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1 # Petrothermal Energy and Geophysics

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1 **Abstract**—The geological–geophysical, methological, and economic aspects of extraction and use of petrothermal resources (dry rock heat) for heat and electric energy production were considered. Heat collectors are aqueous zones of natural or artificially made cracks in the crystalline rocks of the basement; these rocks are distinctive for higher values of temperature and can be a kind of "heat cauldron." Detection of such collectors can be carried out via geophysical methods. When pumped out of wells and heated to 100–300°C, waters act as a heat carrier for heat energy supply and electric energy generation. If the technical problem of
1 the rapid drilling of 6–10-km wells can be solved, then petrothermal energy will become competitive with the traditional types of energy production and supply.

1 *Keywords*: petrothermal energy, deep wells, heat collectors, geophysical survey methods.

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INTRODUCTION

Inexhaustible and renewable heat and electric energy sources include the heat of the Earth's depths. Heat collectors are cracked zones with underground mineralized waters heated to 100–300°C or artificial hydrofractured cracks in relatively dry rocks, to which surface water is pumped and heated. The first type of zone is located in regions of active volcanism and seismicity at depths of several hundreds to several thousands of meters and they are practically used in hydrothermal energy; the second type of zone is common, but these occur at depths of 6–10 km and can be used
1 in petrothermal energy. By using wells drilled in the zones of thermal or heated rocks, so-called "thermal
2 caldrons" of hydropetrothermal energy can be created.

For a hydrothermal station to function, at least two
3 shallow (1–3 km) boreholes are required: one is used for pumping hot water out and the second is for pumping water back underground after using its heat. Hydrothermal stations are relatively profitable compared to traditional stations that use hydrocarbons
1 (gas, oil, and coal). A petrothermal station requires
3 two deep (6–10 km) boreholes: one is for pumping surface fresh water, which is heated in hot rocks and then pumped up from another well (or wells). The profitability of such stations can be achieved if instru-
3 ments for the rapid and cheap drilling of deep boreholes exist. The profitability of petrothermal stations 1
would become more feasible if a complex of deep geophysical methods could be applied. Geophysical methods enable one to identify the positions of heat collectors that have the highest temperatures (100–300°C) and occur at the shallowest depths. Petrother- 1
mal heat (PetroHP) or petrothermal electric (Petro- 1
HEP) plants may be built above such kettles. In addition, geophysical methods can be used for organizing thermal kettle monitoring during the functioning of stations.

TRADITIONAL GEOENERGY

Intensive extraction of nonrenewable natural energy resources (gas, oil, coal, and nuclear fuel) in the world is still increasing. Oil and gas resources on land are rapidly being reduced. They are abundant in continental shelves, but exploration is expensive and is related to a high risk of ecologic catastrophes.

Russia is undoubtedly one of the richest countries in green resources. But their extraction is being carried out so intensively that independent European energy agencies expect an export deficit of hydrocarbons in Russia as early as the 2030s. The largest Western Siberian province shows a steady decrease in oil extraction. The era of "dry" gas is approaching and the stage of extensive gas extraction is coming to an end as well. For example, gas extraction from the giant deposits of the Lower Ob' Region, viz., Medvezh'e, Urengoi, and Yamburg, is at 84, 63, and about 50%, respectively.

A significant portion of all extracted nonrenewable resources is burned as fuel at thermal and electric stations. In the structure of fuel resources, the share of natural gas is 64%. During the production of heat, the consumption of hydrocarbons is increasing almost twice as fast as compared to that required for electricity. In general, the daily worldwide consumption of hydrocarbons for heat and electricity is more than a million tons of coal and oil and billions of cubic meters of natural gas. The efficiency of gas-based heating plants does not reach 50%, as half of the produced heat is inefficiently used and scattered in space. In the case of coal, an additional demand for a great quantity of oxygen takes place, along with pollution of the environment.

Energy that is equivalent to that produced at heat-powered plants can be produced at nuclear power plants with hundreds of tons of nuclear fuel, rather than millions of tons of hydrocarbons. This difference of four orders of magnitude seems convincing, but there are two issues related to nuclear energy. On the one hand, ecologic safety should be ensured in order to prevent emergencies similar to the Tech River and Chernobyl cases. On the other hand, the mothballing of obsolete and old nuclear power plants is very expensive. A third issue concerns the uranium resources of the world. The extractable reliable resources equal about 3.4 million tons, while about 2 million tons have already been extracted as of 2007 [Gnatus' and Nekrasov, 2008].

