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THE CHOICE OF EQUIPMENT MIX AND PARAMETERS FOR HTGR-BASED NUCLEAR COGENERATION PLANTS

INTRODUCTION

Improvement of heat and electricity supply systems based on cogeneration is one of the high-priority problems in energy development of the USSR. Fossil fuel consumption for heat supply exceeds now its use for electricity production and amounts to about 30% of the total demands. District heating provides about 80 million t.c.e. of energy resources coserved annually and meets about 50% of heat consumption of the country, including about 30% due to cogeneration. The share of natural gas and liquid fuel in the fuel consumption for district heating is about 70%.

The analysis of heat consumption dynamics in individual regions and industrial-urban agglomerations shows the necessity of constructing cogeneration plants with the total capacity of about 60 million kW till the year 2000. However, their construction causes some serious problems. The most important of them are provision of environmentally clean fuels for cogeneration plants and provision of clear air. The limited reserves of oil and natural gas and the growing expenditures on their production require more intensive introduction of nuclear energy in the national energy balance. Possible use of nuclear energy based on light-water reactors for substitution of deficient hidrocarbon fuels is limited by the physical, technical and economic factors and requirements of safety. Further development of nuclear energy in the USSR can be realized on a new technological base with construction of domestic reactors of increased and ultimate safety.

The most promising reactors under design are high-temperature gas-cooled reactors (HTGR) of low and medium capacity with the intrinsic property of safety. HTGR of low (about 200-250 MW(th) in a steel vessel), medium (about 500 MW(th) in a steel-concrete vessel) and high (about 1000-2500 MW(th)in a prestressed concrete vessel) are now designed and studied in the country. At outlet helium temperatures of 920-1020 K it is possible to create steam-turbine installations producing both electricity and steam and hot water. If the helium temperature at the core outlet reaches 1120-1220 K, it will be possible to create a single-loop HTGR-based gas-turbine installation using waste heat for heat supply. The economic feasibility of creating industrial and heating plants with HTGR, rational fieldes of their application in cogeneration systems can be determined after complex optimization analysis of schemes and their main parameters considering the whole complex of really influencing factors in their operation.

INDUSTRIAL AND HEATING PLANTS WITH MODULAR-TYPE HTGR.

The main requirement to nuclear sources for district heating is their safety resulting from the necessity of their more close siting to industrial and civil consumers. The basic heat schemes of industrial and heating plants with modular-type HTGR are realized on the following principles:

- process steam for consumers should be supplied from the third loop;
- hot water for public services should be supplied from the third loop;
- the three-loop schemes foresee a trapping loop.

Fig. 1 presents basic heat schemes of industrial and heating plants based on the 200-250 MW(th) reactors. The considered level of initial steam pressure can be achieved by steam reheating or separation. The use of extracted steam for heating simplifies the steam generator design, reduces the heating surface, and, as a result, increases its safety. The use of a once-through-type steam generator with high steam pressure increases requirements to feed-water quality. The costs on chemical water treatment can be decreased by the process steam production in a steam-generating installation (SGI). Water of the heat network is heated in the two-stage preheater.

If a set of the optimized thermodynamic and discharge parameters of a working medium is characterized by vector X, a set of schemes and variants of structural, load and functional redundancy by vector Y, and the share of capacity reserve in the district heating system accounts for R, the optimization problem of parameters and characteristics of HTGR-based industrial and heating plants is stated as follows:

$$(X,Y,R)^{opt} : \min З_{\Sigma} (X,Y,R)$$

$$Q_r = const; \quad T_1; T_2 = idem; \; X^{min} < X < X^{max} ; \; Y \in Y^* ;$$

$$R = \min R \; [\; H(X,Y,R) > H^* \;]; \; H^{q,e} (X,Y,R) > H^{q,e}_H$$

$$F^*(X,Y) < F(X,Y) < F^{**}(X,Y)$$

where Q_r - reactor thermal capacity, T_1, T_2 - helium temperature at the reactor inlet and outlet; X_{min}, X_{max} - a feasible region for changes in the independent parameters X; Y^* - a feasible set of schemes and variants of structural. load and functional redundancy; $H^{q,e}$ (X,Y,R) -the index of reliable supply of consumers with thermal and electric energy; $F^*(X,Y)$, F^{**} (X,Y)- a feasible region of dependent variables and their functions.

Here the minimized functional are the total expenditures 3sum for the whole service life, that are discounted to the operation start, including:

- cost on uranium production, conversion, enrichment, fuel element production, processing and burial of waste fuel;
- capital investment on plant construction;
- cost on main and auxiliary equipment;
- cost of installation works;
- operating costs;
- cost of all natural and labour resources used;
- additional costs on provision of equal energy and social

The reliability indices of cogeneration systems are calculated by the complex of hierarchically constructed models. The reliability indices of cogeneration for each type of product are determined at the upper level. The calculation method is based on the probabilistic calculations and system state analysis. The coefficient of supply with product of each type and the coefficient of system operation efficiency are taken as reliability indices. The latter index is the probability of the system output being not less than that required by the load curve at any time. The middle level of the complex includes calculation of the structural reliability of combined energy installations regarding the structural, load and functional redundancy of individual elements. The calculation method for reliability indices is based on the application of the Markov model and determines reliability indices that are interdependent as to the electric and heat energy production. The reliability indices of energy equipment elements are determined at the third level. The probabilistic model constructed for calculating failure-free operation is based on the probability that the current loads will not exceed their critical values. The required reliability level of cogeneration is achieved by the proper choice of design features of equipment elements, application of the structural, load and functional redundancy of the plant and the use of system reserve.

