Comparative efficacy of ways of long-term usage of start-up boilers in the scheme of nuclear power plant

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Abstract. There was carried out an analysis of technical characteristics of boiler houses in a number of Russian NPPs. We justified the possibility of their usage for autonomous generation of electrical energy and improvement of maneuvering properties of power complexes as a single object of regulation, as well as the possibility of increasing the total generation capacity of NPP power units during peak hours. Then the selection of the main equipment of house boiler for its autonomous work was done. There were composed basic thermal diagrams of the power complex on the basis of NPP start-up boiler (SUB) and the satellite turbine. The article also considers some options of reconstruction of SUB into the heat-recovery boiler. The developed power complexes are designed to be used on the basis of the two-loop NPP with pressurized power reactors (PWR). They can be applied with serial and projected domestic NPP units with the aim of getting more power, improving the plant capacity factor (PCF), as well as with the aim of NPP participation in the regulation of the load curve above the nominal value with partial replacement of new construction. The power complexes can be a relevant solution in the light of the energy strategy of the Russian Federation, which is aimed at, firstly, further improvement of efficiency and safety at the NPP, and, secondly, solving the problem of adequate maneuverability and ensuring the adjustment range limits in power systems with high share of nuclear power plants. Implementation of new hybrid thermal diagrams allows simultaneous increase in the safety of NPP, and usage of nuclear power plants emergency frequency control in power systems by fast load drop and rise by -4+2 % of the nominal value. Due to the usage of different fuels in power complexes, uranium loading in the core of reactor facilities and gas in SUB, there was proposed and formalized the criterion of "thermoeconomic index". This criterion represents the ratio of the gross receipt from the sale of electricity to the total cost of fuel of all kinds, spent on ensuring power efficiency.

In the Russian Federation there are ten nuclear power plants with 35 power units of various projects, which have start-up boilers, mainly implemented through the use of natural gas and fuel oil. The experience of using nuclear power plants in Russia showed the absence of the need for SUB at normal post-launch operation of NPP power units (meaning the first launch). The equipment of start-up boilers is kept in "cold" reserve and is not involved in the generation process at the stations. According to the normative and technical documentation (NTD) and company standards (CS), the following steps are carried out: control routine boiler startups in SUB; maintenance of the station auxiliary steam drums in "hot" reserve; and special chemical and technological operations on preservation of thermal and mechanical equipment in the "standby" mode.
As can be seen from table 1, thermal power supplied by start-up boilers at NPP is sufficient for connecting drive turbo-generators of low power to them and using these complexes in the boiler diagrams of two-loop nuclear power plants.

**Table 1.** Start-up boiler parameters of some Russian power stations.

| Parameter                          | Leningrad NPP | Baltic NPP | Balakovo NPP |
|------------------------------------|---------------|------------|--------------|
| Boiler capacity, tons per hour     | 80            | 160        | 50           |
| Boiler type                        | ESB 16000     | ZFR-IE 40000 | GM 50-14/250 |
| Maximum working steam pressure, MPa| 1.0           | 1.3        | 1.4          |
| Steam temperature, °C              | 183           | 195        | 250          |

In the project of Balakovo NPP with PWR–1000, start-up boiler doesn't take part in power generation and designed to provide thermal power in the period of construction of process users of the 1st and 2nd loops of four power units of NPP. It also serves for implementation of heat supply to consumers at a closed loop heating of the nuclear plant and the site.

During NPP operation, at start/shutdown works in the units or while carrying out repair works, thermal power of the start-up boilers at nuclear power plants is not generally used as process users of repair and starting power units receive thermal power via auxiliary collector from the operating nearby unit from unregulated extractions of steam turbine plant.

The use of nuclear heating plant units at NPP in a calendar year for a heat supply of consumers is not related to boiler house, since the thermal power of the NHP units of NPP is sufficient.

Subject to all normative documents and recommendations, maintenance of thermal and mechanical equipment of boiler house in a state of readiness is a difficult task requiring large financial expenditures and a large staff of highly qualified personnel.