GEOTHERMAL RESOURCES

The interest in alternative energy sources, which has increased during recent decades, is caused by both the exhaustion of hydrocarbons and by the necessity of solving ecologic issues [Kopylov, 2008]. Objective factors (resources of extracted fuel and uranium and the environmental changes caused by traditional energy) lead researchers to state that a transition to new methods and forms of energy production is unavoidable. As early as the first half of 21st century, new energy sources may almost completely replace traditional ones. Oil, coal, gas, and combustible shales, as well as wood and products of its processing, are to be completely excluded as energy sources. Energy collapse will occur soon: it is expected in Europe by 2030–2040. The earlier advances in this field are achieved, the smoother the transition will be and the more profitable for any country that can create this advance.

The world economy has already aimed at a transition to a rational combination of traditional and new energy sources. Energy consumption was more than 18 billion tons of coal equivalent* as of 2000 and at current tendencies it will reach 30–38 billion tons by 2025 and 60 billion tons by 2050. The development of the world economy in this period will be characterized by a systematic decrease in the share of organic fuel along with a compensatory growth in the share of renewable energy resources of the Sun, the depths, water, wind, etc.

The geothermal energy of the Earth is an inexhaustible thermal energy. It is one of the leading areas among renewable resources. Continuous generation of heat within the Earth and the renewable character of geothermal resources occur due to the radioactive decomposition of long-lived isotopes contained in the geospheres of the planet and due to the transition energy of gravitation differentiation into heat in the deep spheres of the Earth.

It was noted at the World Geothermal Congresses that were held in Japan (2000) and Turkey (2005) that use of the Earth's heat will become one of the principal directions in the energy sector in the third millennium. It is supposed that by the end of the 21st century the share of geothermal resources in the energy balance of the world economy will increase to at least 30%, and even to 80%, based on the most optimistic prognoses [Hittrer, 2000].

The fuel resources of Russia are rich compared to other countries and still provide development of the state energy sector. Therefore, exploring new energy sources has not become an urgent and socially important issue yet. This explains, but does not excuse, the low attention paid by state structures to programs for the exploration of new renewable energy resources, including geothermal ones. The resources of the internal heat of the Earth are subdivided into hydrothermal and petrothermal types. The former are represented by 1
heat carriers, namely, fluids (i.e., groundwaters, vapor, and vapor-water mixtures). The latter consist of geothermal energy contained in hot rocks that are heated owing to deep conductive thermal flows. The total conductive loss of the Earth is estimated at 25 to 32 GW. These conclusions are based on the data from extensive regional geological–geophysical investigations [Geothermal atlas, 2000]. Such investigations have been carried out in Russia with special intensity and, as a result, many various geothermal maps have been made and published at various times. The collected database on deep temperatures enables one to create 2D- and 3D-geothermal models for particular regions.

Hydrothermal resources comprise only 1% of the total geothermal energy resources of the Earth, but their exploration started more than 100 years ago and continues at present due to the relative simplicity of their technological exploration. However, the regions of their possible use for energy purposes coincide with zones of volcanism, where groundwaters receive an additional thermal potential since they contact magmatic bodies and circulate at relatively shallow depths

* In the Soviet Union and Russia this unit is assumed at 29.3 MJ or 7000 kcal (calorific efficiency of 1 kg of coal).

(1–3 km), which are accessible to modern drilling machines.

3 The lifetimes of hydrothermal boreholes are less than 10 years. This is explained by the fact that thermal high-mineralized waters lead to chemical colmatation of wells, salt deposition, and corrosion of equipment. In addition, the sources of hydrothermal energy are distant from consumers in most cases. These are limiting factors for the development of hydrothermal energy. However, we note that the share of hydrothermal energy significantly increased in the last 20 years in Iceland, Mexico, Philippines, Japan, New Zealand, China, Salvador, etc. The total power of all hydrothermal stations in Russia is 73 MW. Before 2000, only one station of this type functioned in Russia; this was the Pauzhetka hydrothermal heat power plant (GeoHEP) in Kamchatka with a power of 11 MW. After the start of new stations in Kamchatka—Mutnovskaya in 2000 (50 MW) and Upper Mutnovskaya in 2001 (12 MW), the power of GeoHEP grew.

