EXPERIENCE OF DEVELOMENT AND OPERATION OF PARATUNKA GEOTHERMAL POWER PLANT

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KEY WORDS

Freon, turbine, electric power, cycle, geothermal power plant

ABSTRACT

Russia was the first country to implement the idea to use non-water vapors as actuating fluids of thermopower plants for power generation. Freon power station UEF-90/0.5 of the 750-kW capacity was built and run in 1965 for electricity production. Geothermal water of Middle-Paratunka deposit with a temperature of 80°C was used as the heating medium. During 1967-1974 exploitation tests of a chladone station were carried out at the laboratory of on-site testing of the Institute of Thermophysics on Kamchatka peninsular. During these tests, UEF-90/0.5 operated 7,200 hours, including 5,050 hours of the industrial mode. "Paratunka" experiment demonstrated that the reliable power plant was developed. Successful works with a low-boiling substance at Paratunka geothermal power station extended the area of efficient transformation of heat energy with low potential into electric power and allowed an increase in use the heat of power resources.

1. INTRODUCTION

Problems caused by development of turbo-units with a unit power higher than 2,000 MW for power-generating units of a steam-water cycle were the main reasons for development of a power station with low-boiling actuating fluids. Simultaneously research in our country and abroad showed the advantages for construction of power plants with different cooling agents used as the actuating fluids. Theoretical and design works performed at the Institute of Thermophysics, Polzunov CKTI, and "Teploelectroproekt" Institute demonstrated that the following increase in economy and unit power above the values reached in vapor turbines is possible with construction of powerful binary water-freon power-generating units [1]. At that, the power of a binary water-freon power-generating unit with keeping of a constant limit lengths of blades can be increased up to 2,000-2,400 MW. At a decrease in condensation temperature below +20°C in a cold season (this is possible only for the water-freon aggregates with air-condensation devices), the economy of water-freon aggregates is 2-3% higher than that for the water-steam plants.

The use of geothermal heat and waste heat of industrial enterprises is very promising for the turbo-units with low-boiling actuating fluids. The heat of the most geothermal sources in Russia is concentrated in overheated thermal waters and vapor-water mixtures with a relatively low temperature (70-100°C). The same can be said about waste heat of industrial enterprises. There are some other fields of industrial-household activities with possible efficient production of power at chladone turbo-units (atomic heat stations, ocean Arctic and tropical power plants, special objects). While using this heat by a traditional scheme with steam production due to

boiling of overheated waters, power production seems to be less auspicious because of a low amount of useful heat.
Nevertheless, according to calculations, for the low-temperature heat, specific power production at power plants with low-boiling actuating fluids is considerably higher than for an ordinary vapor-water cycle. Performed analysis showed that in the temperature range of 110-170°C, electric power production per 1 t of hot water in the low-temperature cycles is 2-3 times higher in comparison with the vapor-water cycles [1]. High economy of heat utilization for outgoing gases of turbines at the compression station of the gas-main pipeline near Houston (USA) is obvious due to experience of freon turbine exploitation by “Trankline Gas Co.” [2]. The freon turbine is used there as the secondary engine in a binary propulsion system of the compression station for natural gas. All three devices: compressor, gas and chladone turbines were assembled on one shaft. The technological scheme allowed an increase in thermal output of a combined binary cycle and economical fuel consumption. The system for heat regeneration of the gas turbine by a chladone low-temperature installation justified hopes of the Company.

2. PARATUNKA EXPERIMENT

The following goals were set at the construction of Paratunka experimental geothermal power station:
1). To make the first turbo-unit with a low-boiling actuating fluid of an industrial capacity to produce electric power by the complete technological scheme and to study operation of all devices.
2). To check possibilities for assembling and exploitation of the chladone turbo-unit in practice under operation conditions of the steam-power electric plant.
3). To produce the first low-temperature geothermal power station with a turbo-unit with a low-boiling actuating fluid.
The main purpose was to solve the problem of cascade water-freon (binary) cycles and promote development of geothermal power engineering [3, 4].
The pilot setup UEF-90/0.5 was designed and constructed according to a decree of the USSR government “About the use of geothermal waters for electrification and direct heating co-generation of Petropavlovsk-Kamchatski and adjacent regions” by the Institute of Thermophysics SB USSR AS (now SB RAS) [5]. During three years the joint-stock company “Mosenergo” together with Institutes VNIIkholodmash and LTIKhP, “Krasny fakel” plant, Kaluga turbine plant and Shatura district power plant-5 were developing and testing the chladone power turbo-unit.
In 1965 the chladone power installation UEF-90/0.5 with a capacity of 750 kW on freon-12 vapors was tested at Shatura district power plant-5 of “Mosenergo” (Fig. 1).