The program of optimization studies consisted of two stages. The problem of optimizing the main parameters of heat schemes was solved at stage 1. The results showed that the level of individual steam parameters accounted for 17.5-18.5 MPa and 818-838 K. The pressure of steam reheating was within the ranges 1.0-1.5 MPa at a temperature of 583-592 K. The extracted steam with a pressure of 8.0-9.0 MPa was rationally used as a heating steam. In the scheme with steam separation the pressure amounted to 0.1-0.15 MPa. At the pressure of the supplied steam above 1.8-1.9 MPa a single-stage steam extraction in the steam-generating installation is realized, at lower pressures a two-stage extraction is reasonable. Table 1 presents the results of comparative analysis of heat schemes of HTGR-based industrial and heating plants.

Table 1. Comparative characteristic of industrial and heating plants

Indices	Three-loop with SGI	Two-loop with SGI and reheating	Two-loop with SGI and steam separation
1	2	3	4
Heat sources, MW (th)	2x250	2x250	2x250
Electric capacity, MW			
in design conditions	102.9	110.7	117.0
in autumn-spring conditions	110.0	117.2	123.5
in summer conditions	136.4	143.4	150.0
Yearly electricity production, MWh	956.7	1013.8	1065.1
Yearly process steam production, thousand t/year	588.7	588.7	588.7
Yearly heat production for public services, MWh/year.	676.7	676.7	676.7
Saving of discounted costs, million rubles/year	0.0	0.95	1.92

The table shows that the scheme of the plant with steam separation is most efficient.

Stage 2 of optimization studies was intended for choosing the structural scheme of nuclear cogeneration plant and the unit capacity. The studies resulted in the economically expedient structural scheme of nuclear cogeneration plants (NCP). A double-block scheme with two reactor units with a capacity of 200-250 MW(th) and a turboset has economic advantages.

A block-type NCP with GTU, based on large HTGR.

The prospects of using the gas-turbine unit (GTU) in Nuclear Power Installation (NPI) are due to the following factors:

-reduction of capital investment;

-elimination of constraints on water consumption owing to the possible use of "dry" cooling towers;

-achievement of high electric efficiency and heat utilization coefficient;

-possibility for wide-range variation in the amount of heat produced without reducing the electricity generation.

Due to all these facts the GTU-based nuclear cogeneration plants with HTGR can be considered as a perspective type of NPI and technico-economic studies on the installation of a similar type-as up-to-date ones.

Complex optimization of schemes, parameters and ways for the equipment arrangement at NCP, whose basic scheme is given in Fig.1, was carried on during decomposition of continuously discrete programming problem with the application of computer modelling of all the main processes occurring in NPI /1/.

The minimized functional, i.e. total costs on NCP during its whole lifetime (3ncp) that are discounted to the year of plant comissioning, includes the following components:

-costs on fuel (uranium production and enrichment, fuel processing, manufactoring the fuel elements, selling the secondary fuel bred);

-cost of the plant construction;

-cost of the main and auxiliary equipment of NCP;

-cost of installation works;

-operating costs (salary,depreciation and maintenance costs, etc.).

Reduction of the variants to the equal economic effect was based on the use of marginal costs on nuclear fuel and electricity. Solution of the similar optimization problem with account of different conditions for NCP operation has the following peculiarities: the total costs on NCP is the sum of costs on NCP for each condition of plant operation. The possibilities for NCP equipment operation were tested in all the conditions.

For manoeuvring the heat load, produced for consumers, the methode of by-passing gas-water coolers 4 and 6 (Fig.2) was used. Consideration was given to NCP with HTGR of a monoblock type of 1060 MW(th) with a pebble-bed core, that operates in uranium-plutonium fuel cycle. The installation will be put into operation in 2010 and will operate in three modes with combined production of electricity and heat in the form of hot water and steam.

Calculations were made on the BESM-6 computer with the help of software package "PEGAS" that uses detailed models of reactor and heat-transformation parts of NPI /2-3/.

During technico-economic optimization of energy installation of any type it is advisable to cover all the possible variants of its designs. Within the framework of the problem solved it is difficult and hardly advisable to study the possible range of parameter change, type of a scheme, variants of arrangement, values of steam and hot water loads in detail. The optimization region is narrowed by preliminary technico-economic studies on NCP that persue the goals:

- estimation of the possible range of cogeneration loads;
- substantiation of the arrangement type for the equipment of the first loop;
- determination of the impact of cogeneration load on the parameters and type of the NCP heat scheme.

The advisability of such an approach is caused by the fact, that the applied mathematical model of NCP has a large number of independent optimized parameters (up to 40) and the overall search for all the factors would require time-consuming computations.

At the stage of preliminary studies NCP was considered without steam generation. (Scheme in Fig.2 had no steam loop. Gas pressure and temperature at the reactor outlet were taken equal to 5 MPa and 1223 K respectively). Height and radius of the core, radius of micro-fuel elements, enrichment of the loaded fuel, gas temperature at the reactor inlet, helium pressure after the turbine and before the second compressor, coolant rate in heat exchangers and pipelines, height of "dry" cooling tower, diameter of its mouth and number of columns were considered as independent optimized parameters.

