Resource assessment of large-block construction of NPP

Andrey Morozenko и Alexey Shashkov
Moscow State University of Civil Engineering, Yaroslavskoe shosse, 26, Moscow, Russia

E-mail: morozenkoaa@mgsu.ru, shashkovaa@mgsu.ru

Abstract. This article explores the features of the use of prefabricated-cast-in-place structures in the construction of nuclear power plants (NPPs), the organizational and economic feasibility of using prefabricated-cast-in-place structures in the implementation of new projects for the construction of nuclear power plants. Modern technological solutions of prefabricated-cast-in-place structures are presented. The organizational and technological features of the use of large-block construction of nuclear power plants in the implementation of foreign projects are identified. Estimated labor and resource costs for the manufacture of large-block structures for the reactor building of nuclear power plants. The dependence of labor costs for the industrial production of reinforcement blocks is obtained, depending on the share of the use of reinforcement blocks in the construction of the reactor building of nuclear power plants. The basic daily resource costs for the production of reinforcement blocks are analytically calculated.

1. Introduction
The history of the use of industrial structures in the construction of nuclear power plants has been around for half a century: prefabricated and prefabricated-cast-in-place structures have been used in the construction of nuclear power plants with VVER and RBMK reactors [1, 2]. The most successful project for the implementation of large-block construction of nuclear power plants in the USSR was the construction of the Zaporizhia NPP [3]. When constructing the Zaporizhia NPP, a reduction in specific labor costs by 25-30% was achieved in comparison with the constructed NPPs of the same capacity [4].

In the post-Soviet era, the designed plants, as a rule, were designed for the construction method with a low level of industrialization: cast-in-place reinforced concrete structures were constructed mainly using piece reinforcement directly at the construction site (“in bulk” reinforcement) and inventory formwork. Block constructions were used only partially, as a rule, for the erection of the inner containment (IC). Examples are the AES-92 and AES-2006 projects.

In the most modern design project of Russian design, VVER-TOI returned to the idea of large-block construction of the main construction projects on the critical path in prefabricated-cast-in-place structures. The main idea of the VVER-TOI project was the acceleration of construction (the introduction of the first block 48 months after the start of construction, the next 40) [5]. Shortening the construction time of power units has a direct economic effect due to an earlier return on investment due to electricity generation [6]. At the same time, new technological solutions are applied, among which it is worth highlighting the use of steel-fiber concrete panels as fixed formwork [7, 8]. Along with reinforced formwork blocks (reinforcement blocks) with steel-fiber concrete formwork, reinforcement blocks with formwork made of metal sheet are also used.
Foreign solutions also have technologies for large-block construction of nuclear power plants [9-11]. The most promising and studied technology is Steel-plate composite (SC) [12, 13]. Unlike Russian technology, where the classic tensile reinforcement bears the tensile load, while steel-fiber-reinforced concrete and metal sheets perform only the role of fixed formwork for the period of concrete construction, the SC technology uses external reinforcement of building structures. Steel sheets play the role of both fixed formwork and sheet reinforcement, perceiving tensile stresses. From the point of view of the organization of production, questions remain regarding the appropriateness of using such structures. Along with the advantages reflected in the installation speed, complex structural blocks SC require high labor costs in factory manufacturing, as well as require equal strength butt joints over the entire area of the structures and corrosion protection and its updates throughout the entire operation of the plant.

It is obvious that the use of industrial structures is aimed at reducing the construction time for the main NPP facilities, which, as a rule, are on the critical path. The most striking example of such buildings is the reactor building. However, with a high knowledge of the technological base of application of reinforcing formwork (strength and deformation characteristics, manufacturing technology of blocks, etc.), the organization of production using large-block prefabricated-cast-in-place structures is extremely poorly studied. Accordingly, there is no streamlined concept for the organization of the construction project, since the first reference unit of the VVER-TOI project, which will be the first power unit of the Kursk NPP-2, is currently under construction. However, already at the moment it is possible to put forward the assumption that structural reorganization can increase the efficiency of large-block construction of nuclear power plants due to the competent redistribution of labor between participants in the construction project.