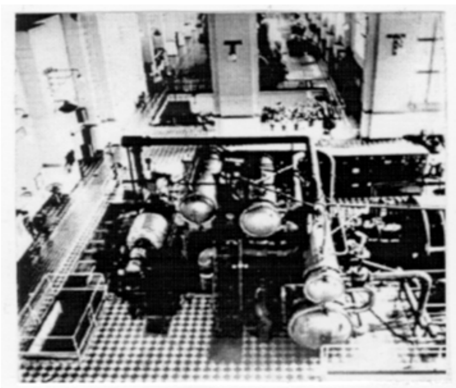

Fig.1. UEF-90/0.5 at the stand of Shatura power plant-5 of “ Mosenergo”

This installation was developed to use the heat of geothermal waters of Middle-Paratunka deposit on Kamchatka for electric power production. The temperature of these waters is 80°C. The technological scheme of the chladone power installation operates according to the Renkin cycle, which is performed by the low-boiling actuating fluid in a closed thermal circuit, where vapor with given parameters is generated due to supplied heat. According to this scheme, liquid freon is successively fed by a feed-pump into three heaters (PFG-150), evaporator (KFG-500) and vapor superheater (PFG-150) of the surface type. After the superheater freon vapor at the pressure of 14 atm and temperature of 65÷75°C is supplied into a turbine, where it is expanded up to the final pressure of 15 atm, and at the temperature of 15°C it is condensed in a surface condenser (KTR-600). Through an intermediate receiver liquid freon passes to feed-pumps, and this cycle is repeated (Fig.2).

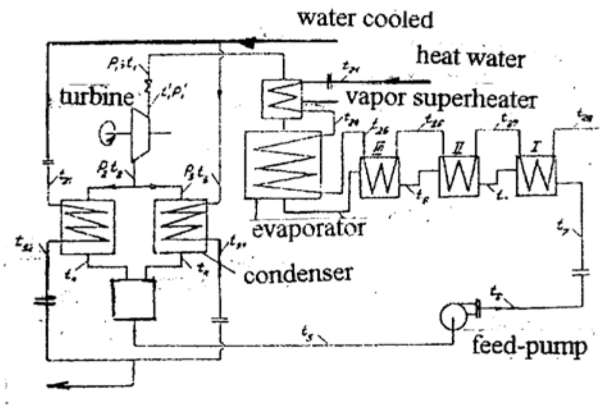

Fig. 2. The principle scheme of

UEF- 90/0.5

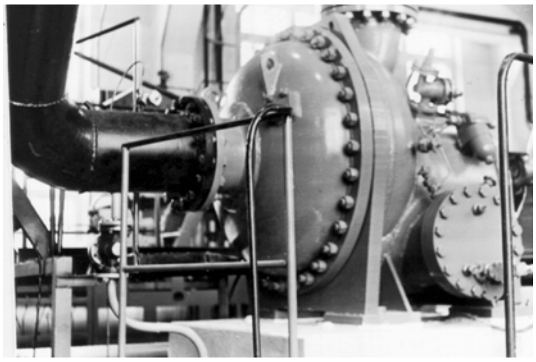

Fig. 3. Turbine TF-60/0.5 on vapors of freon-12

This power installation was completely equipped by Russian serial devices. The freon turbine is a single-stage, centripetal, cantilever with the aluminum working wheel, it was developed and fabricated by "VNIIkholodmash" (Fig.3). Characteristics of freon turbine taken from "VNIIkholodmash" project are shown in Table 1.