In recent years in a number of Russian NPPs there is a removal of the boiler equipment at SUB in connection with its uselessness, economic inexpediency of servicing the entire generating capacity of the boiler. Taking into account significant specific investments for construction of NPP, which can reach the cost $ 2,000/kW and more for new projects of nuclear power plants (including the construction of SUB), the disuse of generating capacity of a boiler house in the generation process during the postrun period appears to be economically inexpedient.

Below one can find the following patterns of use of SUB equipment in a single power complex at the site of nuclear power plants to generate electricity, as well as the possibilities of application of thermal power in the cycle of the main turbo-generator unit (by example of K-1000/60-1500-2 HTZ (Turboatom - Harkovskij turbinnyj zavod)).

We developed a variant of combining boiler house with steam-turbine plants of low capacity in a single satellite unit (figure 1). The drive steam turbine K-12-1.1 UTW (The Ural Turbine Works) is proposed for usage as a low-power turbo-generator. This complex allows us to cover the electric power shortage in power grids in peak hours. The capacity of the proposed complex, consisting of three turbo-generators K-12-1.1 and four boiler units GM-50-14 with a total capacity of 200 ton/h, is 33 MW. The generated power of the presented power complex helps to cover the shortage of electricity during peak hours in the power grid.

The developed complex allows nuclear power plants to participate in primary frequency regulation of the electric network of power grid (at frequency dip) by rapidly rising (surging) load by +2,+4% from Nnom., and it can be used for localization of emergency situations at NPP units with the loss of auxiliary electric power supply of the security system through safety channel reservation of NPP power units. The implementation of power complex of start-up boiler with satellite turbo-generators will allow reservation of auxiliary power supply of safety systems of one of the nuclear
units to the full extent. This power complex enables one to meet the high demands of nuclear safety of international organizations in atomic energy (IAEA, WANO).

Burning natural gas in a boiler unit of the start-up boiler happens only in peak hours, when the proposed complex is turned on. The equipment specifications of the proposed complex are presented below (table 2). The start-up boiler is located in a separate building on the territory of the nuclear plant, and is equipped with four steam boilers of the type GM 50-14/250 with a working steam pressure of $P_{ss} = 1.4$ MPa and temperature $250 \, ^\circ C$.

**Table 2.** Technical characteristics of the boiler GM-50-14/250

| Parameter                                      | E-50-1.4/250GM (GM-50-14/250) |
|------------------------------------------------|-------------------------------|
| Rated steaming capacity, ton/h                 | 50                            |
| Pressure of superheated steam, MPa (kgf/cm²)   | 1.4 (14)                      |
| Superheated steam temperature, °C              | 250                           |
| Feedwater temperature, °C                      | 100                           |
| Fuel                                           | Gas, fuel oil                 |
| Efficiency, %                                  | 93.0 / 91.0                   |

Overall dimensions of the boiler unit, m:

| Parameter         |      |
|-------------------|------|
| Length            | 18.2 |
| Width             | 11.2 |
| Height            | 14.6 |
| Boiler mass, ton (seismic configuration) | 140 (164) |

Installation of three steam turbine turbo-generators of the type K-12-1,1 allows one to use (load) the full start-up boiler capacity. Table 3 provides a brief description of the satellite turbo-generator.

**Table 3.** Technical characteristics of the STP K-12-1,1.

| Parameter                                           | K-12-1,1-3 |
|-----------------------------------------------------|------------|
| Nominal power, kW                                   | 11600      |
| Type of electrical generator                        | T2-12-2    |
| Rated speed, sec⁻¹                                  | 50         |
| Pressure of fresh steam at turbine inlet, MPa       | 1.1        |
| Temperature of fresh steam at turbine inlet, °C      | 248        |
| Nominal pressure in capacitor, kPa                   | 5.88       |
| Rated consumption of fresh steam, ton/h              | 70         |
| Inner relative efficiency, %                         | 79.2       |
| Number of cylinders                                  | 1          |
| Type of condenser                                   | KP (Condenser of receiving tank)-1650 |
| Turbine mass, ton                                    | 46         |
Thermal diagram, designed for boiler house complex and attached turbo-generators, is shown in figure 1.

