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Efficiency Assessment of Hydrogen Production Systems under Fatigue Wear Conditions

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Abstract. The article aims to assess the efficiency of hydrogen facility based on the night-time off-peak energy produced by the nuclear power plant (NPP) in comparison with the pumped storage power plant (PSPP) under conditions of fatigue wear of the master equipment. The relevance of hydrogen facility coupled to NPP units is evaluated. Evidenced is provided for the necessity of assessment and accounting of fatigue wear of the master equipment in the hydrogen facility. A new methodology for assessing the working resource of the master equipment has been worked out with account for the turbine rotor using of a condensation type turbine C-1000-60 / 1500 example under fatigue wear conditions. This methodology is used to determine the maximum number of cycles prior to fracture in the critical elements of the master equipment depending on the cyclic loads per day. A nomograph has been designed to estimate the prime cost of on-peak energy of the hydrogen system considering fatigue wear of the basic facility. Competitive advantages of the hydrogen complex and the PSPP is estimated based on the net present value criterion (NPV). It is shown that the hydrogen system can compete with the PSPP under its relative capital investments at about \$ 660 / kW. The PSPP versions under the relative capital investments over \$ 660 / kW lose their competitiveness compared to hydrogen complex.

1. Introduction

The Nuclear Energy Development Program in Russia stipulates conditions for a pronounced increase in the share of NPPs within the power systems in the European part of the country. According to the Energy Strategy of Russia until 2035 [1], development of the nuclear energy is the primary goal.

Using the PSPPs for load leveling at NPPs has been a common practice aimed to consume the off-peak and generate peak energy. However, PSPPs should be constructed in specific environmental conditions, and, as a rule, away from NPPs. This implies that their charging should be conducted through the power system. In this case, the night-time tariffs will noticeably exceed the prime cost of the NPP electricity that will significantly affect the cost of the generated peak PSPP power. In this regard, it is vital to develop competitive alternative technologies of energy storage.

Application of hydrogen energy systems can be one of these technologies. Among the advantages of this system is a possibility of electricity consumption directly from NPPs at a cost of slack off-peak hours during the night-time minimum electricity consumption with hydrogen and oxygen obtained by water electrolysis and accumulated in the storage system. At peak power load hours, hydrogen and oxygen are fed into the combustion chamber through the piston-type booster compressor station. The obtained water vapor is fed into the steam turbine cycle at increased kw



nominal in the power unit [2-13]. Thus, an NPP based on the hydrogen energy system will ensure the peak electrical demands.

Generation of peak electricity at an NPP due to coupling with the hydrogen energy complex can be effective using steam-hydrogen superheating of the main steam before the primary turbine (Fig.1a), as well as before the supplementary turbine through displacement of steam intended for reheating (Fig.1b) [2, 3].

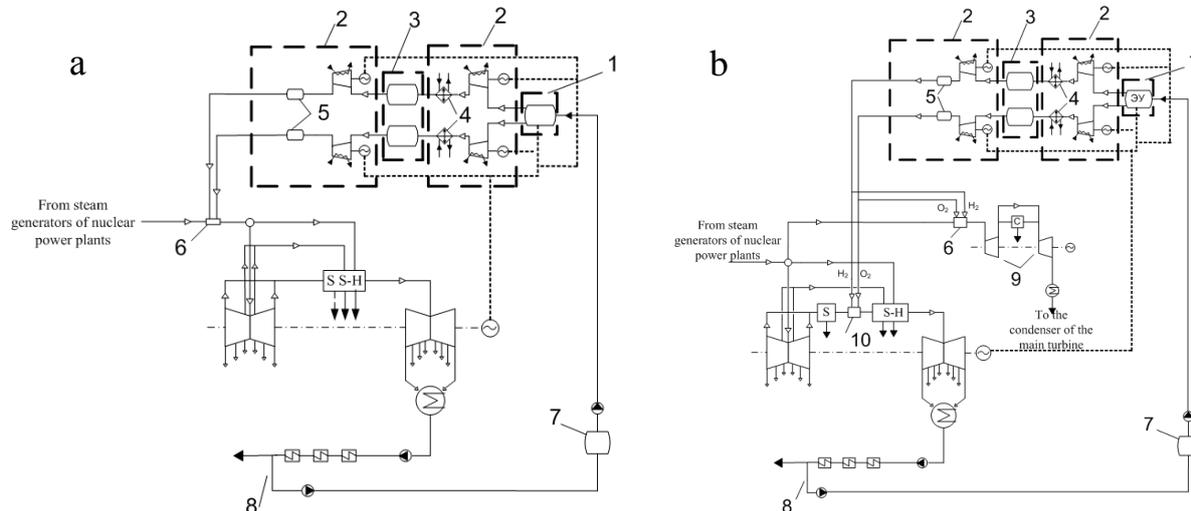


Figure 1. Schematic diagrams of an NPP combination with the hydrogen energy system: 1 - water electrolysis system; 2 – hydrogen and oxygen compression system; 3 - hydrogen and oxygen storage system using tanks; 4 - end cooling heat exchangers; 5 – transitional hydrogen and oxygen vessels; 6, 10 — hydrogen-oxygen combustion chamber for the main steam superheating and displacement of steam used for reheating, respectively; 7 – storage tank; 8 – added-in working fluid recirculation; 9 – supplementary steam turbine; a - steam-hydrogen superheating of live steam before the primary turbine; b - steam-hydrogen superheating of live steam before the primary and supplementary turbines

Specifics of the hydrogen complex coupled with a nuclear power unit aimed to ensure the baseload demand during off-peak night-time hours lies in the fact that under the given conditions you cannot avoid the cyclic start-ups or shutdowns of the hydrogen complex facilities under generation and accumulation of hydrogen and oxygen during off-peak hours and their combustion within the peak period.

