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Features of the Design and Construction of Nuclear Power Plants

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Abstract: The relevance of the chosen topic lies in the need to conduct a comprehensive analysis of the majority of the world's most common nuclear reactors and plants to identify their distinctive features to determine the key factors influencing the way the final object is designed.

The main method of solving this task is to study the reference literature and research of the International Atomic Energy Agency (IAEA), as well as official publications of companies engaged in basic nuclear engineering activities in the producing country.

The results of the conducted research are a list of key factors influencing the definition of the methodology for designing nuclear power plants, as well as a list of possible strategic directions for the implementation of nuclear projects. The results described in the paper can be applied by students and specialists studying the principles and strategies of the nuclear industry development.

Keywords: scientific community, nuclear industry, nuclear physics, construction strategy, research methodology, pressurized water reactor, VVER, PWR, CANDU, steam generators, NPP device, power reactor, nuclear power plant.

Introduction

Design, construction, and commissioning are the main activities of a nuclear power engineering company. In Russia, it is the state-owned company Rosatom, its direct western competitors are the American Westinghouse and the French Orano (formerly Areva).

The International Atomic Energy Agency (IAEA) International Atomic Energy Agency (IAEA), which is recommendatory, assists member countries in developing issues related to safety standards, technical supply, legal support, etc. for the implementation of safe and legal nuclear activities [7].

The most important stage in the construction of a nuclear facility is its design, in which the principles of the whole industry are laid down, resources (fuel, materials, highly qualified personnel, logistics chains, subcontractors, suppliers, etc.), and the ultimate goal of the project are carefully determined.

Considering the general model of NPP design, it is worth outlining its main components and operating principles.

Nuclear power plants use the fissile radionuclide ^{235}U and in some cases ^{239}Pu as fuel.

Energy at nuclear power plants undergoes three types of transformation:

- transformation of nuclear energy into thermal energy;
- transformation of thermal energy into mechanical energy;
- transformation of mechanical energy into electrical energy.

The basis of NPP is a nuclear reactor with a core, in which fuel assemblies consisting of fuel elements (fuel elements of fuel elements of fuel elements fuel elements (fuel elements are compressed pellets of enriched uranium) are immersed.

The uranium is fissioned by bombardment with thermal neutrons, resulting in new neutrons to support the fission chain, a pair of fission fragments (radioactive waste), and an energy of 200 MeV.

A mandatory part of a modern NPP is an automated process control system (APCS). It allows controlling the fission process and also activates the emergency protection system - quick termination of the fission reaction in case of emergencies.

A liquid or gaseous coolant removes heat from the core and converts it into water vapor, which is sent to the steam generator. The mechanical energy generated by the steam generator is then directed to the turbine generator, where it is transformed into electrical energy and sent through transmission lines to the end user.

In addition, the plant has a storage pool for **spent** nuclear fuel SNF, cooling towers, and a cooling pond (natural or artificial).

Depending on the reactor type, a nuclear plant may have 1, 2, or 3 coolant circuits. In Russia, two-circuit NPPs with VVER-type reactors (water-water power reactors) are the most widespread.

The single-circuit scheme is used at nuclear power plants with RBMK-1000-type reactors. The reactor operates in a unit with two condensing turbines and two generators. At the same time, the boiling reactor is itself a steam generator, which makes it possible to use the single-circuit scheme. The single-circuit scheme is relatively simple, but the radioactivity in this case spreads to all elements of the unit, which complicates biological protection.

The double-circuit scheme is used at nuclear power plants with water-water reactors of the VVER type. Pressurized water is supplied to the reactor core, which is heated. The energy of the coolant is used in the steam generator to generate saturated steam. The second circuit is non-radioactive. The unit consists of one 1000 MW condensing turbine or two 500 MW turbines with corresponding generators.

The three-circuit scheme is used at NPPs with fast neutron reactors with sodium coolant of BN type. To exclude contact of radioactive sodium with water, a second circuit with non-radioactive sodium is constructed. Thus, the scheme turns out to be three-circuit.

However, the described principles of nuclear power plant operation do not mean that all plants built and under construction today have the same structure. Different countries that manufacture nuclear reactors are guided by their principles and methodology for developing the design of power units.

Literature Review

To understand the principles, methodologies, and strategies by which different companies produce nuclear power units and power plants in the first place, it is necessary to understand the distinctive features of some of them.

The issue of determining the methodology and strategy in the design, construction, and operation of nuclear power plants is determined by the degree of its elaboration, technological, and research potential of the country that is engaged in the development of the nuclear industry.

The descriptive part of general and specific characteristics of nuclear power units can be found in published research papers, news articles, both the manufacturer's own company and in collections and documents of the international agency IAEA, in which the latter describes the actual differences in nuclear power units of different countries.

Every few years, for requirements or other informational and technological reasons, the agency carries out the so-called "IAEA Mission", in the framework of which scientists are sent to a nuclear industry facility (nuclear power plant - NPP, radioactive nuclear waste disposal facility - RAW or spent nuclear fuel - SNF, as well as mining and nuclear test sites). Based on the data obtained from on-site inspections and studies, as well as documents received upon request directly from the companies performing the above actions, the international agency's reports are formed.

