On the effectiveness of some construction and technological solutions for Nuclear Power Plants

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Abstract. The construction of nuclear power plants (NPPs) involves huge amounts of concrete and reinforced concrete works. In the design of the reactor building of modern large unit is placed more than 200 thous. m³ of concrete. The content of metal in the form of rebar, facing, embedded items in many of the elements exceeds 400 kg/m³ of concrete. The reinforced concrete works in the reactor building to a large extent determine the longer duration of construction and, as a consequence, the resulting costs. Such works are performed with traditional technology – piece reinforcement with the use of relatively small meshes, grating, large and small panel prefabricated formwork, and with industrial methods as well. During industrial approach, which reduces the duration of construction, the reinforcement is performed with the large reinforcing or reinforcing-formwork blocks. However, in this case the duration of the preparatory period will double and there will be additional cost items. Large erection blocks include the extra metal for creation of the necessary transport and erection stiffness; and also provide well-equipped workshops for the manufacturing of blocks. In addition, special vehicles and cranes with high lifting characteristics are required. One of the most important structures of NPPs is the foundation slab of the reactor building. The slab area is 5-6 thousand m², thickness of 2.5 -3 m, duration of erection – up to 1 year. In this work was made an attempt to assess the comparative effectiveness of two common construction and technological solutions for the foundation slab – the traditional one, when performing reinforcing works with piece rods, and the industrial one, when reinforcing with blocks. The cost, labor content and duration of construction are determined depending on structure and construction technology. The boundaries of industrial technology were marked.

1. Introduction

As it is known, the construction of nuclear power plants (NPPs) involves huge volumes of general construction and, in particular, concrete and reinforced concrete works. In the design of constructing Kursk-2 NPP with reactors with a capacity of 1255 MW (el.) will be laid over 800 thous. m³ of concrete, including almost 250 thous. m³ into the reactor’ buildings. The content of metal in the form of rebar, facing, embedded items in many reactor building structures exceeds 400 kg per m³ of concrete.
It is the reactor building concrete works determine to a large extent the overall duration of construction and, as a consequence, the resulting costs. Such works are performed on a traditional technology – piece reinforcement with the use of relatively small meshes, grating, large and small panel prefabricated formwork, and with industrial methods as well. During industrial approach the reinforcement is performed with the large reinforcing or reinforcing-formwork blocks. In the latter, during the manufacturing in the blocks content is already added permanent formwork, including made of steel sheet. There are solutions, when the sheet performs the functions of reinforcement rod, and sometimes completely replaces it. Modern local designs offer to use for many structures the fibrous concrete slabs as permanent formwork.

A typical example of the extensive industrialization of construction is a unified project of NPP with VVER-1000 reactors, implemented on dozens of platforms. The last such unit is put into operation at the Rostov NPP. Almost all of the protective walls and floor slabs beyond the protective sheath are constructed in precast- and in-situ concrete structures, and within its limits - with using steel sheet as working reinforcement and permanent formwork. Record time of construction of a number of power units, particularly of the units No 3, 4 at the Zaporizhia NPP, was connected with the industrial structures.

Today, the actual time of construction of NPPs on the most sites significantly exceeds the scheduled date. Inter alia, it is connected with large volumes and complex geometries of many structures, high unit labor costs on their construction, the lack of industrialization. Industrial technologies reduce the labor costs on the object and, consequently, reduce the construction period. Along with that, the duration of the preparatory period is increasing, and the additional cost items are occurring. In the content of large mounting blocks shall be added additional metal to create the necessary transport and erection stiffness, also it is necessary to provide a well-equipped workshop for the manufacturing of blocks. Usually the special vehicles and cranes with high lifting characteristics are required.

Dozens of works are dedicated to the effectiveness of industrialization in the construction of NPPs, to the choosing of the optimal sizing for the mounting block, to the degree of pre-mounting enlargement. Among the latest could be highlighted [1, 2], but they all were dedicated to the above-ground structures – protective walls and floor slabs, shells and did not affect the foundation part.

In this article is made an attempt to assess the effectiveness of the constructive-technological solution for the foundation slab of the reactor building, as proposed in one of the modern projects, in which the reinforcement works are performed using large reinforcement blocks. It can be noted, that the works on the slab lie on the critical path of the network schedule and along with several other works determine the total duration of the construction. It is interesting, that in all NPPs the slab reinforcement was performed in the single-piece rebar, the reinforcement blocks hardly were used.