The practice shows that where shallow collectors of natural vapor occur GeoHEP is the most effective variant of geothermal energy utilization. Based on a preliminary assessment for the territory of Russia, the resources of thermal waters with temperatures of 40–250°C, mineralization of 35–200 g/l, and depths up to 3 km are sufficient to extract 21–22 million m^3/day, which is equivalent to burning of 3–4 million tons of conventional fuel per year [Povarov et al., 1994].

1 PETROTHERMAL RESOURCES

The extraction of thermal energy from the dry rocks of the crystalline basement is of great signifi-
1 cance for future energy. This petrothermal energy accounts for about 99% of the total resources of underground heat. Massifs with temperatures of 250–300°C can be found within active geodynamic provinces at depths of less than 5–6 km. But deep temperature values of 100–150°C occur at these depths almost everywhere in Russia. At this temperature, the
1 utilization of petrothermal resources for the purpose of energy, especially for heat, becomes both topical and profitable.

Of course, the object of the direct interest is the part of the geothermal energy potential that can be utilized using the modern tools for penetration into the Earth's interiors, rather than the general potential. With advances in traditional and perspective technologies for deep and ultradeep drilling taken into consideration, the technically reachable resources of geothermal energy can be localized within the upper 10–12-km layer of the continental crust. The average thermal capacity of the rocks in this layer can be assumed to be 1000 J/(kg K); the average geothermal gradient, at 20 mK/m. With these parameters, we obtain a total value of accessible renewable geothermal resources of 1.4×10^{16} tons of coal equivalent. Natural vapors, waters, and brines within the uppermost 10–12 km of the Earth's crust concentrate only 0.01 of these resources (1.4×10^{14} tons in coal equivalents). These figures are enormous and they exceed the total estimates of all the known resources of organic fuel on the planet by several thousand times. However, a more grounded estimation of real (available for effective exploration) geothermal resources is possible only on the basis of geological–geophysical investigations, both regional and local, in specific regions of projected petrothermal stations and with an economic analysis 1
taken into account.

The advantages of petrothermal energy sources are 1
common distribution, inexhaustibility, proximity to consumers, relatively low capital and labor demands during exploration, lack of waste, safe exploitation, and ecologic cleanness. The disadvantages are the requirement to drill several deep wells, the inability to transport the energy, the impossibility of storage, and the lack of experience in industrial exploration in Russia.

The first Russian concept of extraction of the main geothermal resources possessed by hard rocks was described in 1915 by K.E. Tsiolkovskii [1999]. In 1920, V.A. Obruchev described a geothermal circulating system (GCS) in a granite massif at a depth of 3000 m in his unfinished story "Heat mine."

The effective functioning of a petrothermal station 1
requires a sufficiently extended heat-exchange interface, which should either be found in a natural state, or created artificially. Such an interface may be found in porous strata or naturally cracked zones occurring at different depths. To increase permeability, induced filtration of the heat carrier should be organized and this heat carrier must have a more effective heat exchange parameter and an increased extractability of thermal energy of rocks, in this case. For this purpose, the method of hydraulic fracturing (hydrofracturing) in massive crystalline rocks can be used.

The theoretical foundations of hydrofracturing mechanics in the Soviet Union were elaborated by Academician S.A. Khristianovich with his colleagues and followers [Khristianovich, 1960; Khristianovich et al., 1957]. The most extensive use of hydrofracturing was in exploration of oil-and-gas beds. Hydrofracturing sharply increases the debit of extracting wells and oil-and-gas recovery. In the last 30–35 years, about 800000 hydrofracturings were performed in the 4
United States; they cover more than 40% of all wells and yield an increase in extraction of about one billion tons. Hydrofracturing has been actively used in Russia as well. For just the fields situated in the Nefteyugansk area of Western Siberia oil extraction was increased by 2 to 12 times as a result of hydrofracturing [Gnatus' and Nekrasov, 2008].