Cyclic loading results in the growth of fatigue cracks [14-22]. Therefore, the master equipment of the hydrogen energy system, including electrolysis plants, metal vessels for hydrogen and oxygen storage, compressor units, hydrogen-oxygen combustion chambers for superheating the working fluid of the NPP steam - turbine cycle, as well as the rotor blades and disks of the steam turbine rotor are subjected to cyclic loading. Such loading is associated with the load rise and subsequent load relief due to time-diversity effect in generation and utilization of hydrogen and oxygen. This leads to the growth of fatigue cracks in the critical elements of the power - generating equipment, which results in the need for its retrofit. Registration of fatigue wear, when estimating efficiency of the atom-hydrogen energy complex, can be made based on the rate of depreciation costs underlying the structure of peak electricity costs. In this regard, our objective is to determine dependence of fatigue crack growth in time and related depreciation costs of the master equipment of the hydrogen complex on the number of cyclic loads.

2. A methodology for estimation the working resource based on a comprehensive generalized criterion

A model of a vessel with an internal pressure is used as the basis to estimate the endurance of the master equipment of the hydrogen complex [23]. The critical element for electrolyzers and hydrogen and oxygen storage tanks is the wall of the process vessel, which is stress-cycled by the internal pressure and temperature changes, whereas the wall of the power cylinder in the piston compressor is stress-cycled under internal pressure and temperature changes.

The schematic in Fig. 1a demonstrates the superheating procedure of fresh steam during the peak hours by mixing with the steam obtained through combustion of hydrogen in oxygen, initially conducted in a non-stoichiometric and further in a stoichiometric relation in line with the design model [8]. The part of the combustion chamber, where stoichiometric combustion occurs, is built in the main piping system before the turbine high- pressure cylinder (HPC). The fresh steam flows outside the chamber and is further superheated. This accounts for an internal and external pressure cycling, and the temperature changes in the wall of the afterburning part of the hydrogen-oxygen combustion chamber using the superheated steam, whereas the combustion chamber is continuously exposed to external pressure and temperature under the nominal operation condition of the power unit. Thus, the model of the vessel exposed to internal and external pressures is used as the basis to estimate the life of the afterburning part in the hydrogen- oxygen combustion chamber [24]. The wall of the afterburning part in the hydrogen-oxygen combustion chamber serves as a critical element.

A model of the flat body of the finite size with applied tensile stress and the tension model of massive detail, respectively [25], is used to estimate the resource cost of the working blades and disks of the turbine rotor as is the case with the C-1000-60 / 1500 type showed in Fig. 1a [23].

Based on the theory of fatigue failure [18-22], the author proposes a comprehensive generalized criterion to estimate the length of a fatigue crack, mm [14-17]

$$l = l_0 + v_0 f^{-\text{tg}\alpha} N \leq 0,1 \dots 1 \quad , \quad (1)$$

where l_0 is the underlying value of the fracture length, mm (taken as equal to 0,002 mm [19]); v_0 is the underlying value of the growth rate of the fatigue crack, mm/cycle; f is the frequency of the cyclic loading, Hz; $\text{tg}\alpha$ is the slope ratio of the logarithmic line to the abscissa axis that shows a decrease in the growth rate of the fatigue crack ($\lg v$) at an increase in the loading frequency ($\lg f$) under a non-variable value of the stress intensity range (ΔK) [18]; N is the limit number of cycles prior to fracture; 0,1-1 is the critical value of the length of a fatigue crack for materials with an ultimate resistance up to 1500 MPa.

The limit number of the cyclic loads (N) is determined by fitting of the conditions when the fatigue crack reaches the lower critical length boundary at 0,1 mm, as in equation (1).

The cyclic loading frequency is the ratio of the number of loading cycles to the time span of the loadings, and is measured in Hz:

$$f = \frac{n}{\Delta t}, \quad (2)$$

where n is the number of loading cycles; Δt is the cycling time span, sec.

In the equation (1), the product $v_0 f^{-\text{tg}\alpha}$ expresses the current calculation value of the fatigue crack growth rate at a given loading frequency, and is measured in mm / cycle [18].

In the general case, the value of the coefficient of tensions intensity is determined using the expression $\text{MPa}\sqrt{\text{m}}$ [18]:

$$K = \sigma \alpha \sqrt{\pi l}, \quad (3)$$

where σ is the loading cycle stress, MPa; α is a non-dimensional coefficient taking considering the geometric dimensions and stress distribution nature; l is the length of the fatigue crack, m.

The values of the non-dimensional coefficient α were taken based on the data [23].

The stress intensity range of the cycle is $\text{MPa}\sqrt{\text{m}}$ [18-23]:

$$\Delta K = K_{\max} - K_{\min}, \quad (4)$$

where K_{max} , K_{min} are the maximal and minimal values of the coefficient of tensions intensity $\text{MPa}\sqrt{\text{m}}$.

K_{max} and K_{min} are at the maximal and minimal values of the cycle stress (σ_{max} и σ_{min}).

It is obvious that the stress intensity constantly occurs under the tension difference in the structural elements of the facility, where the difference commonly results from the changes in the operating pressure and temperature.

As a result of an increase in the load intensity ΔK , the fatigue fracture rate grows from the threshold to the mean amplitude section, as is shown in the fatigue fracture diagram [18]. The rate of fatigue crack growth is characterized by high acceleration over a cycle, whereas the impact of the loading frequency on the possibility of crack closure reduces. At small ΔK , when the growth rate of fatigue fracture is located in the threshold area and is particularly small, the loading frequency can significantly affect its closure, i.e., an increase in the frequency can close the fracture, and, finally, slow down the fracture growth, or on the contrary, a decrease in the frequency can speed up its growth [18].