![Thermal Diagram](image)

**Figure 1.** Estimated way of turbo-generator K-12-1,1 operation including SUB into single power complex. (Patent of the RF № 2602649 [1])

Another use of the boiler house is the project of applying SUB thermal power for usage in low-pressure cylinder of steam turbine plant K-1000/60-1500 -2 of the power unit.

The steam, produced by four power boilers of the type GM-50-14/250 in the total number of 200 ton/h, is sent to receiver pipe of low-pressure cylinders of the main turbine unit with the corresponding parameters.

The design features of the steam path of the STP determine the possibility of increasing the steam flow through the low-pressure cylinder by means of side steam from SUB, without changing the flow of the turbo-generator, due to designed reserves, with almost constant steam parameters. If you increase the steam flow through the steam path of the LPC, humidity in the final stages of the cylinders slightly increases, which is not critical and contributes to the decrease of $\eta_{oi}$ because of loss rising from humidity, while increasing the useful capacity. Thus, the increase in consumption leads to a general increase of the turbine power by 35 MW, to values of 1075 MW depending on the mode of carrying the load, under the assumption that the permitted thermal power of the reactor system today provides 104 % of the nominal power, or 1040 MW (el).
Thermal diagram, designed for a start-up boiler complex and attached turbo-generators, is shown in figure 2.

![Thermal diagram](image1)

**Figure 2.** Way of operation of steam-turbine plant at NPP with SUB in a single power unit. (Patent of the RF № 2602649 [1])

We can also offer the installation of two buildings of high-pressure heater (HPH) of the type PV-2500-97-18A in two lines of the feed water train, with complete set of two groups of HPH, with supply of heating steam parameters \( t_{ss} = 250^\circ C \) and \( P_{ss} = 1.4 \) MPa from a side source – start-up boiler (Figure 3).

![Diagram of power complex](image2)

**Figure 3.** Diagram of the power complex with combined capacity of SUB with two buildings of completed group of HPH of the power unit. (Patent of the RF № 2602649 [1])

Additional installation of two buildings of HPH in turbine house, with steam supply from SUB will allow us to increase electric power of the turbo-generator by 33 MW, due to the heating of the feed water by side steam, i.e. without unregulated extraction of steam from high pressure cylinder (HPC). The steam, produced by four power boilers of the type GM-50-14/250 in the total number of
200 ton/h at SUB site, is sent to two installed buildings of HPH for feed-water heating on the calculated temperature 225°C, under the terms of the NPP operation.

The relatively low steam parameters and the remote location of SUB at the site of the serial nuclear power plant led to the need of implementation of this project at close to SUB power units №1 and 2 with the construction of steam and condensate lines and condensate transfer pumps. The length of the steam and condensate line system is 600, 850 m, for units №1 and 2, respectively.

The proposed project allows one to load start-up boiler at design capacity, to ensure fast assembly of the steam supply diagram of the repaired unit, to provide "hot" standby DH plant at modes of auxiliary consumption, and to increase unit capacity of NP unit. Thus, the increase in steam consumption by limiting the top two regenerative bleed-offs result in the overall increase of the turbine power by 33 MW in nominal conditions, i.e. by 3.3% higher than permitted today 104% Nnom.

In the calculation of economic indexes we applied traditional methods of assessment of efficiency of investment projects.

| Table 4. The economic indexes of the estimated schemes of combining nuclear power plant unit with SUB. |
|----------------------------------------------------------|
| Parameter                                               | Variant 1 | Variant 2 | Variant 3 |
| Net capitalized income in 2036, mln rub                  | 1644.9    | 2168.9    | 1897.5    |
| Payback period of the project, years                     | 5.02      | 0.95      | 2         |
| General costs of the project, mln rub                    | 490.5     | 10        | 20        |
| Useful life of the project, years                        | 50        | 50        | 50        |
| Reconstruction time, years                               | 2         | 1         | 2         |
| Profitability index, rub/rub                             | 3.98      | 201.8     | 185.3     |

The proposed variants of SUB modernization by creating a satellite circuit of NPP allow one to:
- ensure the generation of peak power with high efficiency of turbine and start-up boiler operation at NPP;
- increase the reliability of auxiliary power supply at the expense of additional autonomous power supply of essential consumers of satellite turbine generator;
- improve the safety of nuclear power plants with its full blackout. In this case, the nuclear units receive an additional autonomous source of electricity in the form of SUB with satellite turbine which has its own condenser and generator.