In this work are only taken the reinforcement works, that to the greatest extent, in comparison with the rest, determine the duration of the slab construction. The works on the construction joints, construction / dismantling of formwork, concreting and care for concrete are not taken into account.

2. Methodology and calculations
Reinforced concrete foundation slab of the reactor building is one of the most critical structures of the NPP. It is featured with large thickness, large size on plan, high degree of reinforcement. For constructed NPPs the duration of works on the foundation slab with the volume of the concrete of 12 to 17 thous. m³, the consumption of rebar up to 110-120 kg/m³ was at least 4-6 months. Reinforcement was performed, as noted above, in the single-piece rebar according to the traditional technology. In the project of Kursk NPP is proposed to perform the reinforcement works with reinforcement blocks with the aim of reducing construction time, that had already taken place at a number of NPPs during the construction of walls, floor slabs, protective shells.

In this work is taken a rectangular plate 80 x 80 m with width - 2.6 m. Concrete volume was 16640 m³. Main reinforcement of the slab, top and bottom in two mutually perpendicular directions, class A-600 with a diameter of 36 mm, with a spacing of 200 mm. Specific consumption of the main
reinforcement - 80 kg/m³. In addition to the main reinforcement in the slab is provided the structural reinforcement of class A-500 with a diameter of 16 mm in the amount of 27 kg/m³. Reinforcement is performed with reinforcement carpets up to 6.2 x 11.5 m and spatial reinforcement blocks with dimensions up to 21.9 x 6.2 x 2.42 m and weight up to 38 t. Main reinforcement is located on the long side of the carpets and reinforcement blocks. The bottom carpets are stacked on the base of the slab, on them - reinforcement blocks, on the reinforcement blocks are rolled out the top carpets. The long sides of the carpet and reinforcement blocks are mutually perpendicular. Carpets are joined together by couplings, the main reinforcement of reinforcement blocks connects on the couplings via the reinforcing bars. The distance between the individual blocks on the long side is 1 meter, on the short side is 200 mm (Figure 1, Figure 2, Figure 3).

Reinforcement blocks are made in the workshop on the on-site construction base. Assembly of reinforcement blocks is made on a special stand. On the long side of reinforcement blocks are installed flat welded frames made of main and structural reinforcement. In the transverse direction for the connection of the frames are installed single reinforcing bars on welding and performed horizontal and vertical braces of stiffness with rods of class A240 with a diameter of 16.

![Figure 1. Laying scheme of the foundation slab bottom reinforcing carpets](image-url)
Figure 2. Structure of the foundation slab reinforcement slab model

Figure 3. Stacking scheme of reinforcement blocks
The total mass of rebar in the slab – 1845 tons, including the mass of the main reinforcement – 1331 tons, structural – 449 tons and additional to ensure transport and erection stiffness of the blocks – 65 tons.

During the erection of the foundation slab with traditional method the main and structural reinforcement volume is accepted invariant according to the taken project. Connection of rods on the couplings. As supportive elements for the layout of the rods of the top main and intermediate reinforcement are used rolled sections – racks and beams. Specific consumption of metal structures of racks and beams - 7.5 kg/m³ of the slab volume, and is adopted for the project Novovoronezh-2 NPP, where the slab is erected in single-piece reinforcement (Figure 4).

![Figure 4. Arrangement of the foundation plate of the Novovoronezh-2 NPP](image)

Metal structures are installed over the entire area of the slab and on the entire height of the reinforcement. At the fixing elements are placed the bars of the bottom mesh of rebar, on supporting steel structures are placed structural and the top main reinforcement.

The evaluation is based on data that can be divided into two groups. The first group includes the actual data obtained in the course of construction of Novovoronezh-2 NPP and Belarusian NPP. The second group - normative data, which is in good compliance with the actual parameters. Total labor costs are calculated by the summation of major components, each of which was determined as the product of specific labor costs for the relevant work scopes.

For evaluation of the industrial technology the specific parameters for work in the workshop of the construction base and at the construction site are taken on the basis of the data on NPPs, built in recent years and constructing according to the local projects.