The IAEA also publishes its own informational articles and research papers on its official website [1-2, 8-10].

In addition to the works published by the International Agency, scientific publications of TsNIITMASH "Rosatom" were used to elaborate the topic of the article [4], describing the technical features of reactors of different countries.

To elaborate on the questions posed in this article, the works of I.Y. Listopadov and E.V. Semenov were analyzed. [3], devoted to the El-Dabaa NPP in Egypt, its design features, and strategic goals, as well as Garland Wm.J., Afrov A.M., Vasiliev B.Y., Generalov V.N., Ukrainzeav V.F., Kosourov K.B., Andrushechko S.A., Semchenkov Y.M., and Molchanov V.L., related to the devices of nuclear reactors of various designs [5-7].

Materials and Methods

Comparing the most widespread pressurized water reactor of domestic and Western design, we note that there are only two principal differences:

1. The **fuel rod cladding** (Zircalloy-4 for PWR and E110, E635 for PWR). The domestic sample is more resistant to oxidation and corrosion.
2. The **shape of** the fuel **assembly** is square for PWR and hexagonal for VVER. The hexagonal shape leads to uniformity of neutron parameters.

Another distinguishing feature of the model development of a domestic from a Western pressurized water reactor is the size of the hole in the fuel assembly (see Figure 1). At high pressure, the fuel element shifts to the center, and at high temperatures, the fuel element melts. Thus, the domestic approach in developing the fuel element was primarily aimed at fuel safety; it is more stable in case of emergency incidents. However, due to the peculiarity of the domestic design, the fuel in the VVER burns out faster, which makes the Western design more economically efficient.

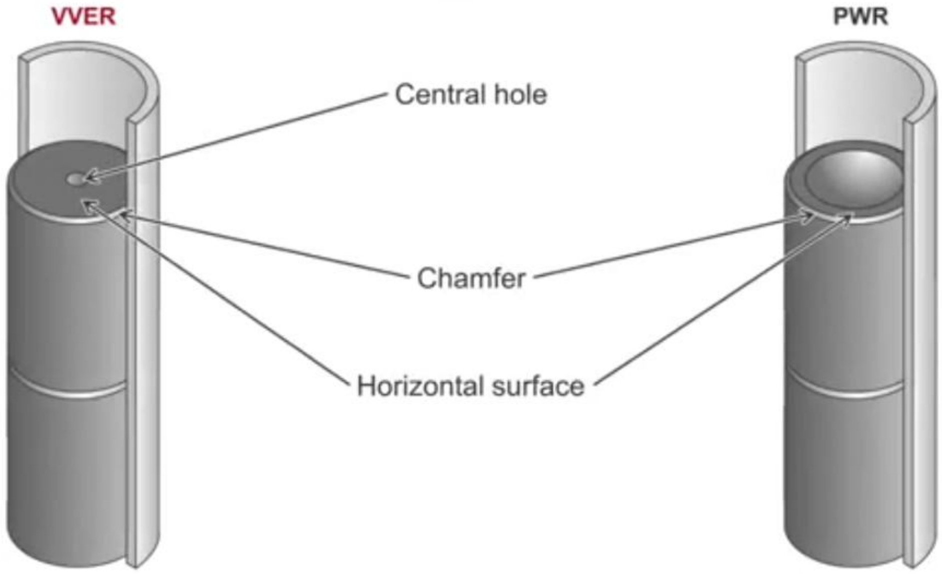

Figure 1 – Differences between domestic and Western fuel rods.

Specific gravity (the inverse of Table 1) is the weight of the material divided by the installed capacity, which is the highest for the Russian design.

Western designs are often constructed and transported by water, which determines **special design conditions**. Russian modern reactors are transported by railroads. This seemingly insignificant difference in logistics determined the emphasis of Russian scientists on more detailed elaboration and study of fuel technologies and calculation of their effect on the design.

The last distinguishing feature of Russian VVERs from Western and Korean nuclear reactor designs is the **position of the steam generators** (see Figure 2).

From the point of view of physics, there is no difference in the vertical or horizontal position of the steam generators, but there is a difference in technology.

The steam generator in a nuclear reactor design is a very vulnerable element. In the horizontal position, the coolant reserve is increased, natural circulation is improved, and the horizontal position is economically preferable because the steam generator does not need frequent replacement, as in some Western designs.

Thus, the model and strategy of nuclear reactor development and design in Russia are tied to safety and technology, whereas in the West it is tied to economic efficiency.

Along with technical and techno-economic strategic features of NPP construction, politics, diplomacy, and general commodity relations with partner countries play a major influence.

For example, during the construction of the Russian VVER-1200 nuclear power plant in Egypt near El Dabaa, in addition to the construction of NPPs consisting of 4 power units, the Russian state company Rosatom offered an integrated solution for seawater desalination.

Table 1 – Distinctive design features of some of the most common reactor models in different countries [4].