The results of studies allowed a number of conclusions to be made (for greater detail see /2-3/):

1) Economic efficiency of different technological schemes of NCP depends on the cogeneration load value Q_c (Fig.3). If heat is supplied to the consumers in the form of hot water only, the dependence is as follows: with $Q_c < 300$ MW, heat load factor (heat load - to - reactor thermal capacity ratio) $\varepsilon < 0.283$, the most complex scheme has the minimum discounted costs; with 300 MW $< Q_c <$ 500 MW ($0.283 < \varepsilon < 0.472$) the preference is given to the scheme with a regenerator and compressor, and with $Q_c >$ 500 MW ($\varepsilon > 0.472$) the simplest scheme becomes competitive as well (Fig.3). If the scheme has a loop with a steam generator and gas cooler, conventionally called as a "steam" one, then the second compression stage should be given up due to necessity of providing the high temperature of helium after regenerator (on the low-pressure side), since the required temperature of water in the loop with a steam generator, that is determined by the parameters of generated steam, is sufficiently high.

2) By the criterion of minimum discounted costs on NCP the integral arrangement of all the equipment in the first loop and reactor in the multi-cavity strong vessel is more advantageous than the separate arrangement of a turboset and heat exchangers (difference in the amount of discounted costs is 1-3 million rubles/year). When a turboset is arranged in the same vessel with HTGR and heat exchanger, the following two variants are equally economic for 3ncp:

a) with a two-flow turbocompressor, located in one horizontal cavity under the core and heat exchangers;

b) with a four-flow turbocompressor located in two horizontal cavities under the core and heat-exchangers.

Heat exchangers, consisting of four sections, are located symmetrically around the core in eight vertical cavities. But preference should be given to the first variant of arrangement, since in the second variant difficulties with the location of a device for unloading the spent fuel elements from the reactor may arise.

3) With the given heat scheme of NCP the optimum parameters of HTGR and equipment of a heat-transformation part depend on the value of Q_c (Fig.4). The behaviour of NCP electric capacity, coefficient of heat utilization and capital investment versus the growth of cogeneration load allows the following values of Q_c to be recommended: for NCP operation without considerable reduction of electricity production Q_c= 200-300 MW.

On the base of preliminary studies of NCP with combined production of electricity,steam and hot water, the heat scheme was selected with a regenerator, one stage of compression and integral arrangement of the heat-transformation equipment of the first loop in the multi-cavity prestressed concrete vessel. According to this scheme, all the heat exchangers consisting of four sections, are located in pairs in accord with the results of preliminary studies: section of a regenerator - section of "steam" gas cooler; section of a gas cooler for heat production-section of a "terminal" cooler; a two-flow single-shaft turbocompressor is in the horizontal cavity under HTGR and heat exchangers.

The program of optimization studies consisted of several stages:

1) At the first stage, in the range of pressures (P_r) and heatings (ΔT_r) of helium in the reactor (P_r= 5-9 MPa, ΔT_r = 300-600 K), joint optimization of HTGR parameters and heat-transformation equipment was held with the use of detailed models of reactor and heat-transforming parts. At the given stage the most typical parameters of steam and water in heat networks, cogeneration capacity, ratio between steam and hot water loads, duration of NCP operation in different conditions (Table 2) were chosen on the base of the analysis of a number of large energy consumers in the European part of the USSR by the values of loads and steam and hot water parameters, characteristics of yearly

load curves, etc (Table 2).

Table 2. Characteristic of NCP operation conditions (SG-steam generator, NWH-network water)

N	Operation condition	Duration of operation condition (hours)	Thermal capacity (MW)	
			SG	NWH
1.	Design	110	215	185
2.	Autumn-spring	4954	215	170
3.	Summer	2936	150	130

The parameters of generated heat were given as follows: steam pressure - 1 MPa, temperature of feed water and steam - 423 K and 453 K respectively, pressure of water in heat networks - 1.5 MPa, water temperature at the reactor inlet and outlet, respectively- 343 and 423 K.

Temperature of helium at the HTGR outlet was taken equal to 1223 K, and some constraints were imposed on the following reactor parameters: average energy intensity of the core $Q_v < 6$ MW/m^3; temperature of fuel element centre $T_c < 1523$ K; temperature gradient of fuel elements grad $(T_{f.el}) < 25000$ grades/m; energy intensity of a fuel element $q_v = 3$ kW/ball; fuel burnout $B_t = 150$ MW day/kg. Besides the values enumerated in the previous sections (excluding the parameters, related to the second compression stage), gas pressure in the reactor was also optimized.

According to the applied decomposition of the problem, the value of 3ncp was found as a sum of the corresponding values for reactor (RP) and heat-transformation (HTP) parts: 3ncp=3rp + 3htp. Studies have shown, that the value of 3rp (that is subject to the influence of pressure in the reactor, gas consumption, core size, indices of a fuel cycle) monotonously increases with the growth of P_r and ΔT_r in the studied range of their change.

Cost of heat-transformation part 3htp have a distinct minimum in the region of gas heating values of 500-600 K in the reactor, that is determined by the behaviour of capital investments and electrical efficiency (Fig. 5a). Fig. 5b illustrates the dependence of discounted cost of NCP on the gas pressure in the rector. The minimum is observed at all the values of gas heating in the reactor and is shifted from P_r = 6.6 MPa at ΔT_r = 600 K to P_r = 7.2 MPa at ΔT_r = 300 K.

In the course of studies at the given typical ratios of electricity, steam and hot water production (Table 2), the minimum discounted costs 3ncp are observed at the values of heating ΔT_r = 600 K and gas pressure in the rector P_r = 6.6 MPa.

2) The goal of the second stage was to study the dependence of the optimum technico-economic characteristics of NCP on the value of total thermal load and marginal costs on electric and heat energy.

Dependences of the optimum parameters of schemes and technico-economic characteristics of NCP on the value of total thermal load were obtained on the base of optimization studies carried on.