Studying this issue poses the task of creating a methodology for the formation of the organizational structure of the project. In particular, the objectives of this methodology is to determine the need for labor and material support for project development and maintenance, construction industry enterprises, logistics facilities and construction organizations. The development of this methodology is necessary for the implementation of foreign construction projects, which have a predominant share in the portfolio of orders of the engineering division of the Rosatom state corporation. Currently, the use of large-block technology for building nuclear power plants abroad is difficult, because there are a number of unresolved problems:

1. The lack of a reference block in the Russian Federation built using large block construction as the main technology for subsequent replication on foreign projects;
2. Weak production base in developing countries, which occupy a major share among foreign customers;
3. Low qualification of local workers and engineering personnel.

Therefore, when developing organizational models for large-block construction of nuclear power plants during the implementation of foreign construction projects in regions with poorly developed material resources and low qualifications of personnel, it is necessary to create several scenarios:
1. With the creation of enterprises only for the duration of the construction of nuclear power plants;
2. With the creation of enterprises for a long time to produce products for the needs of civil and industrial construction in the future;
3. With the delivery of structures from other countries, including from Russia.

All three of these scenarios may be applicable. The decision to choose one of the three scenarios is made individually for each project. However, in order to make an informed decision, it is necessary to analyze labor costs and resource costs for the production of reinforced concrete structures and determine the need for construction industry enterprises to implement a nuclear power plant construction project.

A hypothesis is put forward that the transfer of part of the labor costs from the construction site (during the transition from reinforcing “in bulk” to the production of reinforcing formwork) to the workshops reduces the overall duration of construction by reducing the time of construction and
installation works. To test this hypothesis, it is necessary to determine the labor costs and required resources at least for factory manufacturing and for the installation of reinforcement blocks. This article provides a detailed method for determining the first component: labor costs and resource costs of the industrial production of reinforcement blocks in workshops.

2. Methods
The main study is the resource method [14]. Based on the assessment of the required resources, the dependence of the labor costs for the industrial production of reinforcement blocks is determined depending on the share of the use of reinforcement blocks in the construction of the reactor building of nuclear power plants. Evaluation of resources is based on a sample of statistical data from real production, which provides the closest to real values. Sufficiency of the sample is ensured by the variety of data within the sample and their similarity with data outside the sample due to the typification of the studied structures.

Labor costs and resource costs for the factory production of reinforcing formwork for the needs of large-block construction of nuclear power plants were determined on the basis of statistical data on the manufacture of third-tier blocks of the IC of the first power unit of Rooppur NPP (People’s Republic of Bangladesh, Pabna, Ishwardi, Pakshi Road Station). Data was collected on the manufacture of 12 reinforcing blocks in the workshop on the territory of the construction and installation base of nuclear power plants, which are a closed belt with various types of blocks. Blocks of other IC belts are fundamentally similar. The initial data were the geometric dimensions of the blocks based on the working documentation, data on the size and equipment of the workshop, data on the number and composition of the brigade of workers, as well as a daily schedule. All collected data was analyzed and presented in the required format. As the calculation results, it is necessary to obtain the required labor costs for the production of different types of blocks, the dependence in human labor costs depending on the percentage of the total volume of structures erected by the industrial method, as well as the necessary resources for the manufacture of these structures.

The extrapolation of data on labor and resource costs for the manufacture of IC blocks into blocks for the construction of other reinforced concrete structures of the reactor building is carried out by eliminating production processes that are unique to IC blocks. At the same time, a number of assumptions are made:

1. Production processes that are not unique to IC blocks are similar for all block designs;
2. The type of fixed formwork (metal, steel fiber concrete, etc.) is not taken into account. Abstraction from the type of formwork is ensured by the fact that the calculations are made on the volume of reinforced concrete limited by the block, and not on a ton of the mass of the block;
3. When extrapolating data on the labor costs of manufacturing blocks to blocks of various thicknesses, it is assumed that the labor costs of processes, the volume of which depends on the area of the front surface of the block, does not depend on the thickness. Moreover, that the labor costs of processes, the volume of which depends on the thickness of the block, is directly proportional to it.