In the traditional method of construction the specific labor costs on the preparation of the metal structures in the workshops of the construction and erection base are adopted according to the regulatory documents [3], for the preparation of reinforcement - according to the data of the metal structures workshop of Novovoronezh-2 NPP. On the construction site the specific labor costs on
installation of metal structures are taken on the works production plan of Novovoronezh-2 NPP, on laying of the main reinforcement on a coupling connection, as well as the structural one in overlap are taken on the works production plan of Belarusian NPP.

To estimate the cost of work and materials involved in the operation of machines and mechanisms, wages, overhead and profit estimate are used actual data, Federal and industry estimates standards, methodological document in construction, the data of the Federal state statistics service [4-10]. The cost of works in both options is calculated by resource-index method in the basic prices and recalculated in prices for the 1st quarter of 2017. 

The declared duration of the construction of the foundation slab with industrial method is 50 days. According to expert estimates, the reinforcement works take 70% of the time, or 35 days. For transportation and installation of the reinforcement blocks and carpets at the construction site are involved a trailer truck with a tractor unit, a side car and two crawler crane with capacity of 100 tons. Works on the site are performed in 2 shifts, the specific labor costs for erection and reinforcement works are taken on the works production plan of Belarusian NPP, where the erection of the outer shell was carried out by reinforcement blocks weighing up to 38 tons at the coupling connection.

Duration of reinforcement works according to the traditional technology was calculated on the basis of the industrial duration - 35 days, with adjustment for ratio value of labor costs at the construction site on specified technologies. It was assumed that duration is linearly related to the labor costs. The duration was 55 days. Transport is adopted according to the project of Novovoronezh-2 NPP. Workpieces of rods of the main reinforcement are delivered to the site by the side vehicle. On the site the work is performed by cranes with lifting capacity of 25 tons and crawler cranes - 63 tons.

3. Results
Below are specified the results of the calculations, including, graphical form for clarity (Figure 5, Figure 6).

Total labor costs in the industrial method of construction – 125605 per-hrs, including (specific/total):
- manufacturing of blocks – 87.7 per-hrs/t / 108695 per-hrs;
- manufacturing of carpets – 16.1 per-hrs/t / 8220 per-hrs;
- erection of blocks on the site – 3.5 per-hrs/t / 6125 per-hrs;
- arrangement of joint on couplings between adjacent carpets and blocks – 0.3 per-hrs/unit / 2280 per-hrs;
- installation of reinforcement in the joints between the blocks – 3 per-hrs/t / 285 per-hrs.

Labor costs on site – 8689 per-hrs.

Total labor costs in the traditional method of construction – 50678 per-hrs, including (specific/total):
- preparation of the metal structures in the workshop – 120 per-hrs/t / 15000 per-hrs;
- preparation of the rebar in the workshop – 12.42 / 22108 per-hrs;
- erection of metal structures on the site – 18.07 per-hrs/t / 2259 per-hrs;
- welding of metal structures on the site – 7.9 per-hrs/t / 987 per-hrs;
- installation of reinforcement in foundation slab – 5.8 per-hrs/t / 10324 per-hrs.

Labor costs on site – 13570 per-hrs.

The cost of the industrial method – 155655 thous. rub., including:
- material cost – 58078 thous. rub.
- manufacturing of reinforcement blocks and the reinforcement carpets in the metal structures workshop – 84647 thous. rub.

1 The cost is calculated in the basic prices, excluding VAT, as at 01.01.2000 with recalculation into prices of the first quarter of 2017. The recalculation index of the estimated cost is accepted according to the letter of the Ministry of Construction of Russian Federation No. 8802-XM/09 dated 20.03.2017 for the Kursk region (Central Federal district).
– transport costs – 6198 thous. rub.
– works on the construction site – 6732 thous. rub.

The cost of the traditional method – 112345 thous. rub., including:
– material cost – 63605 thous. rub.
– preparation of metal structures and rebar – 26866 thous. rub.
– transport costs – 11296 thous. rub.
– works on the construction site – 10578 thous. rub.

The erection of the foundation slab with industrial method allows to reduce labor costs at the construction site in 1.56 times, however, total labor costs will increase by 2.48 times in comparison with the traditional method. The main contribution to the total labor costs is the works in the workshop for the manufacturing of reinforcement blocks. In the calculation was adopted the specific rate 87.7 per-hrs/t on actual data for the workshop of the Novovoronezh-2 NPP, which in our opinion is highly inflated. It is estimated, that during the rational organization of work, the specific labor costs on the production of special metal structures should not be more than 40-45 per-hrs/t [11]. Thus, the reduce of overall labor costs in the industrial technology at 40-45% to 70-75 thous. per-hrs. could be expected. Obviously the total cost of the industrial technology will drop significantly too.