Fig. 6a illustrates the dependences of useful electric capacity of NCP and capital investments on the value of Qc. Other dependences (parameters of a coolant in the nodes, design characteristics of equipment, rate of a coolant in the pipelines and equipment components, temperature heads in the heat exchangers, cost characteristics) are presented in a similar way.

Analysis of the impact of marginal costs was performed by maximum, medium and minimum values of marginal costs, typical of the economic regions in the European part of the USSR: South, Center and Urals respectively. Marginal costs on steam load were taken 20% higher, than marginal costs on hot water. The results of calculations of the marginal costs on heat and total costs on NCP for different values of Qc and marginal costs are given in Table 3 and Fig. 6b.

Table 3. Economic efficiency of NCP at different cogeneration loads.

Qc, MW.	Location of NCP	3disc	3ncp	3ncp+ 3disc
		million rubles/year		
250	Urals	28.5	0.0	28.5
	Centre	30.87		30.87
	South	33.42		33.42
400	Urals	15.03	15.92	30.55
	Centre	16.1		32.02
	South	17.63		33.55
550	Urals	0.0	38.73	38.73
	Centre	1.08		39.81
	South	2.21		40.94

It is seen from the figure, that the discounted costs on NCP increase monotonously with the growth of heat load. Increment in the marginal component of costs leads to the distinct minima in the total costs.

Values of Qc in the studied range of changes in the marginal costs on heat, at which the total costs on NCP have the minima, vary from 250 to 320 MW. Hence, the optimum value of Qc for the given type of GTU-based NCP with HTGR in the regions with minimum level of marginal costs on heat is equal to 250 MW (the heat in this case the heat load factor is 0.234). In the regions with maximum level of marginal costs on heat the optimum value of Q_c accounts for 320 MW (heat load factor is 0.3).

The dependences of NCP parameters on Qc similar to those given in Fig. 6a being available, the optimum load and any parameters and performances of NCP can be obtaned using Fig. 6b for the required area of NCP allocation.

CONCLUTIONS

The optimization studies on Nuclear Cogeneration Plants with HTGR allow the following conclusions to be made.

1) NCP, based on the modular-type HTGR and steam turbine installations:

- The results showed that the level of individual steam parameters accounted for 17.5-18.5 MPa and 818-838 K. The pressure of steam reheating was within the ranges 1.0-1.5 MPa at a temperature of 583-592 K. The extracted steam with a pressure of 8.0-9.0 MPa was rationally used as a heating steam. In the scheme with steam separation the pressure amounted to 0.1-0.15 MPa. At the pressure of the supplied steam above 1.8-1.9 MPa a single-stage steam extraction in the steam-generating installation is realized, at lower pressures a two-stage extraction is reasonable.
- A double-block scheme with two reactor units with a capacity of 200-250 MW(th) and a turboset has economic advantages.

2)The block-type NCP with GTU, based on large HTGR:

-With the integral arrangement of equipment preference is given to the variant with location of the one-shaft, two-flow turbocompressor in one horizontal cavity, located in the same vessel with HTGR and heat exchanger below the core.
- If heat is supplied to the consumers in the form of hot water only, the dependence is as follows: with $Q_c < 300$ MW (heat load factor $\epsilon < 0.283$) the most complex scheme has the minimum discounted costs; with 300 MW $< Q_c <$ 500 MW ($0.283 < \epsilon < 0.472$) the preference is given to the scheme with a regenerator and compressor, and with $Q_c > 500$ MW ($\epsilon > 0.472$) the simplest scheme becomes competitive as well.
- If the scheme has a loop with a steam generator and gas cooler, the second compression stage should be given up and for NCP operation without considerable reduction of electricity production Qcis recommended to be less than 300 MW. The following parameters of HTGR coolant are recommended: P_r= 6.6 MPa, ΔT_r =

264

600 K (the outlet temperature of heleum in reactor T_r= 1223 K).

- The optimum value of Qc for the given type of GTU-based NCP with HTGR in the regions with minimum level of marginal costs on heat is equal to 250 MW (heat load factor is 0.234). In the regions with maximum level of marginal costs on heat the optimum value of Qc accounts for 320 MW (heat load factor is 0.3).

-The relation between area of location, optimum cogeneration capacity and optimum NCP parameters are shown; the algorithm for obtaining the set of NCP parameters for any area of location is given.