This installation is completely automated. At a decreased load of generator, turbine speed regulator holds rotation of turbine rotor, softly shutting a throttle at the inlet of chladone vapor into the turbine. The level of chladone supplied into a boiler is regulated by a level controller, which keeps the level of chladone in a boiler, reducing productivity of chladone pumps. Regulation is performed by successive closing of regulating valves at pump discharge. Moreover, when the second pump valve starts closing, the first pump shuts down.

Table 1. Combined table of the gas-dynamic and construction parameters of the turbine

Indices	N, kW	n, rot/min	α_1	β_1	α_2	β_2	η_t	φ	ψ	ρ	Δi_a kcal/kg	t_1 ^0C	P_1 kg/cm^2	P_2 kg/cm^2
Value	878	3000	13^0	$43^0 17'$	$70^0\ 9'$	25^0	0,8573	0,95	0,9	0,35	4,526	65	13,868	5,007

V_1 m^3/kg	V_{1a} m^3/kg	V_2 m^3/kg	C_1 m/s	U1 m/s	W_1 m/s	U_2 m/s	W_2 m/s	C_2 m/s	C_{2r} m/s	D_1 mm	D_2 mm	D_{out} mm	Z_{bl}	Z_n	$D_{n'}$ mm	D_n mm
0,0124	0,0264	0,0372	149,4	109,9	48,89	54,95	73	32,85	30,9	700	350	300	24	29	820	705

l_1 mm	l_2 mm	l_1/D_1	l_n mm	N_q hp	$\mu = D_2/D_1$	x	C_{s1} m/s	M_{c1}	q_n kcal/kg	q_{wh} kcal/kg	q_{out} kcal/kg
22,5	62,5	0,0322	21	7	0,5	0,7355	155,4	0,962	0,2874	0,149	0,1287

where N-output on turbine roller, n-number of revolutions, α_1- angle of absolute input velocity, β_1-angle of relative input velocity, α_2-angle of absolute output velocity, β_2-angle of relative output velocity, η_t-turbine efficieny, φ- nozzle velocity coefficient, ψ-velocity coefficient, ρ-reactivity degree, Δi_a- adiabatic ther malstage drop, t-initial temperature, P_1-initial pressur, P_2-final pressure, v_1, v_{1a},v_2-specific volume: nozzle inlet, turbine inlet, turbine outlet; C_1-velocity of nozzle flow, U_1-peripheral velocity, W_1- relative inlet velocity, U_2-peripheral outlet velocity, W_2-relative outlet velocty, C_2-absolute outlet velocity, C_{2r} -radial component of outlet velocity, D_1-peripheral wheel diameter, D_2-diameter of the outlet et blade edges, D_{out} – diameter of outlet funnel, Z_{bl} - number of wheel blades, Z_n-nozzle number, $D_{n'}$-diameter of inlet nozzle edges,D_n-diameter of outlet nozzle edges; l_1,l_2- widths: inlet et outlet wheel blades, l_n-width of nozzle blade edges, N_q-power of disk friction, μ- value of reverse radiality, x- coefficient of peripheral velocity, M_{c1}-number M; q_n, q_{wh}, q_{out} –specific losses: in nozzles, in wheel channels, with outlet velocity.

Simultaneously, a special regulator keeps chladone pressure constant due to a change in consumption of thermal water through the boiler (at a decrease in load, the valve on a line of hot water supply into the boiler is closed).
The turbine and generator have independent oiling systems. The turbine oiling system is built into the casing. Driving of the oil pump occurs from the turbine rotor through the serrated reducer-change gear. Oil from the pump passes through a filter and comes into a gland seal. After the gland seal some portion of oil is supplied to ball bearings (drop oiling) and the rest part flows into the casing. Oil is cooled in an oil cooler built into the turbine casing. The oiling system of generator bearings, regulation system and turbine protection system is remote. Oil at high pressure is fed from the regulating pump into an oil injector, which pumps oil from the oil tank and supplies it to the regulation and protection units. This injector feeds oil through the filter and oil cooler to generator and exciter bearings and, partially, for the intake of the regulating pump. From bearings oil is drained into the tank.
During 1967-1974, on Kamchatka at the laboratory of on-site testing of the Institute of Thermophysics SB USSR AS, operation of the chladone power installation was checked (Fig. 4).