Thermal stresses within the walls of the process vessels and the elements of the turbine rotor will facilitate additional stresses. Thus, for the vessels under internal pressure, namely, for electrolyzers, working cylinders in reciprocating compressors, hydrogen and oxygen storage tanks, using as an example corrosion-resistant chromium-nickel alloy steel 13Cr19Ni9MoWNBtTi and 09M2S (for storage tanks), the maximum stress in the loading cycle was estimated according to equation (3) based on the expression, MPa:

$$\sigma = \sigma_{tens} + \sigma^t, \quad (5)$$

where σ_{tens} is the tensile stress, MPa; σ^t is the thermal stress, MPa.

The tensile stress intensity for the vessels electrolyzers and hydrogen and oxygen storage tanks, MPa [23]:

$$\sigma_{tens} = \frac{PR}{s},$$

where P is internal pressure, MPa; R is the radius of the process vessel, m; s is thickness of the process vessel walls, m.

Thermal stresses were determined for the interior and exterior surface of walls for the vessels electrolyzers and working cylinders in reciprocating compressors, according to the expressions, MPa [24]:

$$\sigma'_{int} = \frac{\alpha^t E^t (t_{wall}^{int} - t_{wall}^{ext})}{2(1-\mu)} \left(\frac{1}{\ln \beta} - \frac{2\beta^2}{\beta^2 - 1} \right), \quad (6)$$

$$\sigma'_{ext} = \frac{\alpha^t E^t (t_{wall}^{int} - t_{wall}^{ext})}{2(1-\mu)} \left(\frac{1}{\ln \beta} - \frac{2}{\beta^2 - 1} \right), \quad (7)$$

where α^t is the thermal expansion rate, $1 / \text{deg}$; β is the shell thickness rate; E^t is elasticity modulus, MPa; t_{wall}^{int} , t_{wall}^{ext} are the internal wall and external wall temperatures, respectively, °C; μ is Poisson's ratio.

In the calculations based on the equation (5), the maximum value for thermal stresses was used.

For hydrogen and oxygen storage tanks only tensile stresses were taken into account.

Regarding reciprocating compressors, the maximum operation pressure occurs on the interior walls of the working cylinders. For the power cylinder with a constant thickness, at the operating gas pressure acting along its length, the tensile stresses were determined using the expression, MPa [26]:

$$\sigma_{tens} = P_{max} \frac{r_{ext}^2 + r_{int}^2}{r_{ext}^2 - r_{int}^2}, \quad (8)$$

where r_{ext} , r_{int} are the outer and inner radii of the working cylinder, respectively, m; P_{max} is the maximum internal pressure, MPa.

For the walls of the working cylinders in reciprocating compressors, thermal stresses were determined in line with equations (6) and (7).

For the hydrogen-oxygen combustion chamber operating under internal and external pressure loads, the tensile and compression stresses were determined for the inner and outer of the wall considering the thermal stresses using the expressions, MPa [24]:

$$\sigma_{tens}^{int} = \frac{1,73P\beta^2}{(\beta^2 - 1)\varphi} + \sigma_{int}^t, \quad (9)$$

$$\sigma_{tens}^{ext} = \frac{1,73P}{(\beta^2 - 1)\varphi} + \sigma_{ext}^t, \quad (10)$$

$$\sigma_{comp}^{int} = \frac{2P_{ext}\beta^2}{(\beta^2 - 1)\varphi} - \sigma_{int}^t, \quad (11)$$

$$\sigma_{comp}^{ext} = \frac{2P_{ext}(\beta^2 + 1)}{(\beta^2 - 1)\varphi} - \sigma_{ext}^t, \quad (12)$$

where P_{ext} is external pressure, MPa; φ is the weld strength factor.

In the calculations based on the equation (3), the largest value was used for the compression stress over the interior wall.

Ultrahigh-temperature ceramics based on zirconium diboride and hafnium were considered as the material to be used for the hydrogen – oxygen combustion chamber [27, 28].

Estimation of the growth rate of fatigue fracture in the rotor blades and rotor disks of the steam turbine based on the example of a condensation type turbine of the C-1000-60 / 1500 was conducted using the Paris equation, mm / cycle [18-23]:

$$\nu = \frac{dl}{dN} = C(\Delta K)^n, \quad (13)$$

where C and n are the characteristics of the steel cyclic crack resistance.

To determine ΔK , the maximum mechanical and thermal stresses acting on the blades and disks in the cyclic mode and using steam-hydrogen superheating were defined under nominal conditions. This was aimed to determine the cyclic overloaded components of the turbine rotor. A detailed description of the procedure is provided in the following works [29-31]. Regarding the cyclic overloaded blades in the first stage of the HPC turbine rotor, in order to determine a non-dimensional coefficient α in the equation (3), a model of the flat body of finite dimensions with a newly formed crack length at 0.02 mm and applied tensile stresses was used [23].

The parameter ΔK is calculated based on the maximal and minimal stress rates over the turbine blades as a result of the difference in steam pressure at superheating and nominal mode. In this case, thermal stress is determined based on 3-d modeling using the Ansys software package at a superheated steam temperature ranging from 300 to 475 °C at the temperature increase rate of 60 °C / min. The nominal steam temperature is 275 °C.

For the most stress-cycled disks of the first stage of the HPC turbine rotor, the basis for defining the non-dimensional coefficient α in the equation (3) is the tension model of massive detail with a fatigue crack [25]. The ΔK parameter is calculated based on the maximal and minimal radial stress and tangential tension using the method described in [32]. In this case, thermal stresses are determined with account for a uneven heating of the disk body in line with the methodology [32].