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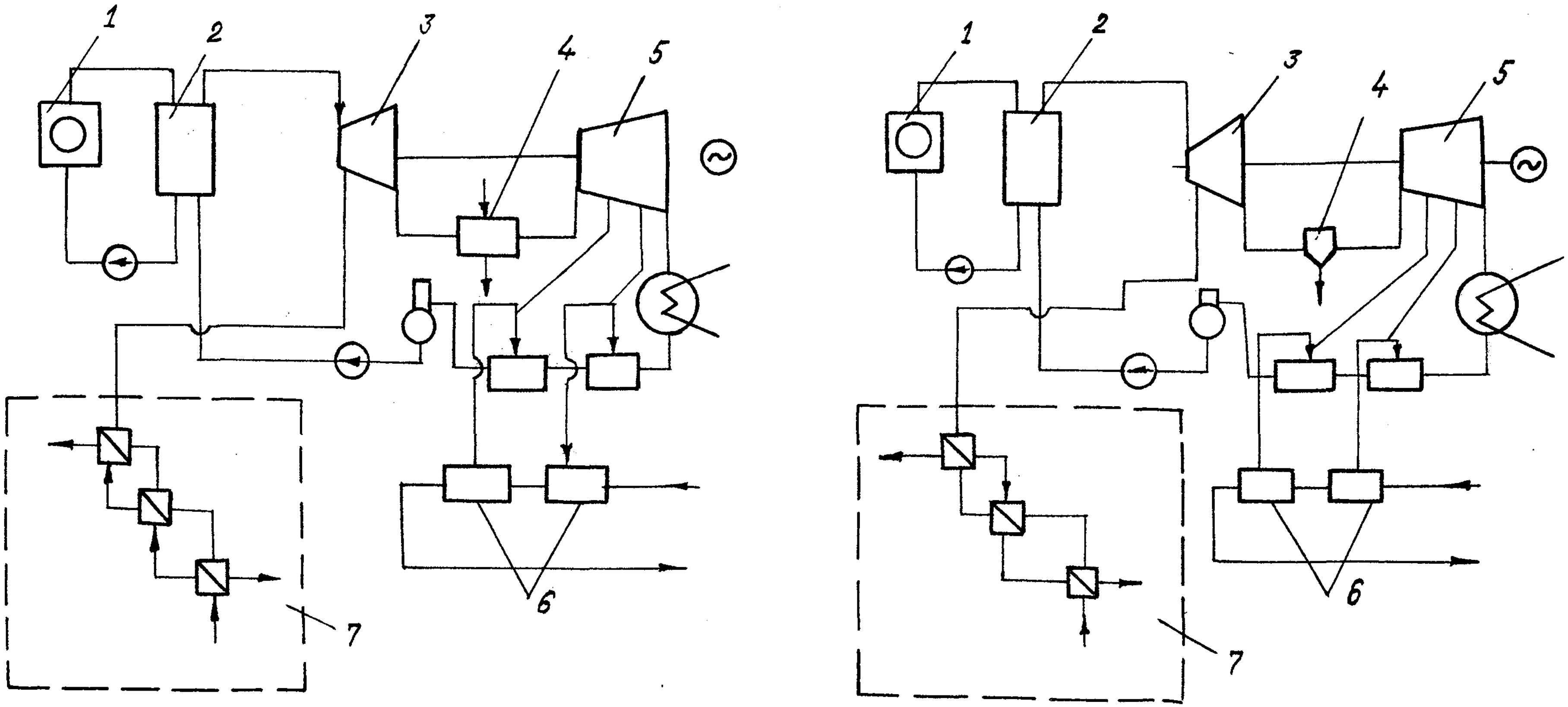

Fig. 1. Basic thermal schemes of industrial and heating plants with HTGR
1 - reactor; 2 - steam generator, 3 - high-pressure cylinder,
4a - steam reheater, 4b - separator; 5 - low-pressure cylinder;
6 - water heaters of cogeneration system; 7 - steam generating installation.