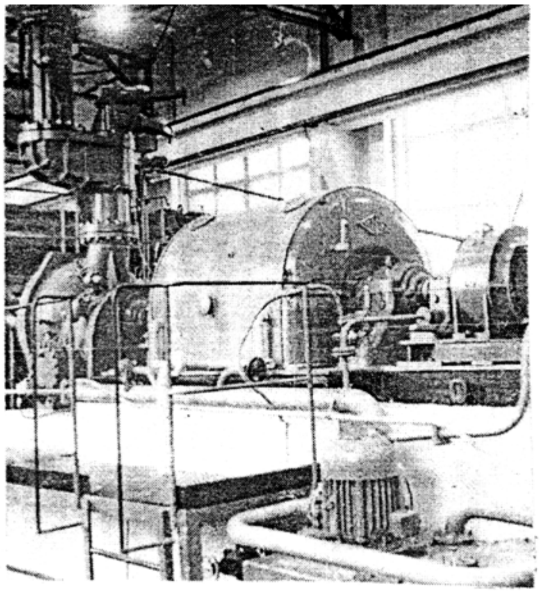

Fig. 4. Freon turbine generator at Paratunka geothermal heat power plant

At the first stage the main goal was to test long efficiency of installation, and at the final stage, it was necessary to test its operation under the industrial mode with power generation. Heat engineering, aerodynamic, corrosion and other tests were carried out to check design calculations.
Calculated and experimental heat transfer coefficients of freon vapor generator are shown in Table 2.
When testing, the maximal power of installation was 684 kW. The total power of 750 kW was not reached because this installation was designed to use hot water with the temperature of 90°C, and the average water temperature of Middle-Paratunka deposit is 80 ±1°C. A decrease in the temperature of thermal waters provided reduction in boiler efficiency, and this did not allowed maximal calculated power of the turbine unit.
A change in real and adiabatic thermal drops of freon vapors in shown in Fig. 5 depending on electric load on generator cleats. Small scattering of experimental points indicates satisfactory accuracy of experiment.

Table 2. Calculated and experimental heat transfer coefficients of freon vapor generator

Indices	Heat exchanging zones of freon vapor generator					
	heating		boiling		overheating	
	calculation	test	calculation	test	calculation	test
θ_{log}, °C	15.5	17.5	14.8	13.6	28.8	16.4
F, m²	361	361	483	483	120	120
q, kcal/(m²·h)	5450	4750	11900	9800	3120	5500
K, kcal/(m²·ºC)	352	272	804	720	107	336

here θ_{log} is the average logarithmic temperature difference, F is the heat exchanging surface, q is specific heat load, K is the heat transfer coefficient.

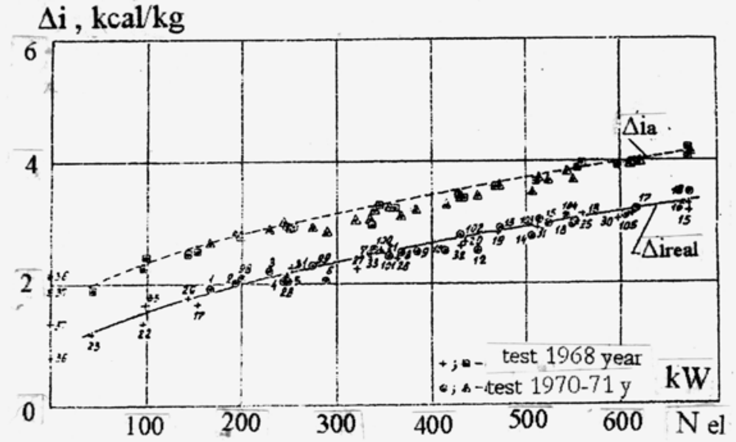

Fig 5. Dependency of electric load on thermal drop location

Dependencies of turbine efficiency and stage reactivity on electric power and dimensionless parameter U_1/C_0 are shown in Fig. 6 and 7, where U_1 is the circular speed of the wheel and C_0 is the rate of gas outflow. It is obvious that reactivity degree decreases with reduction of U_1/C_0 and reaches 0.38 at maximal power (684 kW) and, correspondingly, minimal value of U_1/C_0 (0.585). The character of the dependency curve between reactivity, electric load and U_1/C_0 shows that, when the designed electric load (750 kW) is obtained, the calculated value of stage reactivity (0.35) will be reached also. It is clear that maximal obtained power of 684 kW was reached at minimal U_1/C_0=0.585.