Parameters C and n in the Paris equation were taken for the blades based on the data [33] and the of the 13Cr11Ni2W2MoV heat-resistant steel, for the disks based on the data [34] using the EP741NP (CrNi51CoWDTiANb) heat-resistant nickel alloy as an example of cyclic crack resistance.

For the critical element of the turbine rotor were used the working blades of the first stage of the HPC rotor as most susceptible to cyclic wear. The details of the calculation procedure for the minimal number of loading cycles over the blades and disks of all the stages of the HPC rotor and low-pressure cylinder (LPC) of the C-1000-60 / 1500 turbine are provided in [31].

Estimation of the operation life-time is made based on the time span of fatigue crack growth up to the lower boundary of the critical length equal to 0.1 mm, years:

$$\tau_{0,1} = \frac{N}{N_{p.a.}}, \quad (14)$$

where $N_{p.a.}$ is the annual number of loading cycles, c / year.

Then the annual number of loading cycles will be, c / year:

$$N_{p.a.} = n_{per_day} n_c, \quad (15)$$

where n_{per_day} is the annual number of working days of a combined atomic-hydrogen power unit, days / year; n_c is the number of loading cycles per day, c / day.

Depreciation costs under the cyclic loading will be, rubles / year:

$$Exp_{depr}^{cycl} = \alpha_{depr}^{cycl} K, \quad (16)$$

where α_{depr}^{cycl} is the depreciation coefficient considering the cyclic operation conditions; K is the investments into facilities of the hydrogen complex, or components of the turbine rotor, rub.

The depreciation coefficient of the master equipment of the hydrogen complex, with account for the cyclic operation conditions will be:

$$\alpha_{depr}^{cycl} = \frac{1}{\tau_{0,1}}. \quad (17)$$

3. Estimation of peak electricity costs for the hydrogen facility with account for fatigue wear rate

As an example of the cyclic loading model, Fig. 2 presents the cyclic loading diagram for the master equipment of the hydrogen complex. The timeframe (Δt) for application of the master equipment is conditioned and is given as an example. The number of loading cycles is considered based on the example from 1 to 6 per day. Meanwhile, inter-configuration of the load schedules is built with account for the total charging time period will be considered based on the example of 7 hours / day, and the total discharge time span will be considered based on the example of 5 hours / day. Accordingly, with an increase in the number of cycles per day, the life of a single cycle decreases, as well as the time span between the cycles. By the operation time span of the cycles (Δt), we should understand a certain period of time with a certain number of loading cycles occurring according to equation (2). In Fig. 2, the operation period of electrolyzers corresponds to the charging period of the hydrogen and oxygen storage tanks, while the period of discharge of the tanks corresponds to the operating period of the hydrogen-oxygen combustion chamber used for overheating fresh steam. At the same time, giving a start to the operation of corresponding piston-type compressor units during the charging and discharging periods is taken into consideration according to figure 1.

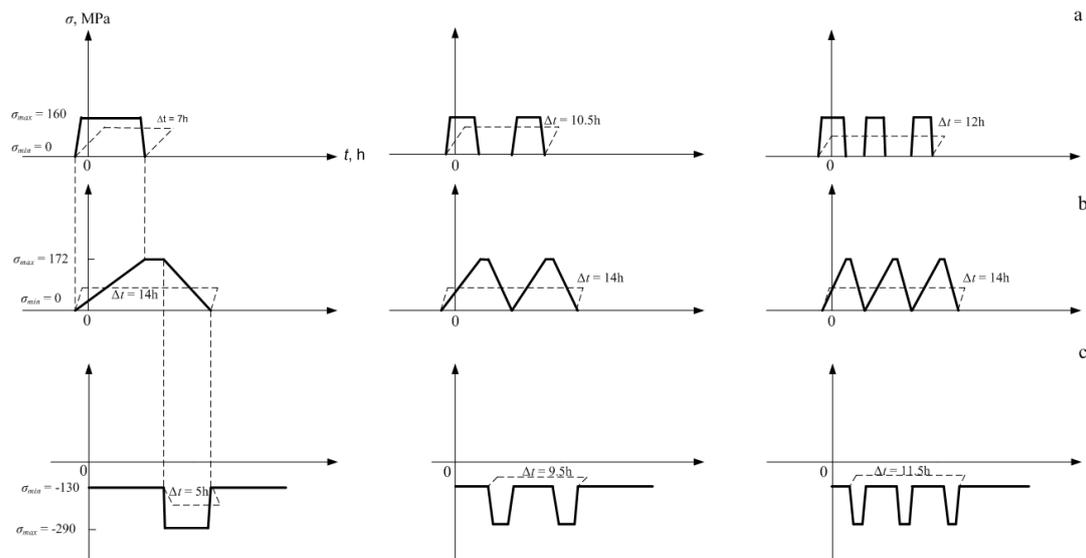


Figure 2. Model of cyclic loading of the hydrogen facility basic equipment: a - electrolyzer; b - container for hydrogen and oxygen storage; c - hydrogen-oxygen combustion chamber

Based on the theory of fatigue failure using the generalized comprehensive criterion to estimate the limit number of cycles up to the destruction of the critical elements according to equation (1), and using the developed methodology for estimating the working resource, Figure 3 presents a comprehensive nomograph which demonstrates the time span of fatigue crack growth up to the critical length, the corresponding depreciation costs, and the final changes in the peak electricity cost of the hydrogen complex depending on the number of loading cycles per day in the master equipment. Additionally, the depreciation costs for the blades of the first stage of the HPC rotor are estimated at 13.1-120.8 million rubles / year under the steam superheat temperature at 300-475 °C, respectively, that facilitates a reduction in the limit number of cycles prior to the failure with 55000 till 6000 respectively. Steam superheating before HPC rotor in options 1-4 is 300 °C at a fatigue crack growth rate in the blades of the first stage of the HPC rotor $1,059 \cdot 10^{-6}$ mm / cycle; in options 5-8 - 325 °C and $3.432 \cdot 10^{-6}$; in variants 9-12 - 375 °C and $1.517 \cdot 10^{-5}$; in variants 13-16 - 475 °C and $1.492 \cdot 10^{-4}$.