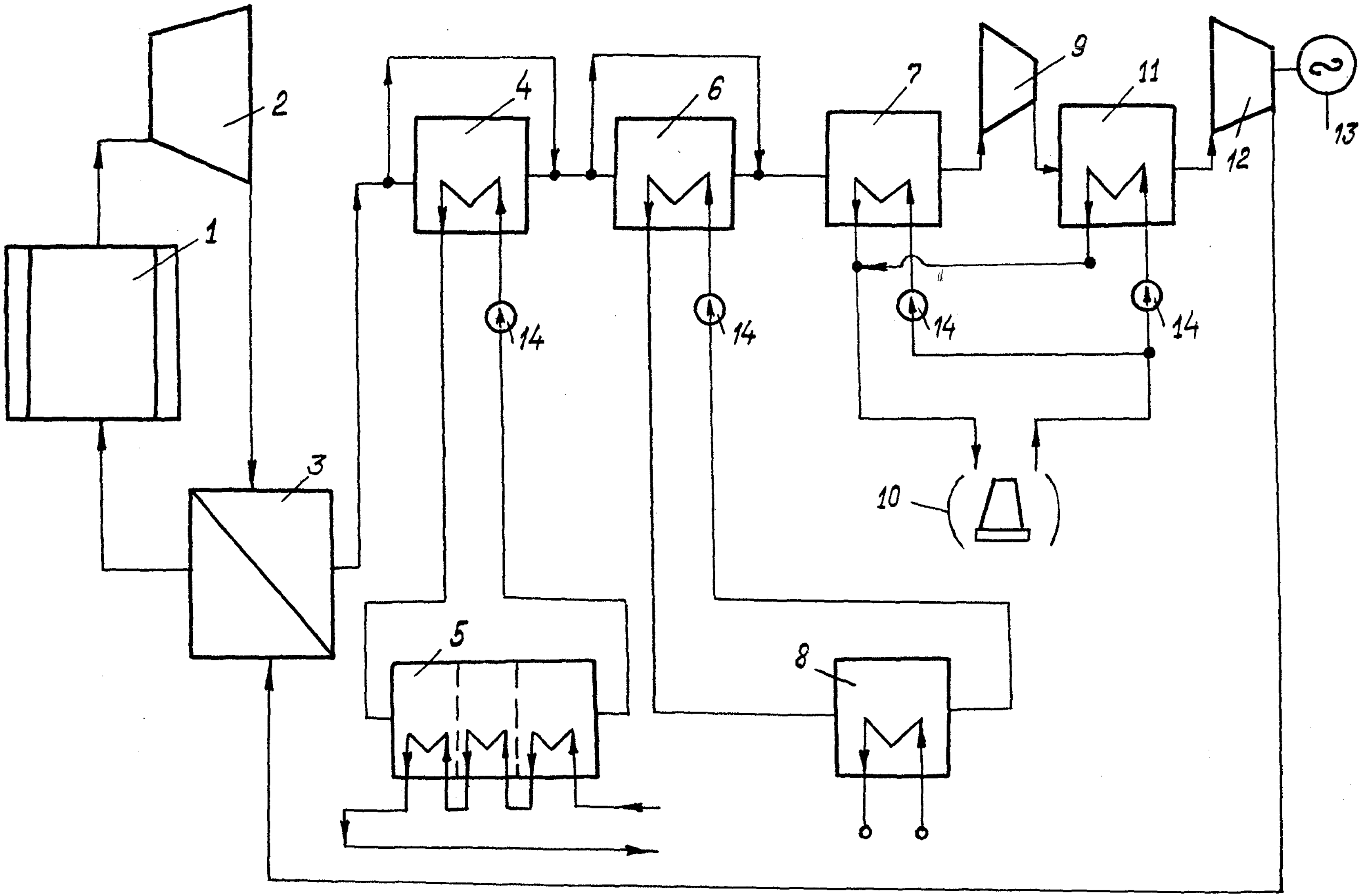

Fig. 2. Basic flow-diagram of GTU-based NCP with HTGR.
1 - HTGR; 2 - turbine; 3 - regenerator; 4 - "steam" gas cooler; 5 - steam generator; 6 - gas cooler for heat production; 7 - "terminal" gas cooler; 8 - water heater of cogeneration system; 9 and 12 - compressor; 10 - "dry" cooling tower; 11 - intermediate gas cooler; 13 - generator; 14 - pump.

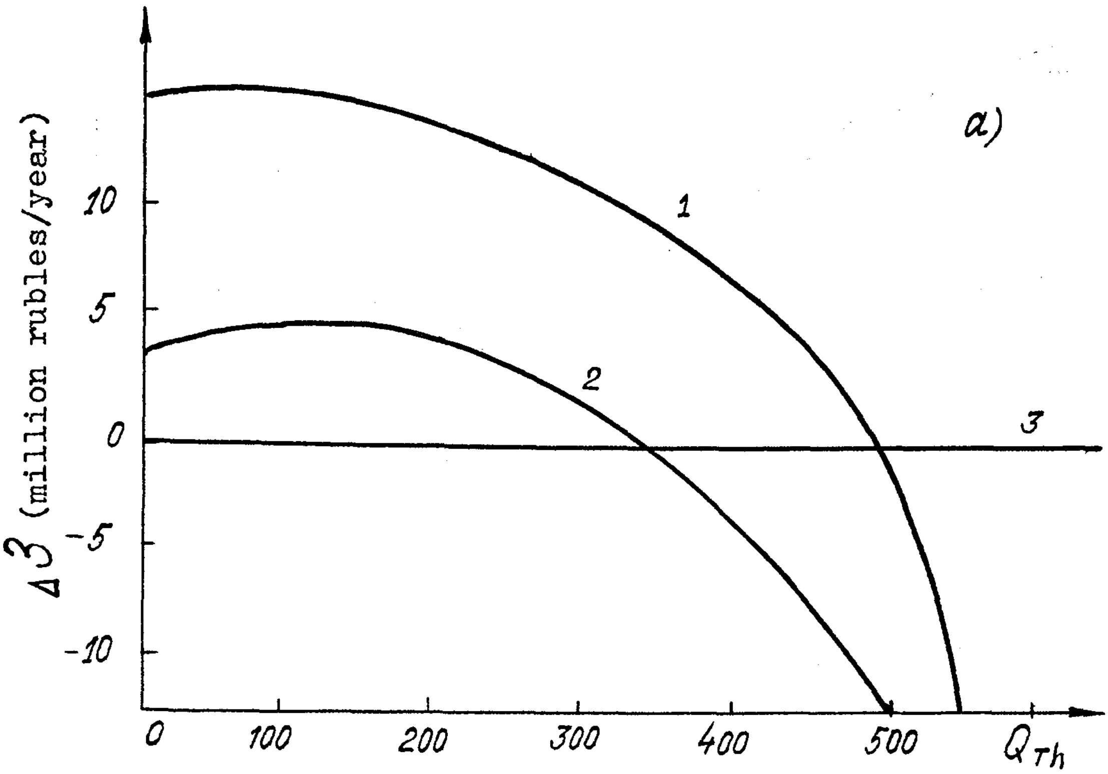

Fig. 3. Competitiveness of NCP schemes versus the most complete scheme (Fig. 2) with different thermal load. 1 - scheme without regenerator, with one compression stage; 2 - scheme with regenerator and one compression stage; 3 - scheme with regenerator and two compression stages.