Due to extrapolation, it can be assumed that at calculated value of U_1/C_0=0.556, the power of turbo-unit will be 740÷750 kW.

The highest turbine efficiency obtained during the tests was 0.82.

According to the diagrams, at U_1/C_0 = 0.556, turbine efficiency becomes η_{ad}=0.84 against calculated η_{ad} = 0.855. For the first experimental freon turbine these coincidence of experimental results may be considered as the satisfactory ones.

Specific production of electricity at maximal obtained electric load was 2.93 kW·h/t.

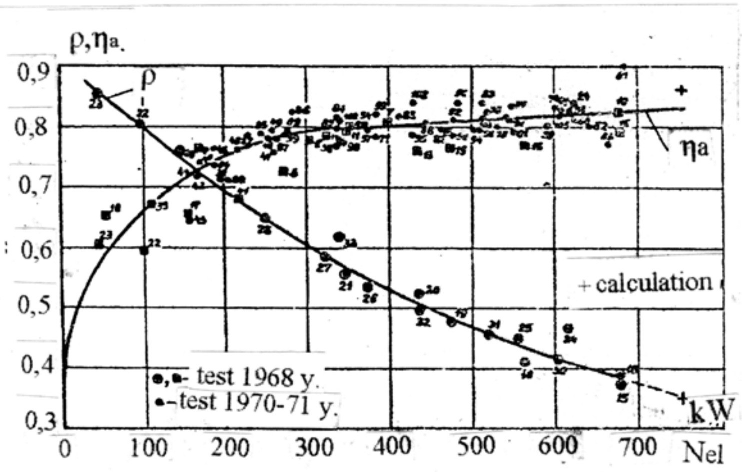

Fig. 6. Mutual influence of stage reactivity, turbine efficiency and electric load on generator cleats

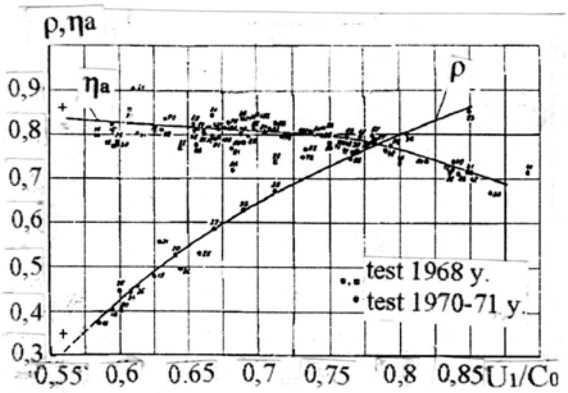

Fig. 7. The effect of U_1/C_0 ratio on turbine efficiency and stage reactivity

Specific production reduced by calculated temperature of heating water of 90 ^{0}C was $N_{el.}/G_{h.w.}$= 3.91 kW·h/t, and this even exceeds calculated data (3.82 kW·h/t).

Changes in heat transfer coefficients depending on the heat load of condensers are presented in Fig.8.