When constructing the dependence of the labor costs for the industrial production of reinforcement blocks depending on the proportion of reinforcement blocks used in the construction of the reactor building of a nuclear power plant, the result is determined depending on the choice of specific structures for manufacturing in prefabricated-cast-in-place structures. Thus, graphically, the dependence is depicted by the area of possible values limited by the maximum and minimum possible values.

3. Results
The dimensions of the blocks were determined by the following parameters: height 14 m, sector angle 27 ... 36 °, inner radius 22 m wall thickness 1.2 m, length on the outside 10.9 ... 14.6 m. On average, the considered blocks limit the volume of reinforced concrete in the size of 198.8 m³. The dimensions of the workshop are 72x39 m, the workshop is equipped with two bridge cranes with a lifting capacity of 20 tons each. The area of the open assembly and storage area is 2100 m², the platform is equipped
with two gantry cranes with a lifting capacity of 50 tons. The number of workers is 50 people per shift. Work is carried out in 2 shifts of 10 working hours. The graph below (figure 1) shows the work on the manufacture of blocks taking into account the flow organization of processes.

**Figure 1.** Schedule of production of IC blocks with daily calculation of processes

The average production time of the IC block is 47 days. At the same time, in the established period (when the workshop produces only the blocks under consideration), 5-6 blocks are produced (on average 5.3 blocks for the indicated period). We get that the average labor costs for the production of 1 block of IC are 8868 man-h. The calculation was carried out according to the formula:

\[
\bar{C}_{IC} = \frac{n_{worker} \cdot t_{shift} \cdot n_{shift} \cdot \bar{n}_{block}}{5.3} \cdot 47 \text{ day} = 8868 \text{ man} - h
\]

\( \bar{C}_{IC} \) – average labor costs for the production of 1 block of IC, man-h;

\( n_{worker} \) – the number of workers in the brigade in 1 shift, man;

\( t_{shift} \) – shift duration (working hours), h;

\( n_{shift} \) – the number of shifts per day, day\(^{-1}\);

\( \bar{n}_{block} \) – the average number of blocks produced in parallel by the brigade;

\( t_{block} \) – average production time of 1 block of IC.

Thus, for the walls of the inner containment, the specific average labor costs of producing blocks expressed in 1 m\(^3\) of concrete of structures limited to the block will be:

\[
\bar{c}_{IC} = \frac{\bar{C}_{IC}}{V_{IC}} = \frac{8868 \text{ man} - h}{1980 \text{ m}^3} = 44.6 \text{ (man} - h)/\text{m}^3
\]

\( \bar{c}_{IC} \) – specific average labor costs of production of IC blocks, (man-h)/m\(^3\);

\( \bar{C}_{IC} \) – average labor costs for the production of 1 block of IC, man-h;

\( V_{IC} \) – volume of concrete structures limited to the block, m\(^3\).

The IC blocks were chosen as the source of statistical data, since at the Rooppur NPP by the large-block method only the inner containment is constructed. Since IC is a special design, in the production of blocks there are special technological processes that would not be in the production of reinforcing blocks for other designs of the reactor building of the NPP. Among these processes: welding of joints, control of welds and corrosion protection from the side of concrete and from the sealed zone, installation of channel formers. To calculate the needs of the entire reactor building in the labor and resource costs of the enterprises of the construction industry, we exclude the processes that are characteristic exclusively for IC blocks. Applying the rearrangement of processes, we obtain the following schedule for the production of blocks, which we call conditional (figure. 2).
Based on the correlation of the daily process calculation schedules, we obtain the labor cost coefficient of conventional blocks 1.2 m thick towards the IC blocks:

\[ k_{1.2} = \frac{452}{616} = 0.734 \tag{3} \]

\[ k_{1.2} \] – the ratio of the labor costs of conventional blocks with a thickness of 1.2 m and IC blocks;

452, 616 – areas of the daily process calculation graphs, expressed by the number of processes per day.