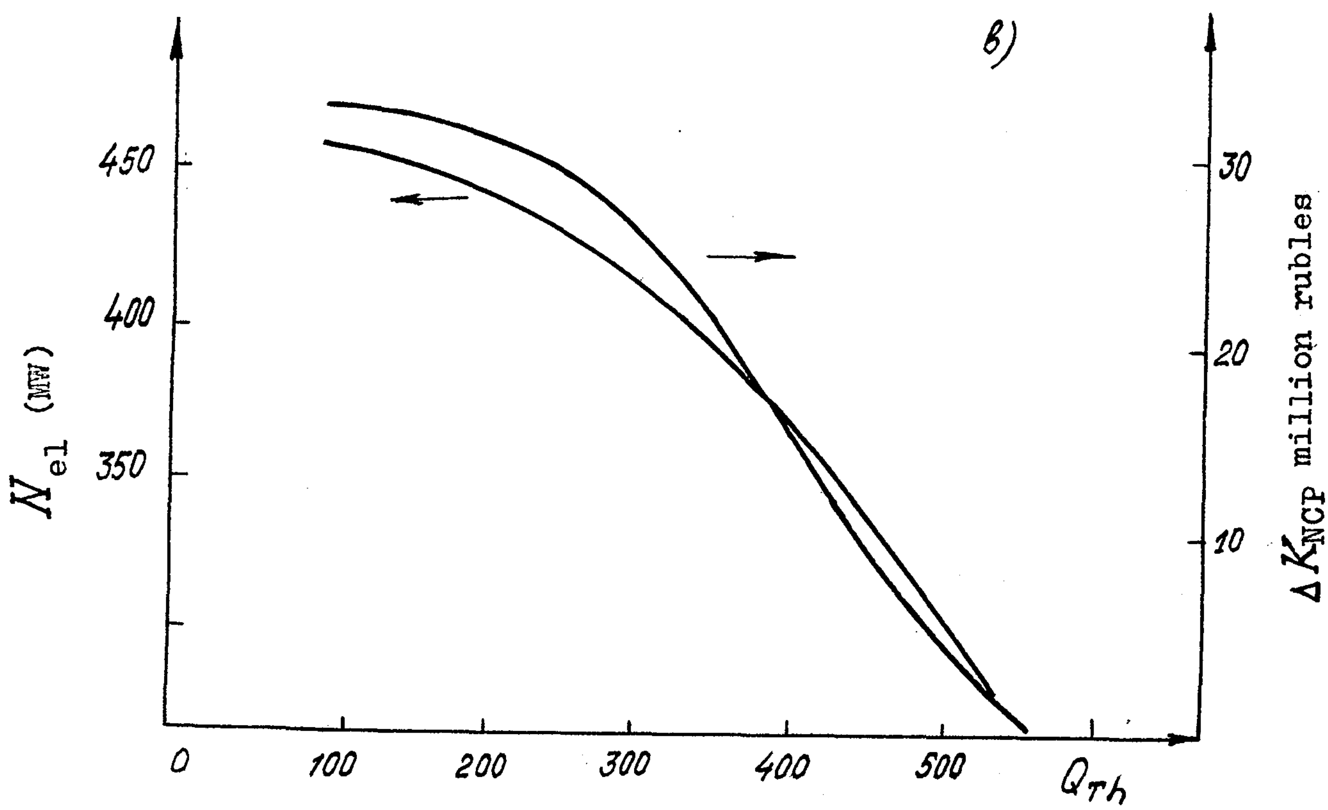

Fig. 4. Electric capacity and capital investments on NCP with different thermal load for the scheme with regenerator and two compression stages.