Parameter	AP-1000	VVER-1200	APR-1400	EPR-1600
Total internal height, mm	12 056	11 185 (outside)	14 800	13 083
Inner diameter of cylindrical shell, mm	4 039	4 250	4 655	4 870
Cylindrical shell wall thickness, mm	203	197,5	284	250
Pressure, MPa	17,2	17,6	17,2	17,6
Temperature, ^{o}C	343,3	350	343,3	351
Weight, t	340	330	573	520
Specific weight, t/MW	0,34	0,28	0,41	0,32

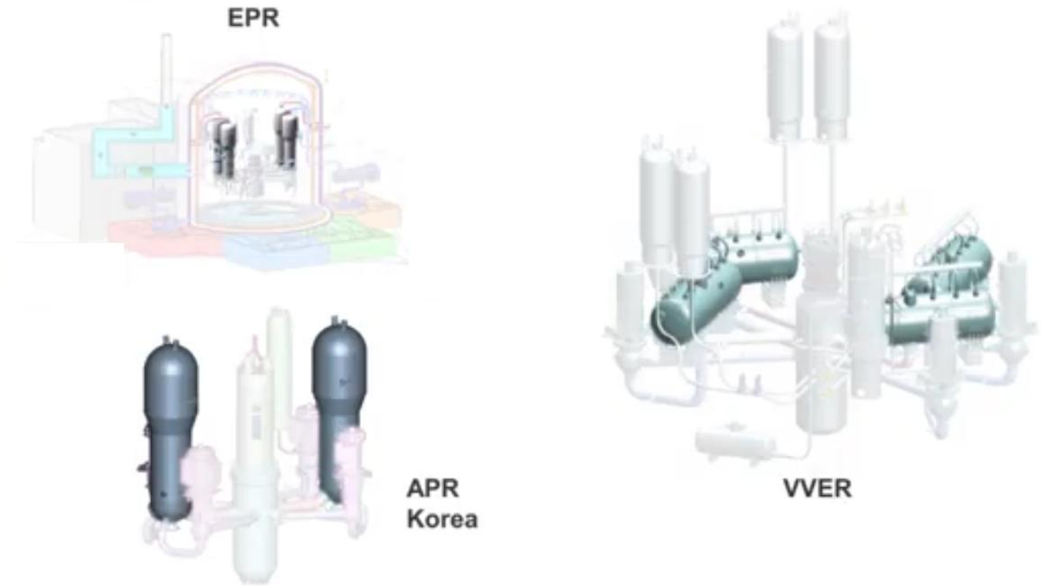

Figure 2 – The position of steam generators in the design of a nuclear reactor.

Thus, the construction of the nuclear plant also solves a host of issues for the Egyptian government, namely:

- Solving the demographic crisis of overpopulation in the cities near the Nile River;
- solving the energy crisis by including four power units with a total capacity of 4800 MW;
- development of the new territory and attraction of investments and tourists (NPP as a city-forming enterprise).

For Russia, this precedent opens an opportunity for interaction with a whole new continent [3].

When determining the methods of plant design, the technical potential of the country and its resources play a great influence.

For example, Canada uses the world's only model of nuclear reactor CANDU (Canada Deuterium Uranium). Comparing it with the Russian VVER, it is important to note that its core is horizontal, its steam generators are vertical, and there is no additional enriched fuel.

The Canadian reactor uses heavy water ($_{D2O}$) as a moderator, which significantly increases the cost of construction, but in contrast to this it greatly reduces the cost of the fuel cycle, as the fuel can work out 2 times longer than in reactors with pressurized water. Canada actively uses this method because geographically, the country has a large number of natural heavy water pools [8].

The reactor is placed horizontally, but as in other reactors, the emergency rods are placed vertically to allow gravity to quickly discharge power and stop the fission chain.

Also, reloading can be done from both ends of the core, and the fuel assemblies (fuel assemblies, packages of sealed tubes containing nuclear fuel) are not long rods, as in vertical reactors, but short packages loaded one after another [8].

Canada built its type of reactor by maximizing its geographic location, resource availability, technical base, and neutrality. The unique combination of these factors in due time allowed this country to develop its type of power reactors and actively apply them. The key features of this pathway are the cheapness of fuel for nuclear power plants, no need to close nuclear plants, and a unique pathway.

Results and Discussions

As a result of the work done in the field of studying the methodologies, strategies, and principles of design and construction of nuclear power plants and power units in particular, it can be concluded that there are three main decision-making strategies in the construction of new NPPs. Namely:

1. The strategy of focusing on the safety of the nuclear plant by detailing the technological and physical processes of the entire plant from the start of the project design.
2. The strategy of focusing on reducing the costs or increasing the value of associated products (e.g. fuel assemblies) to increase the economic impact of the sale and logistics of power units and components.
3. A strategy of political gain by creating a value chain (e.g., seawater desalination) and helping states

address related issues to maintain long-term diplomatic dialog and erect demonstration projects on the continent.

Conclusion

The research conducted in the field of nuclear power plant construction, identification of the basic principles and strategic goals of their design and further erection leads to the conclusion that when developing construction methodology, companies are guided by:

- available resources;
- the level of technological and personnel potential;
- safety of technologies;
- logistical and geographical peculiarities;
- economic and political climate.

These factors have a direct impact on the chosen strategy based on security, technology, politics, or economic benefit.

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