The creation of artificial collectors in the zone of hydrofracturing is the most efficient high-end process during the formation of petrothermal circulating sys- 1
tems (PCS). All the stages of this process must be controlled using a complex of geophysical methods. For

example, the formation of hydrofracturing cracks is accompanied by microseismicity and by an increase in the circulation speed of mineralized fluids. These processes can be controlled by the methods of seismic and electric surveying, respectively. As a collector runs, irreversible processes of the strengthening or weakening of filtration can occur in it. The role played by electric survey methods in monitoring PCS operation is obvious. The creation of an optimal complex for geophysical monitoring is a task that demands special developments, as well as theoretical and modeled research.

A great contribution to the elaboration of ideas on
1 the extraction and use of petrothermal resources was made by Yu. D. Dyad'kin, a Professor of the Plekhanov Leningrad Mine Institute, A.N. Shcherban' and O.A. Kremnev, academicians of the Academy of Sciences of the Ukrainian SSR, and the members of the scientific schools created by them [Dyad'kin, 1974, 1989; Teplo Zempli..., 1974]. They created the foundation of a new scientific field (geothermal physics) and created the technological basis and engineering solutions for the extraction of geothermal energy.

A PCS for the extraction of underground heat consists of the following principal elements: an injector (pressure) well; an underground heat cauldron (collector that includes a zone of natural or artificial cracking); and a production well, through which fluid is transported to the surface. In addition, the system should include a turbine room, cooling towers, condensers, intermediate heat exchange installations, pipelines, and, if possible, installations for the extraction of useful chemical elements from the pumped water, which is then pumped into the pressure well again.

1 For the construction of petrothermal heat plants (PetroHP) for the heat supply of domestic and industrial objects, the temperature of a vapor or vapor–water mixture on the surface should be up to 150°C. This temperature can be achieved for water pumped to a depth of 3 km only for a very high geothermal gradient (up to 50 mK/m). Such high gradients are rare in the territory of Russia, viz., in the North Caucasus (the Stavropol dome, the East Cis-Caucasus Region), some areas of Western Siberia, the Tunka Depression in the Cis-Baikal Region, and in the Kuril–Kamchatka Region. At a background temperature gradient of 25 mK/m, which occurs almost everywhere, a temperature of 150°C can be achieved if the depth of the well is at least 6 km [Karta teplovogo potoka..., 1980].

1 To generate electric energy at a petrothermal heat electric plant (PetroHEP), the temperature at the bottom of a well should be 250–280°C and it should be drilled down to a depth of 10 km. Model estimates carried out in the United States have shown that construction of a geothermal well 3 km deep with the use of traditional technologies of drilling costs about 4 million USD; 6 km, 10 million USD; and 10 km, 20 million USD [Augustine et al., 2006]. These values can be transferred to Russian conditions in the first approximation. According to Savchenko [2008], drilling of a production well in Eastern Siberia costs slightly more than 4 million, and an exploratory well costs 7.5–8 million USD.

Thus, construction of PetroHP and, especially, PetroHEP on the basis of existing techniques of mechanic drilling of wells is not competitive compared to the traditional heat and electric plants. Therefore, the highest-priority task is the creation of new techniques for deep drilling, which would make the process of penetration into the Earth's depths significantly less expensive. The traditional mechanical drilling of deep wells takes years and is very expensive. This is the reason that construction of deep PCSs and petrothermal plants on their basis via traditional drill- 1
ing is economically inefficient.

A group of Russian scientists and specialists, under the leadership of one of the authors, has designed several types of boring header (BS, abbreviation from the Russian "buril'nyi snaryad") [Gnatus', 2007].

We know of no analogues in the world practice: the speed of drilling of hard rocks with average density of 2500–3000 kg/m^3 was up to 30 m/h for one of the first boring headers (BS-1) and this value is higher by an order of magnitude than in the case of traditional mechanical drilling. This significantly reduces the time of drilling and cost of a PCS. Another boring header that is under development is characterized by even higher values of running parameters. The BS-1 boring header has passed industrial tests. It can make wells 200–500 mm in diameter and at up to a 10 km depth; a PCS thermal production* of 200 Gcal/h can be produced under favorable conditions of permeability.

At the temperatures that can exist at the bottom of deep wells, special demands are placed on drilling and casing pipes, cement, drilling technologies, strengthening, and pumping of water into wells, as well as for measuring instruments. Modern Russian drilling machines and equipment are intended to function at temperatures no more than 150–200°C. Therefore, petroenergy implies a problem for metallurgists to elaborate heat-resistant well pipes.

