCl can be hardly used as water for drinking, but they are a valuable industrial raw material. Huge concentrations of their main components - Na, K and Cl can hardly attract interest of the industry as rich commercial deposits of rock salts are still available. However, the brine includes considerable concentrations of microcomponents exceeding tens and hundreds of mg/l. A partial list includes: Li, Rb, Cs, Br, I, U, Ra, Pb, Zn,Cu, Ag, Au. A number of these elements (B, I, Br, rare alkali) are extracted now from thermal industrial brines.

All chemical types of thermal waters, from fresh to brine, contain toxic components dangerous for living organisms.

In volcanic hydrothermal water with low mineralization, they are represented by hydrosulphide-ion, ammonia, boric acid.

In saline thermal waters, usually an associated with oil- and gas-bearing deposits, the most dangerous components, besides those mentioned above, are phenols.

Thermal brines contain all possible complexes of toxic components. Besides, their high salt loading does not permit their discharge into open water systems. If for some reason (an accident at the drilling site, for instance) the brines outburst onto the surface, they can destroy existing vegetation, and transform the landscape into a salt desert covered only by species of plants adapted to high salinity of soil waters.

Some high-temperature geothermal deposits with high discharge, particularly in the North Caucasus - the Daghestan ASSR, Checheno-Ingush ASSR, the Krasnodar district and other regions of the USSR contain high concentrations of phenol. The use of these waters, despite their low mineralization, is hindered by a law prohibiting their discharge into the surface water systems. Poor and expensive technology for removing phenols requires the thermal waters to be discharged back into the same water-bearing horizons. In addition, the reinjection of water will increase the period of exploitation of thermal waters and improve the dynamics of the water head system.

The injection of waste thermal waters back into a water-bearing layer has a decided advantage over other methods of industrial water utilization. However, its application can be restricted both by economic and technological reasons. The economic restrictions cannot be predicted in general form, as they are determined by regional conditions in comparison to expenses of alternative methods of power production (e.g., by traditional fuel). The chemical restrictions can be predicted more concretely.

The first case. Extraction of hot brine fluids and surface flashing (e.g., at the Tarum square, Daghestan) will inevitably result in a fresh water condensate and saturated brine with salt concentration close to a natural brine. The latter is an oversaturated solution bearing suspended crystals of chlorides (halite and salvine), formed after cooling and separation of the distillate. The injection of such a solution back into the water-bearing layer will inevitably cause a gradual colmatage of the filtration zone near the injection hole by chloride salts.

The second case. Injection of waste hydrosulphide-carbon-dioxide waters under conditions of exploitation by the binary conversion system. Even the most efficient use of thermal waters with applications of heat exchangers does not completely prevent corrosion of drill-pipes, pipe-lines, etc. Herewith, the injected solution will bear a high bulk iron concentration, as compared to the initial solution. Not dwelling upon the ways of iron transport in the solution, we must emphasize that the water intake layer will be closed by a finely dispersed iron sulphide. If part of the heat supply system is exposed to atmosphere, the role of the clogging element will be played by iron hydroxide instead of sulphides.

The third case. Injection of phenol-bearing waters after depletion of thermopotential in the system open to atmosphere. In this case the injected water, will bring atmospheric oxygen into a water collector. If the intake layer contains mineral of ferrous iron, they, in combination with the iron from corrosion, can cause an iron oxide colmatage of this layer. Undoubtedly, it is a rather difficult technological problem, but still it can be solved in each specific case. Therefore, reinjection of waste waters is regarded as the most prospective method of thermal water disposal.

The correct estimation of atmospheric pollution requires a comparison between the gas waste of the geothermal power industry and the power cycle based on the burning of organic fuel. We note that the low potential geothermal heat-transfer medium does not practically affect the composition of the atmosphere.

Let us compare the impact exerted by two power stations, 1000 megawatts each, one of them operating on coal, the other on high-temperature geothermal fluid.

If the sulphur concentration in the coal is 1%, the power station discharges into the atmosphere: 140 tons of SO_2, 20,000 tons of CO_2, considerable amount of nitric oxides, hydrogen and other aerosols.

A hydrothermal power station operating on natural steam similar to that of the Great Geyser of Kamchatka (0.2-1.8% of noncondensable gases; among them CO_2 - 82.5%; CH_4 - 6.6%, NH_3 - 3.8%; H_2 - 4.5%)* emits daily into the atmosphere: 860 tons of CO_2 and about 48 tons of sulphur compounds. Keeping in mind that about 30% of H_2S is absorbed by the condensate, its pollution effect is 4 times lower for the sulphur compounds and 20 times lower for carbon dioxide than a coal-fired steam plant (1, 7). A direct comparison of geothermal and nuclear power stations in respect to atmosphere pollution will show that production of electric energy from nuclear fuel is a "cleaner" process for the environment (2, 3).