During development of the nomograph using the calculations made to determine the stress intensity factor and the fatigue fracture diagram [18-23], it was found that for the basic facility of the hydrogen complex the stress intensity coefficient is within the threshold of fatigue crack development. This means that the accepted values of the basic rate of fatigue crack growth in the equation (1) (v_0) correspond to the conditions of the new facility with the basic fatigue crack length of the order of 0.002 mm for electrolyzers, compressors, tanks, and hydrogen-oxygen combustion chambers, and 0.02 mm for the HPC rotor blades.

When estimating electricity costs for the hydrogen complex, the operating costs for electrolysis, compression, hydrogen and oxygen storage in underground cylindrical tanks [35, 36], the hydrogen-oxygen combustion chamber, including the operating personnel payments were taken into account. Particularly regarding the electrolysis procedure, the cost of consumed NPP electricity was taken into account. The cost was at the level of 1.05 rubles / kWh at anticipated prices for the nuclear fuel according to forecasts of the International Energy Agency and the Institute for Energy Research RAS for the term up to 2035 [6, 37]. Efficiency of electrolysis plants is accepted at the level of 80%, and specific energy consumption considering the intermittent operation conditions at 39.77 kWh / kg H₂, compared to the continuous operation conditions at 41.66 kWh / kg [2]. It should be noted that at present electrolyzers with solid polymer electrolytes produced in Italy are characterized by specific electric energy consumption of 3.5-4 kWh / m H₂ (38.9-44.4 kWh / kg H₂). Additionally, account is taken of the costs for the chemically purified water, nitrogen purging, as well as depreciation and repair costs. Specific investments into the NPP units are taken at \$ 2,500 / kW [37, 38].

As for compression, the costs of consumed electricity, lubricating oil, cooling water, depreciation and repair are taken into account. Regarding the hydrogen and oxygen storage, depreciation and repair costs of the cylindrical metal tanks are taken into account, as well as the costs the underground working, concrete embedding and waterproofing [35, 36]. Depreciation costs related with the hydrogen-oxygen combustion chamber are also considered.

Specific investments in electrolysis plants with the capacity of 50 MW amounted to around 400 thousand rubles / kg H₂ / h at the efficiency rate of 1180 kg H₂ / h, and with account for automatic equipment and closed area facilities. This value is obtained based on the generalized unit cost of electrolysis plants produced in Russia or the US [39].

The relative capital investment into the piston-type hydrogen- oxygen compressor systems are made using the data of OOO Compressor Plant (Krasnodar city) and amount to about 3,650–3,200 rubles / kW with the compressor efficiency at 2600–3400 kW, respectively.

The relative capital investment into the metal storage tanks with the volume of 800 m³, considering their underground location at the depth of 100 m and the costs for the underground working, concrete embedding and waterproofing, and accumulation pressure of 4 MPa, amounts to 18,750 rubles / m³ [35, 36].

Estimation of the provided relative capital investments into the hydrogen-oxygen combustion chamber depending on its power output, is made using the expression, rubles / kW (heat.):