The specific average labor costs for the production of conventional blocks, expressed per 1 m³ of concrete of structures limited to a block 1.2 m thick, will be:

\[ \overline{c}_{\text{conv}}^{1.2} = k_{1.2} \cdot \overline{c}_{\text{IC}} = 0.734 \cdot 44.6 \frac{(\text{man} - \text{h})}{m^3} = 32.7 \frac{(\text{man} - \text{h})}{m^3} \tag{4} \]

\[ \overline{c}_{\text{conv}}^{1.2} \] – specific average labor costs of production of conventional blocks with a thickness of 1.2 m, (man-h)/m³;

\[ \overline{c}_{\text{IC}} \] – specific average labor costs of production of IC blocks, (man-h)/m³;

\[ k_{1.2} \] – coefficient of the ratio of labor conditional blocks and IC blocks;

When changing the thickness of the conditional unit in accordance with the thickness of the structures of the reactor building, the labor costs only change for installing vertical and horizontal trusses, as well as installing transverse reinforcement. Labor costs of other processes depend on the area of the external surface of the block and do not depend on its thickness. As can be seen from the graph in figure 2, the total labor costs of the installation of vertical trusses, horizontal trusses and transverse reinforcement is 93/452, or 20.6%. We assume that the labor costs of these works varies in direct proportion to the thickness of the block. When calculating the average specific labor costs (per 1 m³), we take into account that these labor costs will increase inversely proportional to the thickness of the block, since 79.4% of the total labor costs for the construction of the block does not depend on its thickness. Based on these data, we obtain a formula for determining the average specific labor costs of blocks of any thickness:

\[ \overline{c}_{\text{conv}}^{\delta} = \overline{c}_{\text{conv}}^{1.2} \cdot \left(0.206 \cdot \frac{\delta_i}{1.2 m} + 0.794\right) \cdot \frac{1.2 m}{\delta_i} = \frac{c_{\text{conv}}^{1.2}}{\delta_i} \cdot \left(0.9528 m + 0.206\right) \tag{5} \]

\[ \overline{c}_{\text{conv}}^{\delta} \] – specific average labor costs of producing conventional blocks with a thickness of \( \delta_i \), (man-h)/m³;

\[ c_{\text{conv}}^{1.2} \] – specific average labor costs for the production of conventional blocks with a thickness of 1.2 m, (man-h)/m³;

\[ \delta_i \] – block thickness, m.

To determine labor costs for varying degrees of use of reinforcing blocks in the construction of a reactor building, we will focus on the volumes of cast-in-place concrete in the building structures, obtained based on statistical data. The distribution of volumes of cast-in-place concrete by the structures of the reactor building is shown in table 1.
Table 1. Distribution of cast-in-place concrete volumes by reactor building structures

| Design name                  | Concrete volume, m³ | The average thickness of the structure, m | Share in the total concrete volume of the building, % | Share in the total concrete volume of the building, excluding IC, % |
|------------------------------|---------------------|------------------------------------------|-----------------------------------------------------|-----------------------------------------------------------------|
| Foundation slab              | 17062               | 3,0                                      | 17,9                                                | 20,8                                                            |
| Transport portal             | 1056                | 1,5                                      | 1,1                                                 | 1,3                                                             |
| Contour walls                | 6289                | 0,5                                      | 6,6                                                 | 7,7                                                             |
| Annex                        | 29420               | 0,4                                      | 30,9                                                | 35,9                                                            |
| Accident confinement area (ACA) | 16618            | 1,0                                      | 17,4                                                | 20,3                                                            |
| Outer containment (OC)       | 6317                | 0,5                                      | 6,6                                                 | 7,8                                                             |
| Inner containment (IC)       | 13462               | 1,2                                      | 14,1                                                | -                                                               |
| Passive heat removal system (PHRS) | 5106              | 0,5                                      | 5,4                                                 | 6,2                                                             |

When deciding on the degree of use of blocks of industrial manufacture in the construction of nuclear power plants, the priority design is the IC, which in this case is constructed using reinforcement blocks completely. Therefore, the dependence of the increase in labor costs for the manufacture of reinforcement blocks will first increase stepwise by the amount of labor for the manufacture of IC blocks.