Economic calculations of all the proposed variants have shown that they are quite profitable and competitive along with other well-known ways of obtaining additional capacity.

A method of engineering assessment of effectiveness of the start-up boiler (SUB) in the heat balance diagram of the second circuit of the NPP with PWR-1000 [2].

In connection with the use of different types of fuels in power plants: uranium dioxide UO₂ in the basic reactor installations PWR-1000 and natural gas in SUB, there was proposed and formalized a more convenient criterion for assessing the feasibility of integration of various additional "satellite" installations, with the use of different fuel types on one energy site, i.e. in a single complex – "thermoeconomic index". This criterion represents the ratio of the gross receipt from the sale of electricity and other energy products to the total cost of fuel of all kinds for the power site, spent on ensuring power efficiency.

In our opinion, to assess the excellence and the economic viability of integrated (satellite) power units in the base facility on the example of the NPP with initially known investment, thermoeconomic index is more convenient. Let us consider the use of design capacity of industrial heating SUB in a nuclear power plant with power unit PWR–1000, running on natural gas, with 4 boilers of the type GM-50-14/250, with the integration of the heat balance diagram of SUB and heat balance diagram of the second loop of the reactor by feeding superheated steam in low-pressure part of the main turbo-
generator K–1000-60/1500-2 and, as an option—a side source of steam for two buildings of completed group of HPH.

Due to the fact that the economic costs of both projects are relatively minimal and both projects are economically identical according to the energy indicators, the proposed thermoeconomic index (formula) does not contain the cost of buying equipment.

$$\eta_{t/ek}^{br} = \frac{24 * N_{npp} * T_{npp}^{peak} + \Delta N_{sub}^{npp} * T_{peak}^{sub} + \Delta N_{sub}^{npp} * T_{peak}^{sub}}{24 * Q_n * P_n / q_n + Q_{sub} * P_g / q_g * \tau_p}$$

In formula (1): $\Delta N_{npp}^{sub}$ is the power generated by the STP in NPP due to receipt of steam from SUB during $\tau_p$ hours of SUB operation, MW; $Q_{sub}$ is the thermal output of SUB (4 boilers GM-50-14/250) – 130 MW. $T_{npp}^{peak}$, $T_{peak}^{sub}$ is the transfer electricity tariffs (rub/MW*h); $P_n$, $P_g$ are the cost of the used fuel, (rub/kg); $q_n$, $q_g$ are the calorific value of the used fuel (MW*h/kg).

Suggested ratio $\eta_{t/ek}^{br}$ is the criterion, convenient for the primary analysis of simulation models of power complexes, combining two (or several) cycles. These power complexes are characterized not only by the variable circuit and parametric characteristics, but also the changing economic ones of the sales of electric-power production and fuel costs (of two or more types with different characteristics).

Below table 5 shows the results of calculations of the efficiency of the dual-fuel power complexes (2 and 3 variants) based on the thermoeconomic index $\eta_{t/ek}^{br}$.