A few words about "thermocontamination" (thermal pollution) of the surface water system which can result from considerable discharge of waste thermal waters. The term "thermocontamination" itself presupposes a possible ill-utilization of the heat, when the geothermal technological scheme consists of only one consumer depleting an insignificant thermopotential. For example, the Pauzhetka geothermal power station in Kamchatka discharges waters with a temperature of 100°C into the Pauzhetka river. Some greenhouses, not connected into a system of multiple use of hydrothermal power, "heat" the surface water systems by their waste waters with temperatures 40-50°C. It is not completely clear now what is the effect of such "heating" on the water environments and how far the waste thermal waters flow. One thing is clear, that the majority of fauna and flora species are very sensitive to a thermal change of water environments, and therefore the "thermocontamination" of the surface water systems possibly disturbs their ecological balance.

It may be useless to speak about a control over "thermocontamination", as it is simply a violation of technological rules of using thermal waters as a heat-transfer medium.

Another undesirable effect of recovery of considerable amounts of ground thermal waters on the surface is swamping of poorly drained landscape. A basis for hydrologic calculation for draining such a discharge is needed even for thermal waters with good chemical parameters to permit their discharge into surface water systems. Insufficient drainage of the regions with arid climate may cause an efflux of ground waters and soil salinization, and in the regions with humid climate - swamping, i.e., a reduction of cultivated fields. If the area relief does not permit the total removal of the waste thermal waters, the most practical method is pumping them back into the water-bearing layer.

As a whole, the exploitation of geothermal waters causes minimum damage to nature. Only during drilling and construction (a very short period) compared to exploitation, the natural landscape suffers considerable losses. When these works are over, only

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*Pauzhetka thermal waters of Kamchatka have a similar composition: CO_2 - 83.2%, H_2S - 4.4%, NH_3-3.0%, but their power is much lower than that of the Great Geyser of Kamchatka (8).

experienced specialists can estimate that the site is an area of recovery of thermal waters.

It is not so with exploitation of other mineral resources. The world annual production of oil and gas together with transportation from one place to another exceeds 4×10^9 tons. The world recovers annually more than 2×10^9 tons of coal and about 20×10^9 tons of rocks in a form of ore and barren material. The reworked fuel, ore and rocks are absorbed into the atmosphere, soil and water (9). Behind these billions of tons stand dozens of millions of hectares of land dug up by quarries covered by waste piles and hole basements; the land crossed by railways and pipelines.

The development of the world industry, whatever "clear" ways it follows, will undoubtfully change the environment. The damage impaired by economically developed countries, due to pollution of the environment, is estimated by considerable figures. For example, in Japan in 1970, it was equal to 23×10^9 dollars. In the USA for 1977, it was estimated at 25×10^9 dollars (9) for air pollution alone. In contrast for the years 1976-1980, the USSR spent 15×10^9 dollars for protection of the environment. Our country established maximum tolerable concentrations in air, fresh and sea waters (6) for more than 2500 deleterious compounds. The protection of environment is included into a system of state measurements, providing a state of environmental conditions appropriate for vital activities of present and future generations.

With respect to the impact of geothermal power engineering on natural environments, we should note one of the most important aspects determining the significance of the Earth's heat compared to other energy resources.

A geothermal complex of any purpose (power-and-heat generation, power generation, etc.) can be regarded as unique, as all parts of the "Thermocycle" are concentrated in one place.

Other power complexes, using organic and nuclear fuel, spread their thermocycles far beyond their boundaries. A broad consideration of the thermocycle (recovery, processing, and transportation of fuel) shows how considerable its effect on the environment is.

The above mentioned correlation shows that the "natural" or reproduced power sources (heat of the Earth, the Sun, the Wind) being produced by the Earth's nature, are the most acceptable and cleanest.

However, the practical approach to the state of the thermopower balance does not give an opportunity to hope for any essential replacement of the traditional organic fuel for the reproduced power sources. The main objective nowadays is the use of environmentally clean power sources wherever possible. The efficiency and reliability of natural "power generator" are confirmed by the long-term use of thermal waters in our country.

BIBLIOGRAPHY

1. Berman, E., Geothermal power. "Mir", (Moscow, 1978) (in Russian).

2. Dvorov, I. M., Abyssal heat of the Earth. "Nauka", (Moscow, 1972) (in Russian).

3. Dvorov, I. M., Geothermal power generation. "Nauka", (Moscow, 1976) (in Russian).

4. Dvorov, I. M. and V. I. Dvorov, Thermal waters and their use. "Prosveshchenie", (Moscow, 1976) (in Russian).

5. Dvorov, V. I., Thermal waters of Cheleken and geochemical properties of their formation. "Nauka", (Moscow, 1975) (in Russian).

6. On protection of environment. Documents of the USSR Communist Party and Government for 1917-1981. Izdat. Politicheskaya literaturea, (Moscow, 1981) (in Russian).

7. Bowen, R. G., Effect of geothermal complexes on the environments. In "Geothermal power","Mir",(Moscow, 1975) (in Russian).

8. Pauzhetka hot waters of Kamchatka. "Nauka", (Moscow, 1965) (in Russian).

9. Sidorenko, A. V., Protection of environments and rational use of natural resources of the USSR, Vestnik Academy of Science SSSR., (Moscow, 1978) (in Russian).