The average unit labor costs of producing conventional blocks of various thicknesses, calculated by the above formula to determine the average unit labor costs of blocks of any thickness (5) based on the data from table 1 are shown in table 2.

Table 2. Averaged specific labor costs for the production of conventional blocks of various thicknesses

| The average thickness of the structure, m | Specific labor costs, (man-h)/m³ |
|------------------------------------------|---------------------------------|
| 0,4                                      | 84,6                            |
| 0,5                                      | 69,0                            |
| 1,0                                      | 37,9                            |
| 1,2                                      | 32,7 (44,6 for IC)              |
| 1,5                                      | 27,5                            |
| 3,0                                      | 17,1                            |

Based on the data obtained, we deduce the dependence, taking 953.3 m³ for 1% of the use of reinforced units in the total volume of reinforced concrete structures of the reactor building. The analytical form of the median of this dependence will look as follows:

\[ C_{ind} = 54291,338 \cdot x - 165102,7 \]  

\( C_{ind} \) – labor costs of the industrial production of reinforcement blocks for the reactor building of nuclear power plants, man-h;

\( x \) – required share of manufacturing reinforced concrete structures of the reactor building in industrial structures, %.

It should be borne in mind that the minimum share of \( x \) can be equal to 14.1% (production of VZO in industrial structures). With values less than 14.1%, the labor costs will be zero.

This dependence is shown in the form of an area limited by broken lines, showing the boundary indicators of increasing labor costs, shown in figure 3. The presence of area, and not a single graph, is due to variations in the sequence of construction of blocks of different thicknesses. It should be borne in mind that labor costs with a share of using reinforcement blocks over 80% are purely theoretical, since the real share of using industrial structures rarely exceeds 80% of the total volume of buildings. The remaining 20% or more are butt joint constructions, as well as complex structures constructed in inventory formwork.
Figure 3. The magnitude of labor costs for the industrial production of reinforcement blocks, depending on the proportion of the use of reinforcement blocks in the construction of the reactor building of nuclear power plants.

As the parameters of specific resource consumption, we will consider the need for workshop premises, in the square of open areas, in bridge and gantry cranes. All specific needs will be determined for 1 man-h of labor costs of the production of structures. The formula for determining the specific resource consumption for each parameter will be written in the following form:

\[ r_i = \frac{Q_i}{n_{\text{worker}}^{\text{shift}}n_{\text{shift}}} \]

- \( r_i \) – specific resource consumption of the \( i \)-th parameter;
- \( Q_i \) – quantitative measure of the \( i \)-th parameter;
- \( n_{\text{worker}} \) – the number of workers in the brigade in 1 shift, man;
- \( t_{\text{shift}} \) – shift duration (working hours), h;
- \( n_{\text{shift}} \) – the number of shifts in days, days\(^{-1}\).

We get that at 1 (man-h)/m\(^3\) the labor costs of production of IC blocks per day requires 2.8 m\(^2\)/(man-h·day) of workshop premises, 2.1 m\(^2\)/(man-h·day) of open areas and at 0.002 (man-h·day)\(^{-1}\) bridge and gantry cranes.

Since it is not possible to determine a quantitative change in the use of resources in the manufacture of blocks of various configurations, we conditionally assume the values obtained are constant for blocks of various configurations. The refinement of the data obtained is possible only based on further collection of statistical information.

4. Discussion

The data obtained in this article are an important addition to existing standards, since they allow you to take into account a greater number of nuances that arise in real production. It allows you to use more accurate values when organizing new investment and construction projects.