| SUB operating time during the peak period, days, h/day | Thermoeconomic efficiency |
|------------------------------------------------------|---------------------------|
| Tariff ratio                                        | P_g, rub/kg               |
| Basic $\frac{rub}{MW*h}$                            |                           |
| Peak $\frac{rub}{MW*h}$                             |                           |
| 1300, rub/MW*h                                      | 5                         |
| 1800, rub/MW*h                                      | 10                        |
| 1300, rub/MW*h                                      | 15                        |
| 1800, rub/MW*h                                      | 30                        |
| 1300, rub/MW*h                                      | 40                        |
| 10                                                   | 5.91                      |
| 15                                                   | 4.80                      |
| 30                                                   | 3.49                      |
| 40                                                   | 2.95                      |
| 10                                                   | 6.5                       |
| 15                                                   | 5.1                       |
| 30                                                   | 3.8                       |
| 40                                                   | 3.3                       |
| 10                                                   | 6.7                       |
| 15                                                   | 557                       |
| 30                                                   | 4.4                       |
| 40                                                   | 4.5                       |
| 10                                                   | 6.97                      |
| 15                                                   | 6.07                      |
| 30                                                   | 5.09                      |
| 40                                                   | 4.59                      |

Below table 6 shows the results of calculations of the efficiency of the dual-fuel power complexes (2 and 3 variants) based on the thermoeconomic index $\eta_{t/ek}^{br}$.

| SUB operating time during the peak period, days, h/day | Thermoeconomic efficiency |
|------------------------------------------------------|---------------------------|
| Tariff ratio                                        | P_g, rub/kg               |
| Basic $\frac{rub}{MW*h}$                            |                           |
| Peak $\frac{rub}{MW*h}$                             |                           |
| 1300, rub/MW*h                                      | 5                         |
| 1800, rub/MW*h                                      | 10                        |
| 1300, rub/MW*h                                      | 15                        |
| 1800, rub/MW*h                                      | 30                        |
| 1300, rub/MW*h                                      | 40                        |
| 1500/1500                                           | 5.89                      |
| 1500/1800                                           | 4.79                      |
| 1800/2500                                           | 3.48                      |
| 1500/1500                                           | 5.7                       |
| 1500/1800                                           | 5.5                       |
| 1800/2500                                           | 3.8                       |
| 1500/1500                                           | 6.1                       |
| 1500/1800                                           | 5.5                       |
| 1800/2500                                           | 4.4                       |
| 1500/1500                                           | 5.09                      |
| 1500/1800                                           | 5.08                      |
| 1800/2500                                           | 4.58                      |

| Gas export                                          | C_n^{ex}=58.3 rub/MW h(ton) |
|                                                     | C_g^{ex}=2160 rub/MW h(ton) |
| x_{n/g}^{ex}                                         | 1.66                       |
| 1500/1500                                           | 1.30                       |
| 1500/1800                                           | 1.112                      |
| 1800/2500                                           | 1.73                       |
| 1500/1800                                           | 1.40                       |
| 1800/2500                                           | 1.22                       |
| 1500/1500                                           | 2.16                       |
| 1500/1800                                           | 1.62                       |
| 1800/2500                                           | 1.58                       |
Conclusions
1. The proposed method for preliminary determination of the thermoeconomic efficiency index of new projects allows one to more fully (along with the thermodynamic analysis) consider the impact of heterogeneous (and sometimes differently estimated) fuel costs in the power complex.

2. Suggested ratio $\eta_{t/ek}^{br}$ allows us to estimate the effect as thermoeconomic flux ratio of gross gross receipt to fuel costs (in both fuel types – UO$_2$ and gas), which provide this gross receipt. In this time horizon we can study any period or a number of connected periods, for example, if it is necessary to account for different service lives of equipment for multi-fuel power plants.

3. Recommended rational number of given multi-unit NPP of model SUB depends on the price ratio of UO$_2$ and natural gas, which today in conventional fuel equivalents is $x_{n/g}^{cf} = 0.12 \div 0.15$ in Russia and reaches $0.03 \div 0.07$ for weighted average prices for gas sales abroad as substitutable export resource.

4. The higher these rates for peak electricity in comparison with the basic one, the more profitable the operation of these power plants becomes with other conditions being equal. The indicator $\eta_{t/ek}^{br}$ in these conditions is higher with the price of gas in Russia, than $p_{ex}^{g}$ – with its export price. Beneficial essence of this indicator lies in the possibility of the aggregated comparison of the profitability and choice (under lack of investment) of the power industry, where the expected effect is higher.

References
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