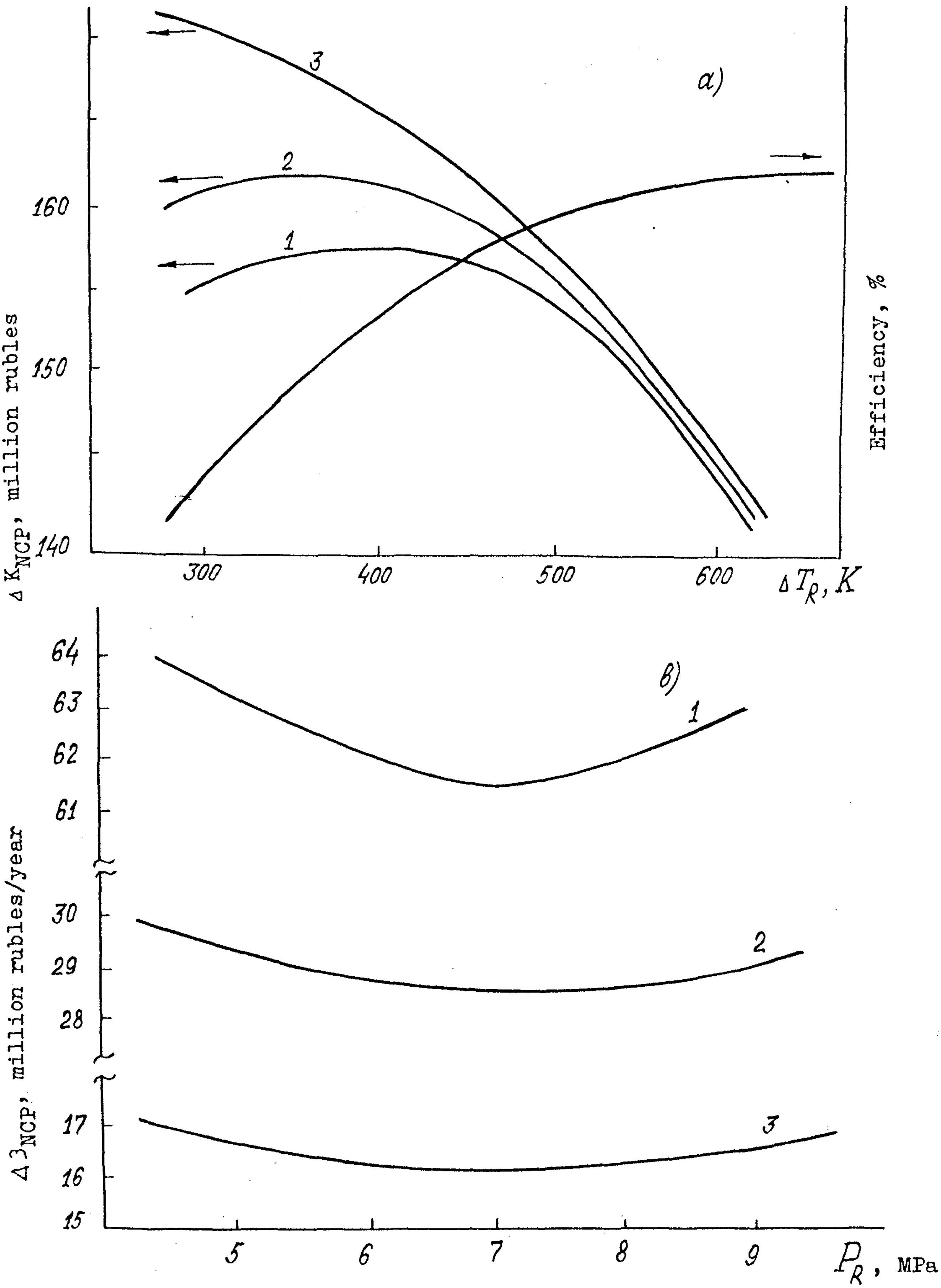

Fig. 5. Dependence of a) capital investments and electric efficiency of NCP (I - P_R=5.10 MPa, 2 - P_R=7.15 MPa, 3 - P_R=9.20 MPa) and b) discounted costs on NCP on the pressure (P_R) and heating (ΔT_R) of gas. (1-ΔT_R=300K, 2-ΔT_R=450K, 3-ΔT_R=600K).

B-3

269

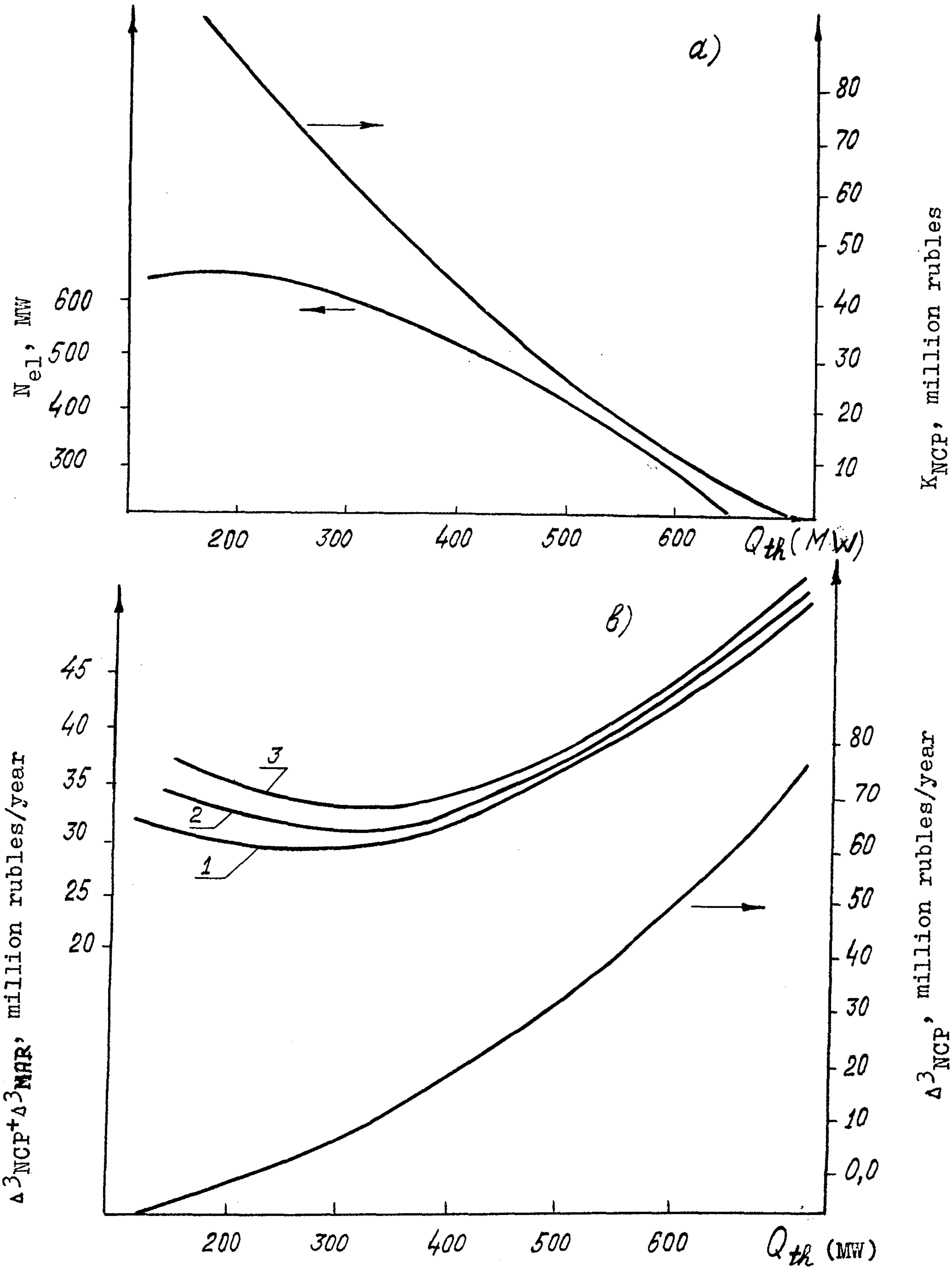

Fig. 6. Dependence of a) capital investments and electric capacity of NCP and b) discounted costs on NCP with and without account of the marginal costs on heat (1 - Urals, 2 - Centre, 3 - South of the European part of the USSR) on the value of thermal load.

B-3