The efficiency of a PCS consisting of two wells at up to a 10 km depth is sufficient for a vapor supply to the turbines of an electric plant at a volume of 83.3 Gcal/h at an average temperature of 250°C. For this power level of a supplied vapor, the working power of a PetroHEP can exceed 25 MW. It can be equipped with Russian-manufactured low-inertia turbines with a power of 25 MW. To provide consumers with heat, a PetroHP with a power of 50 Gcal/h (at an average PCS temperature of 150°C) would be sufficient.

FINANCIAL COSTS FOR PETROTHERMAL HEAT AND ELECTRIC PLANTS 1

Pre-project calculations enabled the evaluation of investments in PetroHEP and PetroHP and the evaluation of approximate specific investments and the price of the produced electrical energy and heat in 2008 prices on this basis. These are summed from the costs for the drilling complex and the construction of the PCS, power plant, heat exchangers, water supply system, and other ground facilities [Gnatus' and Nekrasov, 2008].

Investments in the drilling complex are estimated at 940 million rubles; this complex includes a heavy drilling rig and a BS-1 boring header delivered jointly for the producer's price. The capacity of this complex is 2000 km and the running period is 10 years. The investment in the drilling complex of one PCS can be estimated proportionally to the summarized length of the PCS wells. At an average well depth of 10 km, it equals 9.4 million rubles; at 5 km, 4.7 million rubles.

Investments in the circulating system for hydrofracturing of hot dry rock (during the construction of two wells and associated facilities) are evaluated at 300 million rubles at an average depth of each well of 10 km and a summarized depth of 20 km. Reduction of the depth to 5 km decreases investment costs for a PCS to 230 million rubles (the total length of the wells is 10 km). If hydrofracturing is not required, investments in PCS are reduced to 280 and 210 million rubles, respectively.

An 25 MW electric plant in power in a ready-to-operate version is estimated at 400 million rubles, on average. The total costs at this point depend on the number and type of installed turbines. Running time of a PCS and electric plant is assumed to be 30 years.

At a BS-1 boring header speed of 30 m/h, the time required for drilling two wells of up to 10 km is approximately 1 month, including all technological pauses and readjustments.

At the stage of design before the start of experimental–industrial works, the investment in PetroHEP and PetroHP can be evaluated only approximately, with ~25% precision. Therefore, in the most expensive case, at a thermal gradient of 25 mK/m, total investment costs for a PetroHEP (2 wells of 10 km) and PetroHP (2 wells of 6 km) are about 885 and 232 million rubles, respectively; the specific values are 35500 rub./kW and 4640000 rub./Gcal per hour, respectively. This is quite comparable to the specific investments for the construction of a modern power plant that functions on the basis of other types of renewable energy sources [Kopylov, 2008]. It also should be taken into consideration that with reduction in the depth of a well by two times (which is possible under favorable geothermal conditions), investments decrease by approximately 15–20%. If artificial hydrofracturing is not required, investments may be decreased by an additional 5%.

During calculation of the cost of electric energy and heat, the main factors are auxiliary power consumption of the PetroHEP and depreciation reserves. Without going into a detailed financial analysis, which was made in [Gnatus' and Nekrasov, 2008], we only mention that the price of electric energy is evaluated at 0.55 rub./kW per hour at a well depth of 10 km each and 0.46 rub./kW per hour for 5-km wells. The price of electric energy produced at a PetroHP is estimated at 52.7 rub./Gkal for well depths of 6 km each if artificial hydrofracturing is required; in the case of a naturally cracked zone, the cost is estimated at 40.3 rub./Gkal. This is much less than the cost price for 1 Gcal of heat produced at modern heat power and boiler plants that work on the basis of organic fuel. If the depth of the PCS wells is less, then the cost of heat will be less than the cited values. Additionally, the price of electric energy produced at a PetroHEP is characterized by high stability, in contrast to that of thermal stations, whose efficiency substantially depends on variations in fuel prices.

These calculations have shown that using the Earth's deep heat in Russia is quite reasonable in terms of economic characteristics and, therefore, this can be an innovative field in thermal energy.