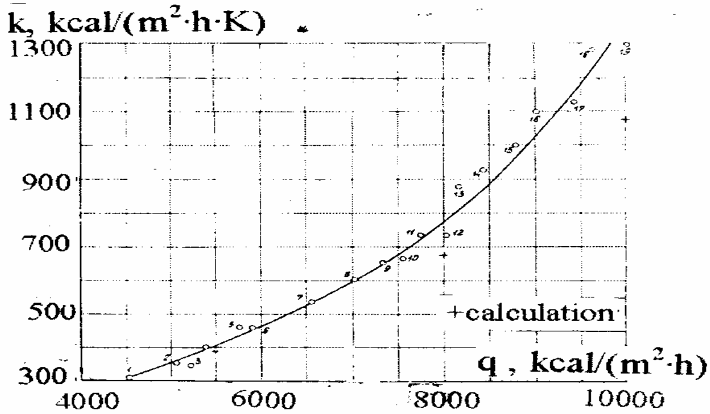

Fig. 8. Heat transfer coefficient vs. condenser heat load

3. LOW-BOILING SUBSTANCES AS ACTUATING FLUIDS

According to previous research [6], the efficiency of thermodynamic cycle with chladone is in reverse dependence with the upper level of cycle temperatures (in comparison with steam). It was determined that within the temperature range of between 80-200 ^{0}C, specific electricity production in cycles with chladone was one and half times higher in comparison with the vapor-water cycle. At the temperature of chladone vapor of 130-150 ^{0}C, similar thermodynamic efficiency can be obtained both for chladone and vapor-water cycles, where the highest steam temperature is equal or slightly exceeds 200 ^{0}C. Therefore, it is useful to consider chladones as the actuating fluids from the point of low-potential heat of geothermal sources, recycling of secondary power resources, etc. Quantitative results of thermodynamic investigations show that an increase in power efficiency is maximal in the area of lower final temperatures (pressures) of chladone.

In the range of final expansion of chladone vapor, a change in final pressure P_f by 0.1 MPa (the ambient temperature changes by 10 ^{0}) leads to alteration of device efficiency by 2% (Fig.9).

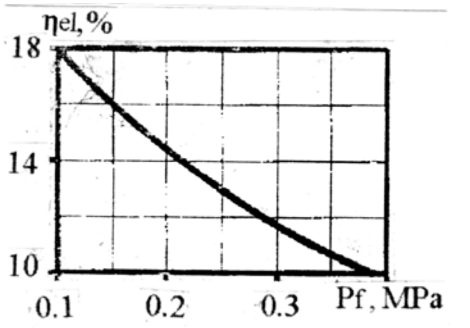

Fig. 9. The effect of final pressure on the cycle efficiency

Simultaneously, a 10-degrees change in the initial vapor temperature in front of turbine T_0 на 10 ^{0}C provides alteration in efficiency η_{ef} ~ by 0.26 % in the studied range of initial pressures (Fig.10. [R21: 1-P_o=1.5 MPa; 2-P_o=2.0 MPa; P_f=0.1 MPa]).

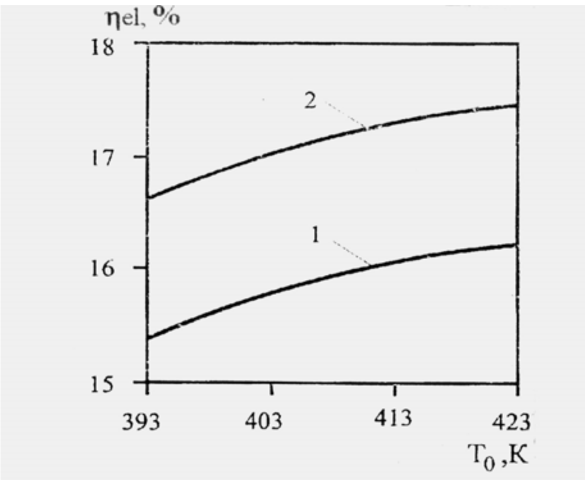

Fig. 10. A change in electric efficiency of the thermal circuit depending on the initial temperature of chaldone

After examination of properties of 150- substances performed by Marchwood Laboratory of the Central Electricity Generating Board of the United Kingdom, it was determined that the best actuating fluid for low-temperature power installations is chladone-R21 [7,8] with ozone depletion potential ODP=0.04. Numerous investigations carried out in our country showed that due to thermodynamic properties and heat transfer characteristics, chladones-R11, R12, and R21 are the most promising as low-boiling actuating fluids for low-temperature installations [9]. Recently synthesized chladone-R123 with ODP=0.02 is also interesting.
Since production of some fluorine-chloride organic compounds is stopped because of ozone saving by Montreal and Kyoto protocols, production of hydrocarbons, two-component low-boiling actuating fluids and water-ammoniac solution (in the technological scheme, its production is called "Kalina-cycle") is of a particular interest. The low-boiling substances from these compounds were used by power devices at specific industrial plants:
"Raft-River", "Magmamax", "Hyber", etc. (USA); "Mitsusima-plant" , "Otake", "Nigorikava" (Japan); "Orkuveita Husavikur" (Iceland). Thus, from the point of application of low-boiling substances for electricity production, in various countries, the firms-producers establish different priorities in criteria for the choice of actuating fluid due to conditionals, which determine technical abilities and economic appropriateness for construction of the power installation. It is necessary to note that transfer of environmental contamination problem from the global level to a local one leads to the fact that all substances used as actuating fluids do not meet the main demands of fire, explosion and non-toxic safety.