Based on further statistical analysis of other components of the NPP construction project, such as design, transportation, enlargement and assembly, as well as taking into account current regulatory documents, it is possible to build a comprehensive model of the project and make an accurate analysis of the reduction in the construction time of the NPP and the optimal distribution of labor between the
participants of investment construction project. This model should become the basis of a new methodology for the formation of the organizational structure of the project for large-block construction of nuclear power plants, based on which in the investment and construction projects for the construction of new nuclear power plants around the world should be formed in the future.

5. Conclusions

1. Large-block construction is a relevant and promising method of organizing the construction of new nuclear power units, including the implementation of foreign projects. Since there is extensive experience in the construction of reinforced concrete blocks of about 14% of reinforced concrete structures, this figure can be brought up to 80%.

2. The dependence of the labor costs for the industrial production of reinforcement blocks depending on the share of the use of reinforcement blocks in the construction of the reactor building of a nuclear power plant allows us to determine the need for labor costs for the partial or maximum possible use of industrial structures. In addition, when setting in the inverse problem, determine the maximum degree of use of industrial structures in construction based on the existing labor and resource base.

3. The use of a large share of the manufacturing of building structures of nuclear power plants by the industrial method transfers a significant part of labor costs from the construction site to the factory floor. This requires a fundamental transformation of the organizational structure of the investment and construction project.

References

[1] Petrosyants A M et al. 1987 *Atomic Science and Technology of the USSR* ed Petrosyants A M (Moscow: Energoatomizdat)

[2] Gritsenko A S The technology of large-block installation of non-removable formwork of reactor compartments of nuclear power plants 1990 *Diss.* (Kiev)

[3] Pergamenshchik B K, Telichenko V I, Temishev R R 2011 *Erection of special protective nuclear power plant designs* (Moscow: MPEI pub. house)

[4] Morozenko A A и Voronkov I E 2014 Improving the efficiency of organizational and technological solutions when constructing nuclear power plants on the basis of contemporary russian and foreign experience *Promyshlennoe i grazhdanskie stroitel'stvo* no 10 pp 74-79

[5] Osokin A 2012 VVER-TOI Construction Organization Project (Rosenergoatom) no 12

[6] Morozenko A A and Shashkov A A 2019 Organizational and technological aspects of large-scale construction of nuclear power plants *Science and Business: Development Ways* no 5(95) pp 28-33

[7] Dorf V A, Krasnovskiy R O, Krol I S и Kapustin D E 2016 Prefabricated-cast-in-place technology of building construction using nondetachable steel-fibre-concrete form *North of Russia: Strategies and Development Prospects* (Mat. of the II All-Russian Scien. and Pract. Conf.) pp 77-82

[8] Kapustin D E, Rogachev K V и Kapustin A E 2014 Application of permanent fiber reinforced concrete formwork *Regional architecture and engineering* no 2 pp 102-109

[9] *Construction Technologies for Nuclear Power Plants* 2011 (Vienna: IAEA)

[10] Presley B L and Weber B 2009 Modularizing containment vessels in new nuclear power plants *Power Business and Technology for the Global Generation Industry* vol. 153 no. 11

[11] Kajiyama N, Hamamura K and Murayama K 2009 Hitachi’s involvement in nuclear power plant construction in Japan *Hitachi Review* vol. 58 no. 2 pp. 48-52

[12] Chakraborty S, Sinha S, Chakraborty S, Das S, Shiv Yadav S C, Mandal M K and Kumawat S 2016 Nuclear Power Plants: Innovative Construction Technique and Design *Journal of Energy Research and Enviromental Technology (JERET)* vol. 3 issue 3 pp. 176-180
[13] Varma A H, Malushte S R and Lai Z 2015 Modularity & innovation using steel-plate composite (SC) walls for nuclear and commercial construction *11th Int. Conf. on Advances in Steel and Concrete Composite Structures* (China, Beijing, Tsinghua University) 3-5

[14] Morozenko A A 2010 Material and resource assessment of sustainable functioning of enterprises in the construction industry *Vestnik MGSU* no 2 pp 261-263