THE APPLICABILITY OF GEOPHYSICAL METHODS IN PETROTHERMAL SURVEYING 1

The deep geophysical methods for surveying crystalline basement structure at depths of more than 10 km (gravimetric, magnetic, seismic, electric, and thermal surveys) can be applied for detection of heat collectors in the basement that occur at the shallowest depths and the highest temperatures. Heat collectors can be extensive faults or isometric zones of rocks with temperatures higher than that in the surrounding rock massif. The drilling costs become less if collectors occur at shallower depths. The locations of heat collectors that are favorable for exploration can be found in any region of a projected PetroHEP or PetroHP. The nature of these anomalously heated zones is related to uneven energy and mass transfer from the mantle. Detection of these zones will require the organization of fundamental geological–geophysical studies. Concerning the innovative-practical potential of geophysical studies, these works will surely lead to a decrease in the depths of wells and, therefore, to lower costs.

The creation of petrothermal geophysical methods 1
for the detection of heat collectors and their classification in terms of favorable conditions of heat extraction and monitoring will lead to the design of theories, technical tools, technologies, and interpretation methods of geophysics and, in the end, will lead to lower costs for thermal energy.

CONCLUSIONS

First, let us determine whether exploration of petrothermal resources is efficient for Russia and 1
which advances can be achieved.

Petrothermal energy will allow: 1

—Avoidance, at least in part, of the consumption of fuel resources for energy and heat production. Substitution of the deep heat of the Earth for fuel resources (oil, gas, and coal) would enable one to use them in a more rational way which, in its turn, would reduce the acuteness of exploration for hydrocarbon deposits located under extreme conditions and increase the export potential of energy resources.

—Reduction of the traffic flow of fuel goods, thus increasing the transfer capability of gas pipelines and railroads for other purposes. Fuel goods are moved in
1 the first place by cargo traffic, so exploration of petrothermal energy would make a visible contribution to the solution of transport problems in the country.

—A significant reduction in ecological risks, because fuel combustion would be avoided; therefore, harmful emissions to the atmosphere and discharges to water and soil would be avoided. The role played by the ecological factor is continuously increasing and can be assessed at many billions in losses due to harm to human health and harmful effects on biogeocenoses.

—Jump starting the development of "know-how" technical tools and stimulating the requirements for specialists and personnel. The newly designed and manufactured installations and their components would include: drilling complexes; metallic heat-resistant pipes; turbines (with power ranging from several to several hundreds of megawatts and higher); electric generators, and other electric and heat engineering equipment; facilities for the chemical purification of water and extraction of valuable chemical compounds from it; pumping equipment (including ultrahigh pressure); measuring tools for temperatures up to 300°C, etc.

—The creation of a new branch of geophysics,
1 petrothermal geophysics, for the detection of heat collectors with the highest temperatures at the shallowest depths in the basement and for monitoring of these collectors during well boring and PetroHEP and PetroHP functioning.

—Stabilization of prices for electrical and heat
1 energy, because petrothermal stations do not require fuel transportation, which, in its order, would help to solve several topical social issues (the reliability and stability of the energy supply for domestic purposes; the reduction of energy costs required for the full-scale supply of the country's population in agricultural production in greenhouses, especially in cold and distant regions; the production of energy for freezers that are required to store agricultural and other products and, therefore, decreasing their losses; constant warming of airport runaways to increase their reliability and the regularity of air communication).

It is difficult to list all the possible areas of the Russian economy that can be developed and transformed under the influence of exploration for heat at depths. Based on the available data on the heat resources at depths of 10–12 km within the land, they are sufficient to supply the country's needs for hundreds of years.

The creation and development of petrothermal 1
energy should be directed, first of all, at the provision of energy to people, especially in towns and urban settlement with populations of up to 150000 people. It is these settlements where electric energy supply is most unstable; the heat energy supply is provided by low-efficiency heat sources and hot water is absent, although the share of energy costs in budgets is continuously growing.

The nearly unrestricted placement of petrothermal 1
energy plants would enable their distribution within the country's territory and location near energy consumers; in this way, the investment and transaction costs for further transportation of fuel and electric energy would be reduced. The practical exploration of the petrothermal resources of the Earth would effect 1
the development of the Russian economy in a positive way that is of strategic value for our country.

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