4. FUTURE TRENDS. RUSSIAN MARKET

An increase in economic efficiency of Russian regions, whose industrial-economic activity is base on imported organic fuel despite local energy resources of geothermal sources, can be obtained due to involvement of these sources into economy and gradual dislodgment of organic fuel. Simultaneously, energy safety of the region grows. Despite a low density of available energy from low-potential sources, the main arguments for development of power plants are as follows: power saving, on-site power generation, environment protection, social effects, possible competitiveness due to a decrease in exploitation expenses because of an absence (absolute or partial) of fuel component at rising prices on organic fuel.
As one type of national power resources, geothermal sources are of a high potential. Today economic potential of geothermal sources of Russia is estimated as 3450 pJ/year [10]. The use of at least 5% of this potential will allow annual introduction of about 500 MW of electric capacity. An estimate of economic efficiency of low-potential energy carriers for electricity production at low-boiling actuating fluids was made for the conditions of Kamchatka region. Considering rise in prices on industrial engineering in the North-East regions by the factor of 1.8 in comparison with the first territorial region, specific investments will be 1916 USD/kW. Total investments, required for construction of geothermal power plant, are determined with consideration of their introduction by the beginning of exploitation, construction period of 2 years, normal discount of 8% and 7% of the bank capital rate. The estimated pay-out period is determined as 4-5 years. At the output power cost of 15 c/kW and service life of 30 years, the net discounted profit for the geothermal power plant of the 1.5-MW capacity will be 4,045,000 USD.
Implementation of low-potential secondary power resources of industrial enterprises for power generation is possible using chladone power installations. Analysis performed allows us to assert that oil processing, chemistry and ferrous metallurgy, as the main power-consuming industrial branches, are simultaneously the large sources of waste heat, approximately equivalent to 100-1500 million tons per year. The main heat losses (up to 60%) are related to low-potential power carriers with the pressure close to the atmospheric one and the temperature of up to 130 ^{0}C. By the estimates of VNIPIEnergoprom, the limit power saving by heat technologies caused by application of multiple-use power saving equipment will allow saving of about 30% of

consumed power (the considered technology for power generation uses such an equipment) [11]. Every percent of saved power resources will provide an increase in the national income up to 0.35-0.4% [12].

5. CONCLUSIONS

An experience of construction and exploitation of the first power plant with complete technological cycle on low-boiling actuating fluid R12 at application of low-potential heat carriers (80 ^{0}C) allows the following conclusions:
1. Testing chladone (freon) installation at the pilot geothermal heat power plant of the Institute of Thermophysics SB AS USSR at Middle-Paratunka thermal sources demonstrated the efficiency of the applied scheme with chladone cycle and the main equipment: chladone turbine, its regulation system, heat exchangers. Containment of chladone pumps and thermal circuit as the whole was proved.
2. Testing was carried out under conditions different from the calculated ones: the real temperature of thermal water was 81 ^{0}C instead of 90 ^{0}C, considered in calculations.
3. Installation FEU-90/0.5 is easy operating and reliable in exploitation.
4. At a cold state, the installation can be run for 30-40 min., and at a hot state, it requires 5 min.
5. High density of chladone circuit can be obtained without application of any specific materials and devices. At testing, total losses of chladone were 2.2-2.5 %. It should be noted that main part of losses occurred through the safety valves, at circuit opening and air removal from the condensers, i.e., these are losses, which can be easily eliminated in the following similar turbo-units.
6. The automation and protection system, developed on the basis of probes and sensors used by refrigeration engineering, operates stable and reliable, providing maintenance of all required parameters in the given ranges.
7. Only chladone feed-pumps should be seriously re-developed. The used pumps of 4KhGV-60-40-5 type are unreliable, short-lived, and their efficiency is very low – of about 25 %.

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