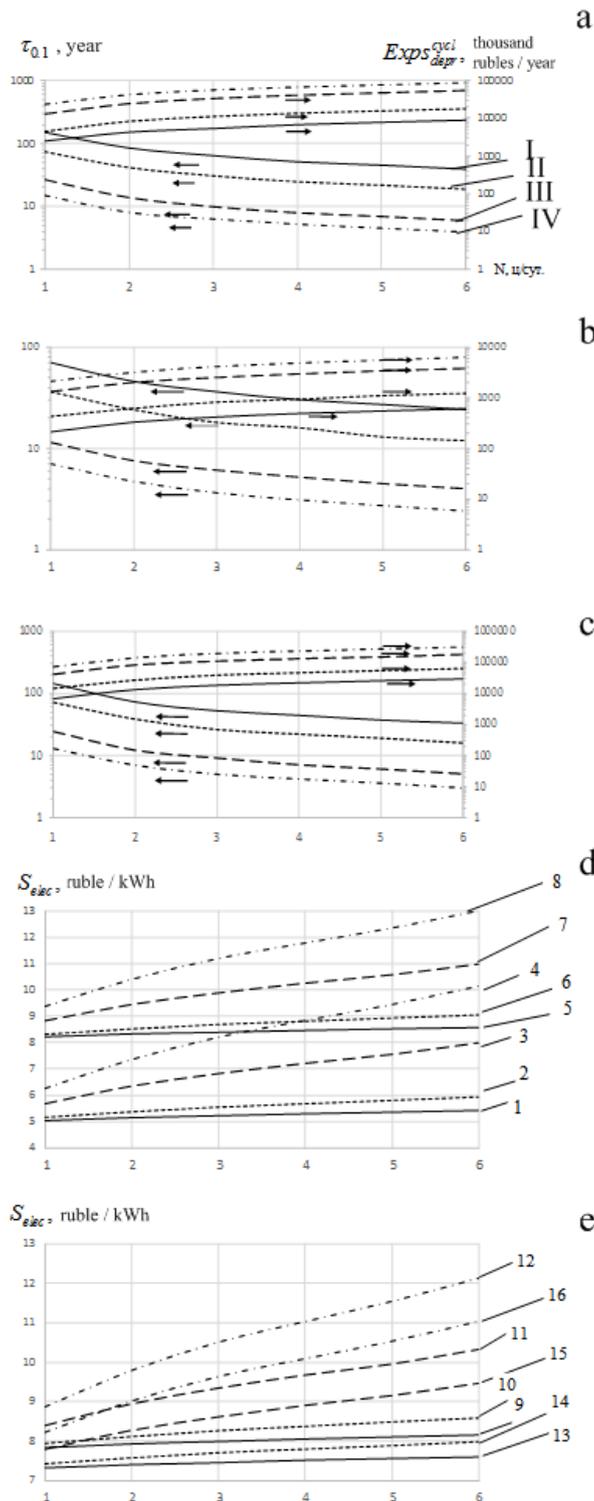


Figure 3. A nomograph used to determine electricity costs of the hydrogen complex under a tight cyclic operation conditions: a - electrolyzer; b - metal hydrogen (oxygen) storage tank; c - hydrogen-oxygen combustion chamber; d, e - peak electricity cost; I - base value for the fatigue crack growth rate for hydrogen facility basic equipment $v_0=5 \cdot 10^{-8}$ mm/cycle; II - $v_0=1 \cdot 10^{-7}$ mm/cycle; III - $v_0=3 \cdot 10^{-7}$ mm/cycle; IV - $v_0=5 \cdot 10^{-7}$ mm/cycle; 1-4 – at the off-peak failing power needed for hydrogen and oxygen generation at 175 MW; 5-8 - 310 MW; 9-12 - 570 MW; 13-16 - 1000 MW

$$k = k_{base} \left(\frac{Q_{base}}{Q} \right)^{1-b}, \quad (18)$$

where k_{base} is the underlying value of the relative investments into the hydrogen-oxygen combustion chamber, rubles / kW; Q_{base} is the underlying value of thermal capacity of the hydrogen-oxygen combustion chamber, kW; Q is the set value of thermal capacity of the hydrogen-oxygen combustion chamber, kW; b is the approximation rate (taken as equal to 0.8).

The underlying value of the relative capital investment into the hydrogen-oxygen combustion chamber is taken as 20% of the relative investments into the GTE-110, and amounted to around 6960 rubles / kW. The underlying value of thermal efficiency of the hydrogen-oxygen combustion chamber is 20 MW.

Fig. 3 shows that an increasing the number of loading cycles per day results in accelerated fatigue of materials used for the critical elements in the of the basic hydrogen complex facility, which significantly reduces the timeframe of fatigue crack growth up to the critical value, and, moreover, leads to an increase in depreciation costs and corresponding increase of peak electricity costs. It should be noted that in providing an NPP with the baseload, the start-up of the hydrogen system facility can be ensures mainly at night-time slack off-peak hours of electric load, i.e., primarily, one starting procedure per day. The cost of peak electricity depends on the cost of upgrading the steam turbine facility in the cases of fresh steam superheating over 300 ° C.

4. Estimation of net present value for the hydrogen facility with account for fatigue wear rate

For the comparison standard of the hydrogen complex and PSPP we take the net present value (NPV) at the similar amount and tariffs for the supplied electricity. The annual number of power generating cycles (days) is 335 related to the hydrogen energy complex and the NPP unit, taking into account the scheduled annual outages (30 days) for repair. Duration of the night-time off-peak failure period for generation of hydrogen and oxygen by water electrolysis is taken as 7 hours / day. Duration of participation period in covering peaks loads is considered based on the example of 5 hours / day. The calculation horizon is 25 years. The construction period for the hydrogen complex and PSPP is 4 and 6 years. The discount rate is 10%. The Income tax is 20%.

The necessary operation costs were estimated with account for the variants under comparison. Regarding the PSPP, electricity costs were estimated with regard for the charges from the power-supply system at strategic electricity costs up to 2035 made in accordance with the predictive extrapolation equation [6]. Based on the global review of the PSPP projects, the calculations are made with reference for the investments ranging around 660-1500-2000 dollars / kW (39.6 - 90 - 120 thousand rubles / kW at the dollar exchange rate of 60 rubles) [6].

Since the PSPP is characterized for high beneficial accumulation efficiency, in order to bring the variants to the similar rate of peak electricity supply, the variant with the hydrogen complex was estimated with reference to costs for replaceable peak-load gas turbine (based on the example of GTE-110 (gas turbine electric power unit) under moderate tariffs for gas fuel according to [6]. Thus, the compared variants are brought in line with the similar electricity consumption at off-peak hours.

Figure 4 presents the results of calculating the net present value (NPV) of the hydrogen complex and PSPP depending on peak power generation ($Elec_{peak}$). The construction period is 4 years for options for generating peak electricity of 875 and 1550 MWh / per day and 6 years for options for generating peak electricity of 2850 and 5000 MWh / per day.