**Figure 5.** Comparative labor costs during the performance of reinforcement works with the traditional and industrial methods

In the transition to the industrial method almost half of the labor costs on the erection of the foundation slab is transferred to factory conditions, causing the reduction by half of the duration of the
works at the construction site. This allows to improve the quality of construction, to smooth out the inevitable seasonal factors affecting the construction process.

Reduction of the labor costs at the site with the industrial method of 1.56 times, on 20 working or 28.5 calendar days, is accompanied by general reduction of the construction period and the economic effect associated with it.

Figure 6. Comparative cost during the performance of reinforcement works with the traditional and industrial methods

To determine the economic effect of the changes in works technology and the reduction of construction period was performed the comparison of the discounted costs associated with the erection of the foundation slab. Since in both cases the works are on the critical path of the NPP construction, was taken into account the change in the duration of power unit construction in general.

Were considered two conditional possibilities:
- reducing the length of the critical path leads to early commissioning of the unit;
- reducing the length of the critical path allows you to begin construction and to reduce economic losses from freezing of capital investments.
The use of the first possibility is connected to the need of early delivery of equipment early performance of the scheme of electric power distribution, and performance of a number of other conditions, so it is hardly feasible, except in the case of correcting the already growing late. Therefore, the comparative effect was calculated based on the second possibility, involving much less assumptions. It took into account only the losses from freezing investments in the longer version, which were determined by the formula:

$$E_{freez} = \sum_{t=1}^{m} \frac{K_{1t} - K_{2t}}{(1+d)^t}$$

where $m$ – number of considered periods;
$K_{1t}$ and $K_{2t}$– capital investments for the compared variants at period $t$;
$d$ – discount rate;
$t_0$ – date of the assignment.

Thus, the economic effect will essentially depend on the discount rate, the assessment of which, generally speaking, depends on macroeconomic indicators. Typically, the value of the discount rate when evaluating the performance of the investments is taken to 10% per year [12].

In the calculation the total capital investments for the power unit of 1200 MW are accepted 150 billion in 2016 prices, the duration of construction taking into account the preparatory period of 7 years, the quarterly distribution of capital investment – similar to the power units VVER-1000, discount rate – 4%.

As the result of the calculation was determined the specific economic effect from the reducing the duration of the power unit construction in the amount of 154.7 million rub. per month (excluding reductions in fixed costs and the additional costs, when increasing the capacity of construction-assembling organizations – effects "from contractor").

If the installation of rebar with industrial method saves 20 working days, then with the settlement fund of working time of 21 days/months, the savings from reducing the duration of construction will amount to 147.3 million rub.

Then the total economic effect from the use of large block reinforcement installation will be 112.3 – 156.7 + 147.3 = 102.9 million rub.

4. Findings

a. The technology of erection of the foundation slab of reactor building of the modern local NPP with power units of 1200 MW with the use of the reinforcement blocks (industrial technology) in comparison with traditional reinforcement in the single-piece rebar allows to reduce labor costs for reinforcement works on-site by 1.5-1.6 times, and the total construction duration on approximately 20 working days.

b. The cost of reinforcement works on the foundation slab when using the blocks increasing by 43.31 million rub., or 39%, compared to traditional reinforcement. However, the total economic effect, taking into account the reduction of the duration of the construction of NPP power unit for block technology, will be 102.9 million rub.

c. The main disadvantages of the taken industrial method of implementation of reinforcement works on the foundation slab include the following:

- does not improve one of the main indicators, which is declared today on the market of NPP projects – the construction duration of NPP "from the first concrete to the first criticality";
- introduction in the early stages of construction of block technologies requires accelerated development of the construction base with the erection of well-equipped workshops, the involvement of special vehicles and cranes with high lifting characteristics with the relevant financial costs;
workability of joints between adjacent reinforcement blocks is questionable. The real labor costs on the connection of rebar of adjacent blocks on the couplings (more than 60 joints with each of the two ends of the block) could be extremely high, which will increase the duration of works on site. As we know, is taken the option with loop joints.

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