Fig. 4 demonstrates that the PSPP efficiency is significantly impacted by the rate of relative capital investments, as well as by the cost of electricity demanded under the charging mode, Effectiveness of the hydrogen complex is highly influenced by the fatigue wear of basic facility, including the operation blades of the first stage of the HPC rotor. It is obvious that competitive

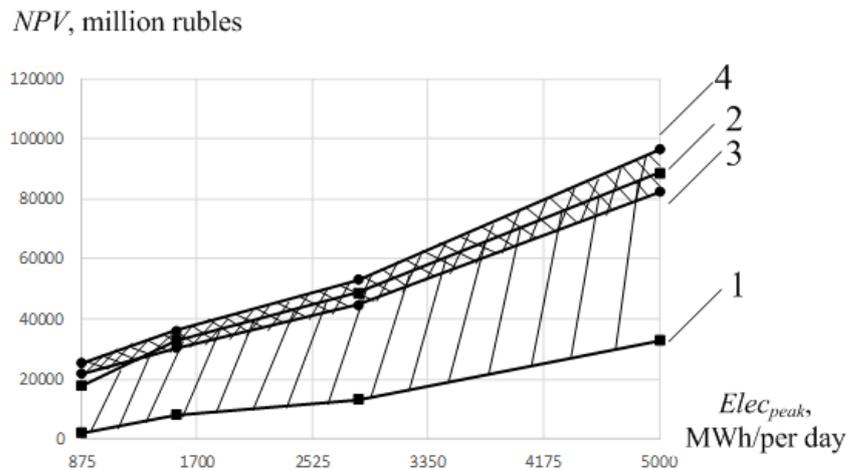


Figure 4. Results of the NPV calculation for the hydrogen complex and PSPP: 1,2 - PSPP at relative capital investment of 2500 and 660 dollars / kW, respectively; 3, 4 – the hydrogen complex at $v_0 = 5 \cdot 10^{-7}$ mm / cycle, $N = 6$ c / day, and $v_0 = 5 \cdot 10^{-8}$ mm / cycle, $N = 1$ c / day, respectively

advantages of the hydrogen complex depends on intensity in the usage of basic facility and susceptibility of materials to the cyclic fractures under the influence of various operating pressures and temperatures. As the estimates show, the hydrogen complex can well compete with the PSPP at its relating capital investments about \$ 660 / kW under the threshold value of the rate of fatigue crack growth for hydrogen facility basic equipment no more than $3 \cdot 10^{-7}$ mm / cycle, and the number of loading cycles per day no more than 6, at a steam superheat temperature before HPC rotor of 300-475 °C, which corresponds to the growth rate of the fatigue crack in the blades of the first stage of the HPC rotor $1.059 \cdot 10^{-6} - 1.492 \cdot 10^{-4}$ mm / cycle, respectively. The PSPP variants at the relative capital investments over 660 dollars / kW cannot compete with the hydrogen complex.

5. Conclusions

1. Using the theory of fatigue fracture, a new methodology has been developed to system estimate of the working resource and depreciation coefficient of the master equipment of the hydrogen complex, including the turbine rotor on the example of a condensation type C-1000-60 / 1500 under stress-cyclic operation conditions.

2. A novel comprehensive nomograph has been designed to estimate the timeframe of fatigue crack growth up to the critical length, depreciation costs, and peak electricity costs, depending on the number of cyclic loads in the basic facility of the hydrogen complex per day.

3. The NPV for the hydrogen complex is estimated based on the impact of fatigue wear in comparison with the PSPP. It is shown that competitiveness of the hydrogen complex depends on intensity of the basic facility performance and resistance of the applied materials to cyclic fracture. Compared to the PSPP, the hydrogen complex is characterized for competitive advantages under the relative capital investments about \$ 660 / kW and under the threshold value of the rate of fatigue crack growth for hydrogen facility basic equipment no more than $3 \cdot 10^{-7}$ mm / cycle, and the number of loading cycles per day no more than 6. Herewith depreciation costs are estimated at 13.1-120.8 million rubles / year under the steam superheat temperature at 300-475 ° C, respectively for the blades of the first stage of the HPC rotor on the example of a condensation type turbine of the C-1000-60 / 1500. The PSPP variants at the relative capital investments over 660 dollars / kW lose their competitive characteristics compared with the hydrogen complex.

References

- [1] Ministry of Energy of the Russian Federation 2014 *Strategy Energy of Russia on Period Till 2035 year* p 263
- [2] Aminov R Z and Bairamov A N 2016 *Combination of Hydrogen Energy Cycles With Nuclear Power Plants* (Moscow: Science) p 254
- [3] Aminov R Z, Yurin V E and Egorov A N 2018 *Combining NPPs With Multifunctional Power Plants* (Moscow: Science) p 238
- [4] Aminov R Z and Bairamov A N 2017 Performance evaluation of hydrogen production based on off-peak electric energy of the nuclear power plant *Int. J. of Hydrogen Energy* **42** pp 21617-25
- [5] Aminov R Z, Bairamov A N and Shatskova O V 2009 Assessment of the Efficiency of Hydrogen Cycles on the Basis of Off-Peak Electric Energy Produced at a Nuclear Power Station *Thermal Engineering* **54** pp 940-5
- [6] Aminov R Z, Bairamov A N and Garievskii M V 2019 Assessment of the Performance of a Nuclear–Hydrogen Power Generation System *Thermal Engineering* **66** pp 196-209
- [7] Aminov R Z, Schastlivtsev A I and Bairamov A N 2017 On the issue of investigating the kinetics of processes in dissociated water steam *Int. J. of Hydrogen Energy* **42** pp 20843-48.
- [8] Aminov R Z and Bairamov A N 2011 *System of Burning of Hydrogen for Steam-Hydrogen Overheat of Fresh Steam in Cycle of Atomic Power Plant* Patent RU № 2427048
- [9] Aminov R Z and Bairamov A N 2016 Hydrogen Production Competitive Efficiency Estimate by Method of Water Electrolysis on Basis Off-peak Electricity *News of the Russian Academy of Sciences. Power Engineering* **4** pp 84-90
- [10] Aminov R Z and Bairamov A N 2014 Systems problems investigate of atomic power engineering and some ways of their solution *Proc. of Int. Scient. Conf. "National Congress by PowerEngineering"* **1** (Kazan: Kazan State Technical University) pp 12-23
- [11] Aminov R Z and Egorov A N 2011 Methodology for assessing the thermodynamic efficiency of additional heat supply in wet-steam cycles of nuclear power plants *The news of higher education institutions. Problems of power engineering* **11** pp 20-29
- [12] Shpilrain E E, Sarumov U A and Popel O S 1982 Hydrogen using in power engineering and in energytechnological complexes *Atomic-hydrogen power engineering and technology* **4** pp 5-22
- [13] Malyshenko S P, Nazarova O V and Sarumov U A 1986 Hydrogen using as energy carrier in power engineering some thermodynamic and technical-economy aspects about this *Atomic-hydrogen power engineering and technology* **7** pp 105-126
- [14] Bairamov A N 2017 System analysis of the stress-cyclic mode of operation of the main equipment of the hydrogen energy complex in combination with nuclear power plants *Atomic-hydrogen power engineering and technology* **7** pp 105-126
- [15] Bairamov A.N 2019 Life cycle assessment of hydrogen energy facility by criterion for maximum load frequency *Int. J. of Hydrogen Energy* **44** pp 5696-5703
- [16] Aminov R Z and Bairamov A N 2018 Participation efficiency of the NPP with the hydrogen production facility in primary frequency regulation of the power system *Journal of Physics: Conference Series* **1111** 012023
- [17] Aminov R Z, Bairamov A N and Garievskii M V 2020 Estimating the system efficiency of the multifunctional hydrogen complex at nuclear power plants *Int. J. of Hydrogen Energy*. **45** pp 14614-24
- [18] 1990 *Mechanics of Destruction and Strength of Materials* vol 4 ed Panasyuk V V (Kiev: Naukova Dumka) p 680
- [19] 2010 *Machine-Building: Encyclopedia on Machine-Building* vol II-1, ed Frolov K V et al (Moscow: Machine-Building) p 852
- [20] Kogaev V P, Mahutov A P and Gusenkov A P 1985 *The Calculations Detail of Machines and Constructions on Strength and Long-Lived* (Moscow: Machine-Building) p 223
- [21] Pavlov P A 1988 *The Foundations of Engineering's Calculations of Elements Machines on Fatigue and Long-Lived Strength* (Leningrad: Machine-Building) p 252

- [22] Troshchenko V T 1987 *The Stability to Crack of Metals at Cycles Loads* ed Lapteva N Z et al (Kiev: Naukova Dymka) p 256
- [23] Cherepanov G P 1974 *The Mechanics of Frail Destructions* ed Safray V M et al (Moscow: Science) p 640
- [24] Lashchinsky A A and Tolchinsky A R 1970 *Fundamentals of Design and Calculation of Chemical Equipment* ed Loginov N N (Leningrad: Mechanical Engineering) p 752
- [25] Kostyuk A G 2007 *Dynamics and Strength of Turbomachines* vol 3 (Moscow: Publishing House MPEI) p 476
- [26] Frenkel M I 1969 *Piston Compressors* vol 3 (Leningrad: Mechanical Engineering) p 747
- [27] Portnova E N 2016 *Obtaining Ultra-High-Temperature Ceramic Materials Based on Zirconium and Hafnium Diborides* dis. for the degree of cand. tech. sciences (Permian) p 137
- [28] Bairamov A N 2019 *Hydrogen Combustion System for Steam Overheating of Fresh Steam in a Cycle of a Nuclear Power Plant With a Swirling Flow of Components and Using Ultra-High-Temperature Ceramic Materials* Patent RU № 2709237
- [29] Bairamov A N 2017 Evaluation of the operating resource of the most loaded rotor element of the additional steam turbine with steam-hydrogen *Journal of Physics: Conference Series* **891** 012252
- [30] Aminov R Z, Bairamov A N and Moskalenko A B 2020 Estimation of resource capabilities of the NPP turbine unit under the primary frequency control of the current in the power system *Journal of Physics: Materials Science and Engineering* **791** 012004
- [31] 2019 *Scientific Basis Development for the Construction of Hydrogen Cycles in Integration With Wet- Steam Nuclear Power Plants* research report (Saratov) p 70
- [32] Zhiritsky G S and Strunkin V A 1968 *The Construction and Calculations on Strength of Details Steams and Gas Turbines* (Moscow: Machine-Building) p 523
- [33] Gorbovets M A and Nochovnaya N A 2016 Paris equation parameters when testing the fatigue crack growth rate of heat-resistant titanium alloys *Proceedings of the All-Russian Scientific Research Institute of Aviation Materials* **4** pp 13-19
- [34] Golubovsky E R, Volkov M E and Emmausky N M 2013 Estimation of the rate of development of a fatigue crack in nickel alloys for gas turbine engine disks *Engine Bulletin* **2** pp 229-235
- [35] Bairamov A N 2012 Metal containers development and justification for storing hydrogen and oxygen at underground arrangement as part of the hydrogen energy complex *Problems of improving the fuel and energy complex: collection of scientific papers* vol 7 (Saratov: Saratov State University) pp 18–27
- [36] Bairamov A N 2014 Technical and economic aspects of underground placement of metal storage tanks for hydrogen and oxygen as part of the hydrogen energy complex *Proceedings of academicenergo* **2** pp 79-86
- [37] Aminov R Z, Shkret A F and Garievsky M V 2017 Thermal and nuclear power plants: competitiveness in the new economic conditions *Heat power engineering* 2017 **5** pp 5–15
- [38] Veselov F V, Makarov A A, Makarova A S, Novikova T V and Pankrushina T G 2017 Strategic prospects of the electric power industry in Russia *Heat power engineering* pp 40-52
- [39] Marchenko O V and Solomin S V 2007 Hydrogen production analysis of the efficiency using wind power plants and its use in an autonomous energy system *Int. Scient. J. of Altern. Energy and Ecology* 2007 pp 112–118